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Modelling and Optimization of Waste-to-Energy Developments for Net Zero Energy Buildings (NZEBs)

A thesis Submitted to the College of Science and Engineering in
Fulfilment of the Requirements of the Degree of Doctor of Philosophy
(PhD) in Mechanical Engineering at the University of Glasgow

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Abstract

The pressing issues of waste management and decarbonizing the building sector in the context of climate change and global warming necessitate innovative solutions. This study explores Net-Zero Energy Buildings (NZEBs) and waste-to-energy technologies as pivotal low or zero-carbon alternatives to conventional fossil fuel-based approaches in building construction and waste management.

Waste-to-energy technologies emerge as crucial players in the development of NZEBs, simultaneously addressing the triple crisis of waste accumulation, climate change, and escalating energy demands. The chosen waste-to-energy technologies employ thermochemical and biochemical processes to convert diverse waste feedstocks available in Glasgow. These technologies operate under specific operational conditions tailored to the unique characteristics of the waste materials. The waste treatment methods under consideration in this study include gasification (thermochemical), pyrolysis (thermochemical), and anaerobic digestion (AD). Three distinct types of feedstocks- gardening waste, food waste, and wood waste are considered to assess the efficacy of these technologies across various wastes.

Energy hails from green sources, particularly bioenergy, playing a critical role in combatting fossil fuel depletion and climate change. Despite its increasing share in the energy mix, gaps persist in understanding the technological configurations of bioenergy-supported NZEBs, optimal feedstock, technology selection, and the absence of relevant optimization models.

Scotland, where waste and building energy are significant contributors to individual emissions, becomes the focal point. Glasgow, chosen for its sizable population guaranteeing consistent waste supply, aligns with the city's commitment to decarbonization, which will be evident in strategies such as Net Zero by 2045. This study aims to showcase how low-carbon energy production from waste aligns with the city’s energy plan and supports waste management strategies. These plans and strategies are thoroughly examined in Chapter 7 of this study. This critical assessment delves into the current state of Scotland's zero waste initiatives and evaluates the region's renewable energy policies and targets. The evaluation encompasses environmental impact, economic implications, and alignment with climate policies.

The research question centres on the economic and environmental feasibility of waste-to-energy technologies supporting NZEBs and sustainable waste management schemes within Glasgow. A feasible project should demonstrate carbon savings compared to conventional methods in waste

management and energy production, ensuring positive returns on economic investment without outweighing the environmental benefits. The study critically assesses waste-to-energy technology development, considering environmental impact, potential carbon savings, financial implications, cost benefits, and climate policy.

The novelty of this study lies in establishing a procedure defining how waste-to-energy technologies can serve as a renewable energy source for the burgeoning NZEBs and contribute to sustainable waste management. Environmental impact analysis and economic assessment results contribute valuable datasets to existing research. Life Cycle Assessment (LCA), Cost-Benefit Analysis (CBA), Multi-Criteria Analysis (MCA), and Multi-Objective Optimization (MOO) have been conducted to determine the feasibility of waste-to-energy projects to support NZEBs and sustainable waste management schemes.

Designing various waste-to-energy scenarios based on biomass waste feedstock, the study employs thermochemical and biochemical technologies to convert different waste feedstocks, including gasification, pyrolysis, and AD. The ten designed scenarios allow for a comprehensive comparison of environmental and economic results, considering variations in waste feedstock type and technology, leading to differences in energy production rates, yields, and process carbon emissions.

The environmental approach centres on the LCA method, evaluating environmental performance through carbon-saving potential using Global Warming Potential (GWP) as the impact indicator for waste-to-energy technologies. The study reveals that waste-to-energy technologies can reduce 65% of CO_2-eq emissions per tonne of feedstock. During transport and collection, emissions amount to 10 kg CO_2-eq per tonne of feedstock, with diverse technologies powering the plants resulting in a range of 10 to 25 kg CO_2-eq per tonne of feedstock.

The economic assessment utilizes CBA to determine whether carbon savings outweigh the expected costs of waste-to-energy technologies, providing a comprehensive comparison of the economic feasibility of different waste-to-energy technology scenarios. In Scenario 5, the total energy production demonstrated the capacity to meet the average annual energy needs of 12,117, 12,096, and 12,094 households in districts A, B, and C, respectively. Among the scenarios, Scenario 9 is the most suitable technology-feedstock combination for NZEBs in Glasgow, boasting the highest efficiency at 70%.

The sensitivity analysis reveals a direct correlation between economic, technical, and environmental parameters with technological advancements and the optimal technology pairing. Enhancing these parameters can amplify benefits, ensuring sustainable and systematic waste management. Hence, sensitivity analysis plays a crucial role in identifying optimal solutions for waste management.

It is concluded that waste-to-energy technologies are economically viable for energy production in Glasgow. The outcomes of multi-objective optimization point towards the feasibility of optimizing scenarios to minimize both total cost and GWP. Through various analyses conducted in this study, it is evident that waste-to-energy technologies can harness Glasgow's waste for energy production, diminish the environmental impact of waste management practices, and yield economic advantages for both the energy and building sectors.

This research adds valuable datasets to academia and the energy industry, providing insights into environmental impacts and economic viability. The study's novelty lies in establishing a framework for waste-to-energy technologies supporting NZEBs and sustainable waste management schemes.

Acknowledgements

As I approach the conclusion of my research journey, I feel compelled to pause briefly and reflect on the distance I've travelled, the challenges I've faced and conquered, and the losses I've incurred. Acknowledging the invaluable support I have received from individuals and institutions during this arduous and solitary expedition is crucial. First and foremost, I extend my gratitude to God, who has been my steadfast companion throughout this odyssey.

I wish to express my heartfelt appreciation to Dr. Siming You, my supervisor, who played a pivotal role by scrutinizing and guiding my work during critical junctures and offering invaluable suggestions to enhance the quality of my research. Dr. Siming You provided unwavering assistance and allowed me to contribute to tutorials and demonstrations at the University of Glasgow as part of his research group. I look forward to the possibility of continued collaboration in the future.

I also thank the University International Student Support team for enhancing my stay with memorable family excursions in the enchanting landscapes of Scotland. Gratitude is also owed to the University's Financial Aid team for their timely assistance through the Hardship Fund when my sponsors faltered in meeting their obligations. Without their support, completing my research would have remained an elusive goal.

My profound appreciation extends to the entire staff at the School of Engineering, who accompanied me through every stage of my research, especially during the challenging times imposed by the COVID-19 pandemic. I want to assure them that I exerted my utmost effort to prove myself deserving of their assistance.

Most significantly, I dedicate this research project to my family, who have consistently stood by me, supported my choices, and followed my progress with unwavering enthusiasm, love, and care. To my family, I apologies for any inconveniences and difficulties that may have arisen along the way. While setbacks and unmet expectations may occur, our family values of character, strength, hard work, and honesty remain steadfast. The victims are my neighbours, friends, and loved ones. In addition, I would like to dedicate this work to the victims of the devastating flooding in Libya, which includes my neighbours, friends, and beloved community members.

Additionally, I dedicate this work with immense gratitude to my homeland, Libya, for allowing me to embark on this research journey. In these trying times, Libya requires its best and brightest to unite

and labour diligently, steering her away from ignorance, corruption, and tyranny. This path, guided by democratic values, can lead to the restoration of freedom and justice.

Lastly, I acknowledge that faith, charity, and hope are the driving forces that enable us to surmount all obstacles. As I finally turn my gaze forward, I hope the immense effort invested in this endeavour will yield fruitful results someday. In the meantime, I can only conclude with these words: Mission Accomplished!

Declaration

I affirm that this thesis, titled " Modelling and Optimization of Waste-to-Energy Developments for Net Zero Energy Buildings (NZEBs)", has been authored solely by me, and I have not presented it, either in its entirety or partially, for any other academic degree at the University of Glasgow or any other educational institution. The content within this manuscript is my creation unless specifically indicated otherwise within the text.

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ASAM
April 2024

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List of abbreviations	
NZEBs	Net-Zero Energy Buildings
AD	Anaerobic digestion
LCA	Life Cycle Assessment
MCA	Multi-Criteria Analysis
CBA	Cost Benefit Analysis
GWP	Global Warming Potential
MSW	Municipal solid waste
US	United States
G	Gasification
P	Pyrolysis
GW	Gardening waste
FW	Food waste
WW	Wood waste
GHG	Greenhouse gases
EU	European Union

NZ-site-EB	Net-Zero Site Energy buildings
NZ-EB	Net-Zero Emissions buildings
NZ-source-EB	Net-Zero Source Energy buildings
NZ-cost-EB	Net-Zero Cost Energy buildings
PH	Passive House
EE	Energy Efficiency
UNDP	United Nations Development Programme
UK	United Kingdom
AH	Active House
GWEC	Global Wind Energy Council
PV	Photovoltaic
GSHPs	Ground Source Heat Pumps
ASHPs	Air Source Heat Pumps
CO_2	Carbon Dioxide
BCR	Benefit-cost-ratio
CAPEX	Capital expenditure

CH_4	Methane
CO	Carbon Monoxide
H_2	Hydrogen
IRR	Internal rate of return
N_2	Nitrogen
C_2H_5OH	Ethanol
HVAC	Heating, ventilation, and air conditioning
O&M	Operation & Maintenance
MOO	Multi-Objective Optimization
MP	Mathematical Programming
MILP	Mixed-Integer Linear Programming
CHP	Combined heat and power
EUAB	Equivalent uniform annual benefit
EUAC	Equivalent uniform annual cost
LCOE	Levelized Cost of Energy
ORWARE	Organic Waste Research

WRCM	Waste Recycling and Cost Model
FU	Functional unit
AP	Terrestrial acidification potential
PMF	Particulate matter formation
EP	Eutrophication potential
AHP	Analytical hierarchy process
COP26	Conference of the Parties
LED	Light-emitting diode
HRES	Hybrid Renewable Energy Systems

Chapter 1 – Introduction

This chapter provides an overview and introduction to the waste-to-energy concept, accompanied by background information and the rationale for this study. This is achieved by delineating the project's goals and objectives. This work's significance to the broader research landscape, the overall structure of the thesis, and the underlying project framework are also expounded upon, with due reference to the included published papers.

1.1 Background

The rise in emissions of harmful substances from traditional fossil fuels has created a demand for cleaner, renewable energy sources. Renewable sources, particularly sustainable and environmentally friendly, have garnered significant attention. One such source is energy from waste. This form of energy is both eco-friendly and renewable. It involves the conversion of waste into gaseous, liquid, and solid fuels through commonly employed thermochemical and biochemical methods. These fuels can subsequently be harnessed to generate energy. Growing concerns about the future of global energy stability underscore the importance of exploring alternative energy sources. An essential criterion for any alternative energy solution is its environmental compatibility. In alignment with these criteria, waste-to-energy emerges as a critical player in renewable energy generation [1].

Over 2.1 billion tonnes of municipal solid waste (MSW) are produced annually worldwide. However, only 16% of this is recycled, while 46% is disposed of unsustainable [2]. The US generates 12% of the global municipal waste, while China and India generate 27% [2]. Waste production per capita ranges from 2.1 kg/d (Europe and North America) to 0.77 kg/d (South Asia region) [3]. It has been estimated that by 2050, the globe will produce approximately 3.40 billion of waste annually [4]. European regulation has given priority to recycling, waste prevention, and reuse. Although landfilling continues to be the most widespread practice, recycling and waste incineration have demonstrated a considerable rise in recent years. The primary purpose of MSW incineration has been to achieve energy recovery and decrease the mass and volume of solid waste [5].

Waste pile-up is a critical issue that must be addressed to achieve Sustainable Cities and Communities as part of the UN’s Sustainable Development Goals. One of the most effective solutions would be energy recovery from waste [6]. Economic and environmental analysis methods are utilized to gauge the comprehensive performance of waste management systems for sustainability. CBA and LCA are two methods widely used for evaluating the complete performance of waste-to-energy systems.

A systematic waste management strategy to ensure its sustainability and effectiveness is crucial. Additionally, the sustainable utilization of waste can generate relevant energy products, indicating that waste can be exploited to produce sustainable energy while enhancing environmental sustainability. The waste-to-energy pathway converts bio-based waste into energy or fuel (e.g., biogas and syngas), which can be used for energy generation. Various technologies focusing on waste treatment have been formulated. However, it is imperative to consider technical, economic, and environmental factors in developing such technological alternatives to address sustainable waste management. Moreover, the increasing importance of environmental conservation has led to the adoption of renewable energy technologies in modern buildings, resulting in the emergence of NZEBs, promising solutions for decarbonizing the building sector.

This PhD dissertation adheres to the guidelines set by the University of Glasgow. The study was funded by the Libyan government and was conducted in collaboration with Dr. Siming You. Dr Siming has been working for several years on utilizing waste as a renewable energy source at the University of Glasgow, focusing on optimizing energy systems, the impact of renewable energy in electricity markets, and future power networks. The author contributed to developing processing methods for waste utilization to produce renewable energy for NZEBs, considering technical, economic, and environmental factors. MCA was used to identify the most cost-effective and environmentally friendly technology-feedstock combination for waste-to-energy systems-based NZEBs development, which is entirely new.

Addressing building-related greenhouse gas emissions, energy efficiency, and using renewable energy resources are vital opportunities. Glasgow has undergone revitalization through community restructuring, regeneration, and reinvention, and decentralized energy supply is an essential component of smart grid systems. Understanding the city's current energy position and changes is vital to developing a plan to guide future energy use. The city also has a high energy demand to support the development of NZEBs. A comprehensive case study on distributed energy supply system optimisation is needed to keep the design of sustainable energy supply systems for these buildings. This study aims to contribute to the sustainable deployment of additional renewable energy capacity by developing an efficient, low-carbon energy and environmental system through process integration and optimization. Additionally, the study aims to design a novel configuration of renewable energy-supported NZEBs and evaluate their profitability and carbon footprint.

1.2 Aims, Objectives, Research Questions, and the Contribution of the Thesis

This section outlines the core objectives, key research questions, and the study's novelty in advancing the integration of waste-to-energy technologies towards achieving NZEBs.

To address the challenge of sustainable energy in the journey towards net-zero carbon emissions, this project aims to develop community-scale low-carbon energy solutions that empower residents as active participants in clean energy creation. Specifically, the project will create a holistic energy system model of waste-to-energy to evaluate the feasibility and scalability of sustainable low-carbon energy interventions within Glasgow. The outcomes at the local level will contribute to broader city-level sustainability objectives. The model will incorporate economic and environmental considerations, aligning with the United Nations Sustainable Development Goals. To facilitate a more comprehensive sustainability assessment, the project will apply the LCA method and conduct CBA to evaluate the system's sustainability.

1.2.1 Aims of the Thesis

This study aims to investigate the techno-economic and environmental impact of waste-to-energy technologies to support NZEBs in Glasgow. The research focuses on analyzing the feasibility of different waste-to-energy technologies and their potential to contribute to the achievement of NZEBs. The study considers the economic costs, carbon emissions, and other environmental impacts of implementing these technologies. This project also provides a comprehensive analysis of Glasgow and Scotland's waste regulations and renewable energy policies, shedding light on the Scottish Government's initiatives to advance these critical sectors as part of the broader goal of achieving net-zero futures. It discusses the issue of waste management in Glasgow and the potential for waste-to-energy technologies to address the issue of waste pile-up, climate change, and increased energy demand. This type of research is crucial for identifying sustainable solutions that can help reduce carbon emissions and support the transition to a more sustainable energy system.

The specific objectives are to:

- Assess the techno-economic feasibility: investigate waste-to-energy solutions' economic viability and technological feasibility as a viable means to power NZEBs.
- Evaluate environmental impact: Analyze the ecological implications of waste-to-energy technologies, including emissions reduction, waste management, and sustainable resource utilization.
- Critically assess the existing waste regulations and renewable energy initiatives.

This project is centered around the idea of distributed bioenergy generation to support the development of NZEBs. This concept aligns with the United Kingdom's energy policy, which seeks to encourage the utilization of renewable energy sources, energy conservation, enhanced energy efficiency, and decentralized energy generation that individual buildings can harness.

The outcomes will enable policymakers to make informed decisions to fulfil NZEBs. The project will develop an optimal configuration design for bioenergy-supported NZEBs. This project will serve as a feasibility study of the futuristic NZEBs route and will provide data support for the design of pilot-scale NZEBs in the future.

1.2.2 Questions

- How does this study differ from existing research and contribute to the current knowledge? What is the novelty of this study's contribution?
- What are the direct economic and environmental benefits that the most appropriate technology-feedstock can provide to the city of Glasgow?
- What is the overall energy potential to support NZEBs in Glasgow?
- What is the most promising technology-feedstock combination for waste-to-energy developments suitable for NZEBs?
- What are the strategies for achieving net-zero futures regarding global, national, and local decarbonization?

1.2.3 Objective of the Thesis

1. Compare the economic viability and environmental impact of different scenarios of bioenergy technologies for various wastes (gardening waste, food waste, and wood waste) that are used to support the NZE development of an individual residential building based on LCA and CBA to identify the most appropriate technology-feedstock combination.

2. Develop a bioenergy route identification framework by incorporating the CBA and LCA approaches into a MCA model for bioenergy-based NZEBs development, which is entirely new. The MCA model will be applied to balance the solutions' trade-offs. The results from the MCA model will illustrate which scenario is the most favourable scheme among the different scenarios for supporting NZEBs and the waste-management system. The best trade-off solution will then be identified.

3. Apply the framework in Glasgow, its contribution is that it facilitates informed decisions for NZEBs development.

4. A comprehensive evaluation of global, national, and local decarbonization strategies, coupled with an analysis of Scotland's waste regulations and renewable energy landscape, offering insights into the Scottish Government's enhancement initiatives toward achieving net zero emissions.

1.2.4 Project Framework

Figures 1.1 to 1.2 illustrate the various stages of this project and the analytical methods employed to achieve its objectives. These figures concisely summarise the project's flowchart, outlining the key steps and analytical processes. Ten scenarios have been designed to represent available conversion technologies and waste feedstocks. These scenarios include Gasification with food waste, AD with garden waste, and pyrolysis with wood waste (Scenario 1). Gasification with garden waste, AD with food waste, and pyrolysis with wood waste (Scenario 2). AD with garden waste, pyrolysis with food waste, and gasification with wood waste (Scenario 3). AD with food waste, gasification with wood waste, and pyrolysis with garden waste (Scenario 4). AD is with garden waste, AD is with food waste, and gasification is with wood waste (Scenario 5). AD is used with garden waste, AD is used with food waste, and pyrolysis is used with wood waste (Scenario 6). AD with garden waste, gasification with food waste, and gasification with wood waste (Scenario 7). AD with garden waste, pyrolysis with food waste, and pyrolysis with wood waste (Scenario 8). AD with garden waste, gasification with food waste, and gasification with wood waste (Scenario 9). AD with food waste, pyrolysis with garden waste, and pyrolysis with wood waste (Scenario 10). Table 1.1 displays these scenarios alongside their corresponding feedstock types.

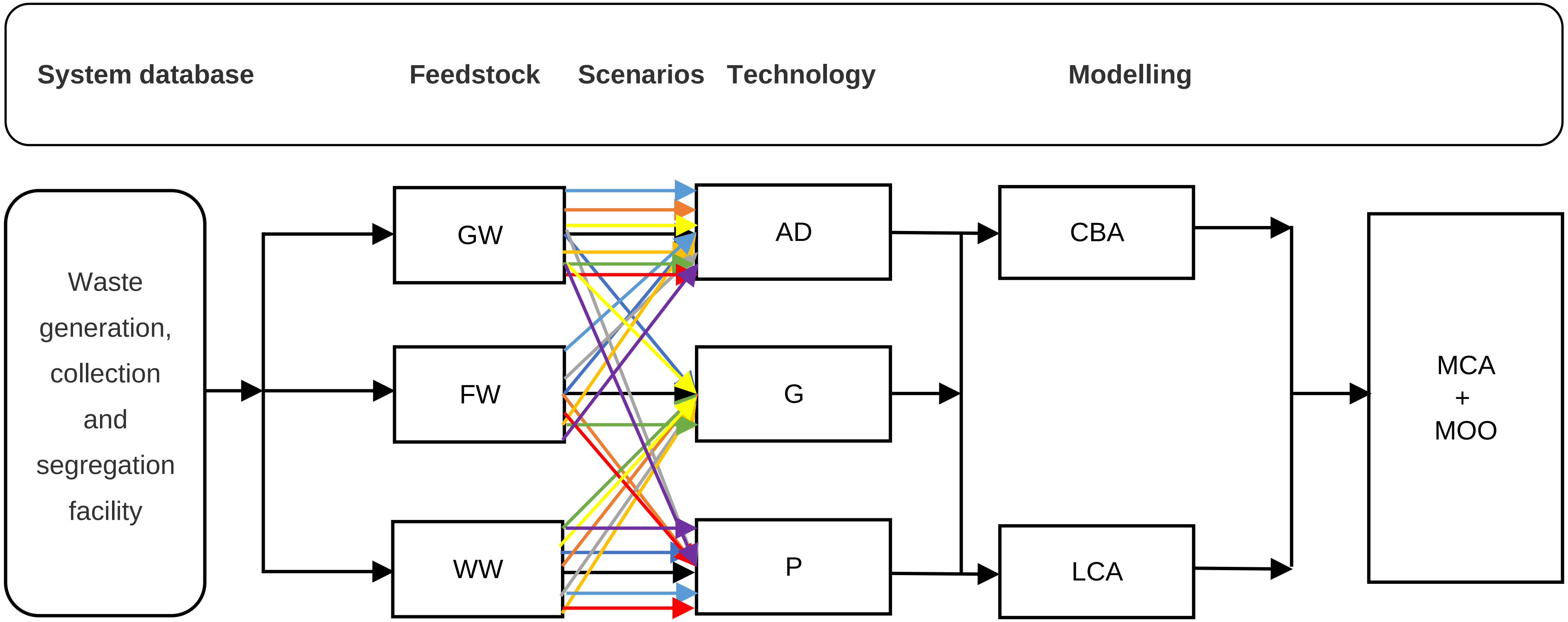


Figure 1.1 Scenarios design modelling.

Table 1.1 Scenarios design modelling (appropriate technology-feedstock combination).

Abbreviations	Technologies	Gasification	Anaerobic digestion	Pyrolysis
		G	AD	P
	Wastes	Gardening waste	Food waste	Wood waste
		GW	FW	WW
	Modelling	Cost-benefit analysis	Life cycle assessment	Multi-criteria analysis
		CBA	LCA	MCA
	Scenarios	Scenario 1	Scenario 2	Scenario 3
		⬛	🟦	🟧
		GW→AD	FW→AD	GW→AD
		FW→G	GW→G	WW→G
		WW→P	WW→P	FW→P
		Scenario 4	Scenario 5	Scenario 6
		▒	🟨	🟦
		FW→AD	GW→AD	GW→AD
		WW→G	FW→AD	FW→AD
		GW→P	WW→G	WW→P
	Scenario 7	Scenario 8	Scenario 9	Scenario 10
	🟩	🟥	🟨	🟪
	GW→AD	GW→AD	GW→AD	FW→AD
	FW→G	FW→P	FW→G	GW→P
	WW→G	WW→P	WW→G	WW→P

1.2.5 Contribution of the Thesis

This study's novelty lies in its focus on conducting a waste-to-energy feasibility study for Glasgow, UK, comparing various bioenergy technology scenarios to determine the most suitable technology-feedstock combination to support NZEBs in Glasgow and for effective waste management. Additionally, it evaluates the environmental and economic impact of waste-to-energy conversion, considering factors like greenhouse gas emissions, energy production potential, and cost. utilizing CBA, LCA, MOO and MCA methodologies. While CBA and LCA are established, the novelty lies in their application within Glasgow's waste-to-energy context and in identifying technology-feedstock combinations for distributed bioenergy-supported NZEBs. It aims to represent the most promising scenarios accurately and guide decision-making and policy development in waste management and energy sectors.

There are existing examples of MCA-based NZEB design in the literature. However, this work's contribution lies in the application of these methods within a specific context or the development of novel methodologies to optimize waste-to-energy to support NZEBs. Therefore, this project may indeed be considered novel within the broader field of NZEB design, despite the existence of previous examples. This work is a pioneering effort due to its innovative approach and focus on waste utilization for renewable energy production to support NZEBs in Glasgow. Specifically, it has made a unique contribution by developing novel processing methods for waste utilization to produce renewable energy for NZEBs.

The project designs a novel configuration of bioenergy-supported NZEBs, determining their profitability and carbon footprint. Results will inform policymakers for NZEB fulfilment in Glasgow and serve as a feasibility study for future NZEB designs, applicable to other renewable energy types. Addressing waste regulations and renewable energy in Scotland, it offers insights into the Scottish Government's efforts, reviewing Glasgow's policies as a foundation for waste-to-energy models supporting NZEBs. In addition, this work evaluates global, national, and local decarbonization strategies, focusing on Scotland's waste regulations, renewable energy landscape, and initiatives for achieving net zero targets. The study analyzes various aspects of a net-zero future, encompassing environmental, economic, and policy considerations. Figures 1.2 and 1.3 illustrate the stages of this project.

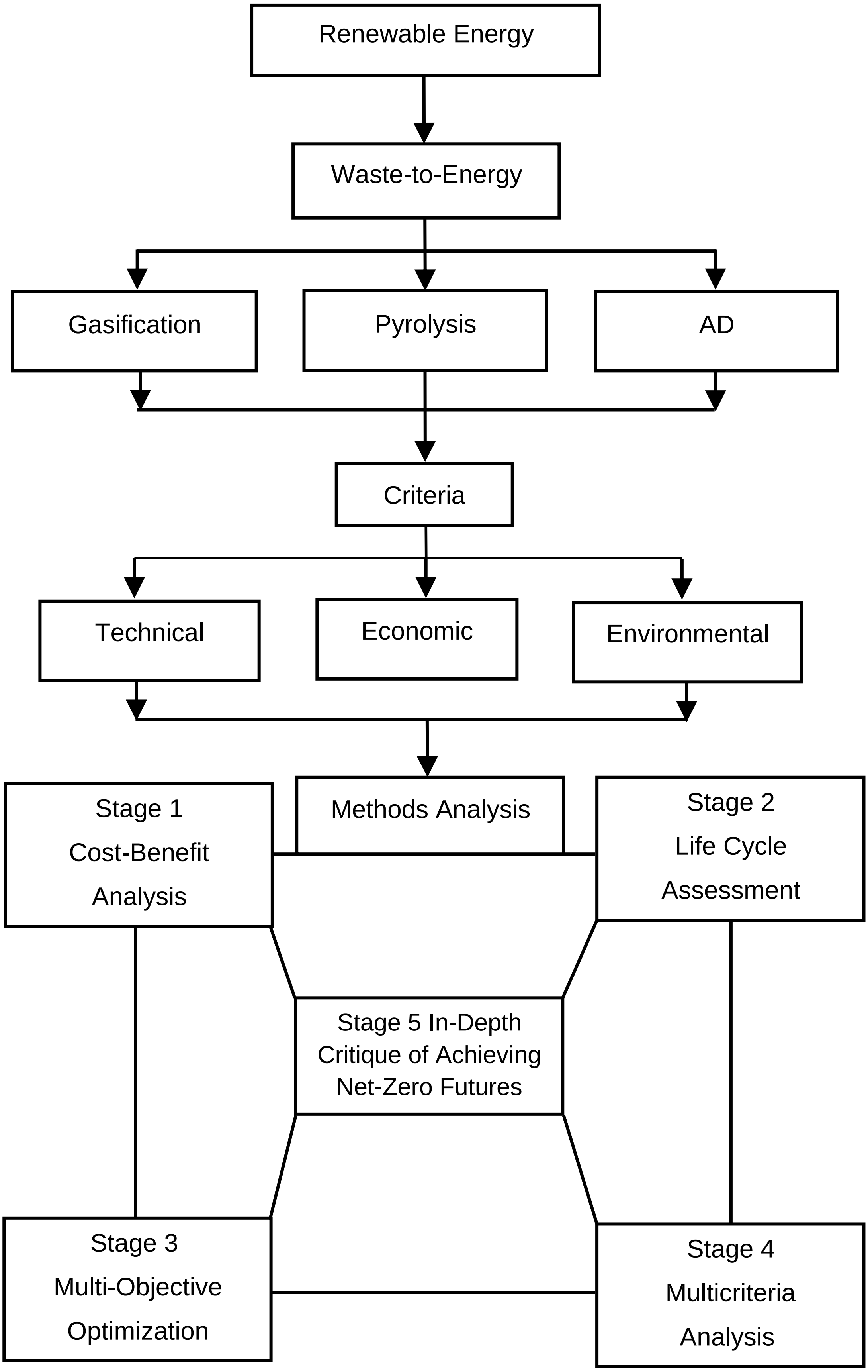
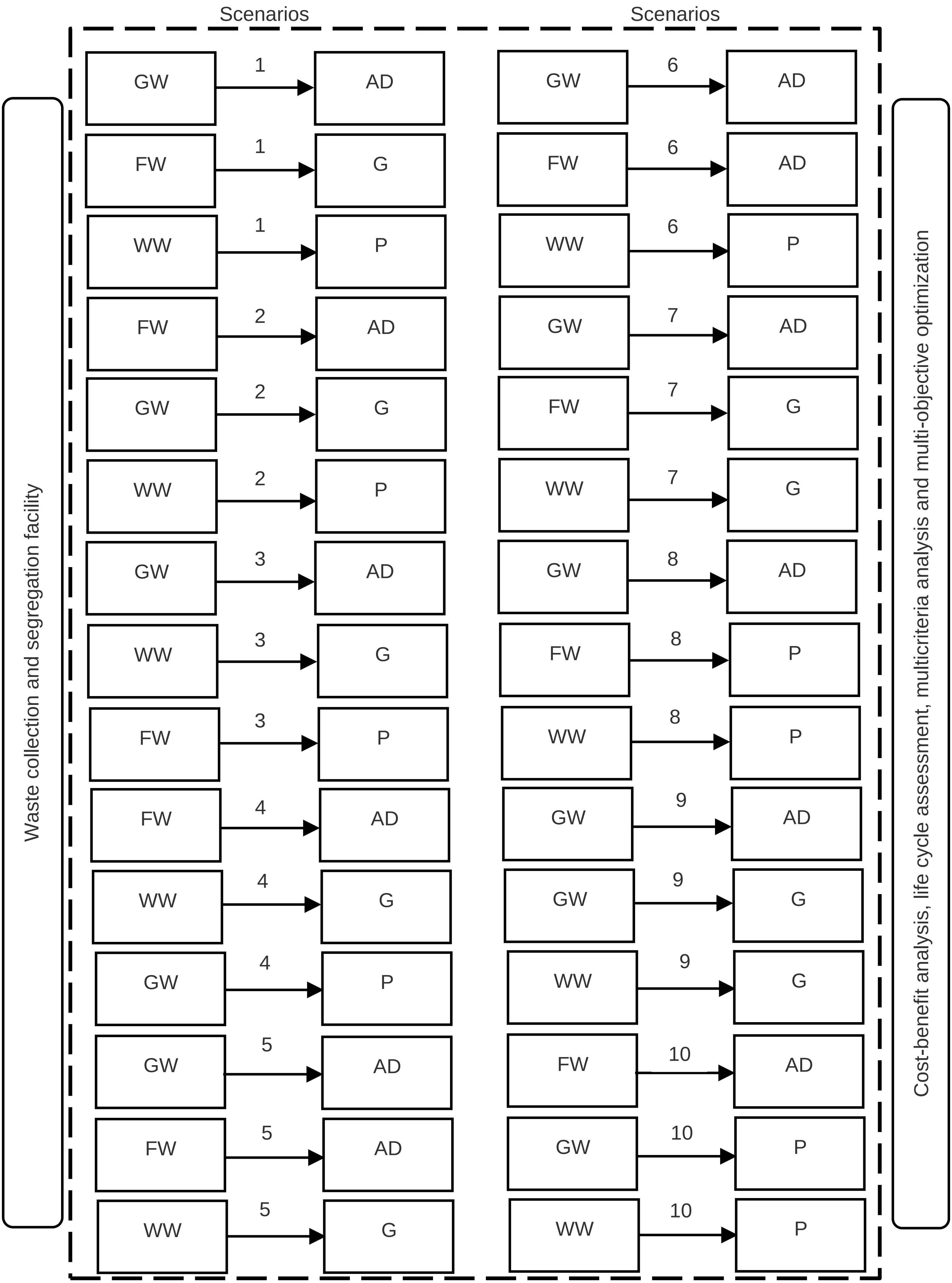


Figure 1.2 Project flow chart outlining the study's various stages and the analyses employed to accomplish the study's objectives.


Scenarios
Scenarios
Waste collection and segregation facility
Cost-benefit analysis, life cycle assessment, multicriteria analysis and multi-objective optimization
GW 1 AD
FW 1 G
WW 1 P
FW 2 AD
GW 2 G
WW 2 P
GW 3 AD
WW 3 G
FW 3 P
FW 4 AD
WW 4 G
GW 4 P
GW 5 AD
FW 5 AD
WW 5 G
GW 6 AD
FW 6 AD
WW 6 P
GW 7 AD
FW 7 G
WW 7 G
GW 8 AD
FW 8 P
WW 8 P
GW 9 AD
GW 9 G
WW 9 G
FW 10 AD
GW 10 P
WW 10 P

Technologies	G Gasification	AD Anaerobic digestion	P Pyrolysis
Wastes	GW Gardening waste	FW Food waste	WW Wood waste

Figure 1.3 Project flow chart outlining the scenarios of the study.

1.3 Thesis Structure

The thesis is structured on a chapter basis, each addressing specific project elements. The chapter outline clearly shows what the finished dissertation will look like. The forthcoming chapters visually represent the project's framework and concise summaries, offering an overview of the thesis's structure and content. The theory is outlined as follows:

Chapter 1: Introduction: it serves as an introductory section that sets the stage for the thesis. It begins by providing an overview of the waste-to-energy concept and its global use as a renewable source of clean energy production. This chapter outlines the background and rationale behind the study, articulating the goals and objectives of the project. Additionally, it emphasizes the research's significance in the broader context, outlines the thesis's structure, and highlights the underlying project framework, referencing included published papers.

Chapter 2: Literature Review shows the previous studies about NZEBs in different countries. It also presents renewable energy supply options with NZEBs and bioenergy technologies. The gaps between the last and the current work are discussed.

Chapter 3: Techno-economic feasibility of waste-to-energy technologies-based net-zero energy buildings: a cost-benefit analysis provides an in-depth exploration of the research methodology. It examines various scenarios of bioenergy technologies to support NZEBs, employing an integrated framework model incorporating a CBA.

Chapter 4: Waste-to-Energy Technologies to Support Net-Zero Energy Buildings in Glasgow: Life Cycle Assessment Perspective evaluates scenarios initially developed in Chapter 3 using a framework model based on LCA.

Chapter 5: Multi-Objective Optimization of Waste-to-Energy Technologies for Net-Zero Energy Buildings; multi-objective optimization to concurrently enhance waste-to-energy technology's environmental impact and economic viability. The primary objective is to minimize costs and greenhouse gas emissions, aligning with the overarching goal of achieving NZEBs.

Chapter 6: Decision Making of Waste-to-Energy Technologies-based Net-Zero Energy Buildings: multi-criteria analysis employs an MCA method to determine the most suitable combination of technology and feedstock, considering economic, environmental, and technical factors. This chapter incorporates the CBA and LCA approaches into a MCA model.

Chapter 7: An In-depth Critique of Achieving Net-Zero Futures: Decarbonization Strategies on Global, National, and Local Levels addresses the existing waste regulations and renewable energy in Scotland and offers insight into the Scottish Government's efforts to enhance both sectors. Conducts a comprehensive evaluation of the current status of Scotland's zero waste initiatives while formulating a strategic roadmap for advancing Scotland's renewable energy policies and attaining sustainable energy targets.

Chapter 8: Conclusion and Future Recommendations serves as the culmination of the thesis, presenting comprehensive conclusions and recommendations. It evaluates the extent to which the research objectives have been met and summarizes the essential findings and outcomes. The chapter delves into the implications of these findings and outlines recommendations derived from them. The focus is on elucidating and assessing the significant findings, inspiring their connections to the literature review and research objectives. It provides compelling arguments in support of the discussions made. Moreover, it acknowledges the study's limitations and suggests avenues for future research and work to address them.

Chapter 9: Achievements, Impacts, and References encompasses the Student’s Researcher Development Log, providing a comprehensive summary of the impact of COVID-19 and difficult personal circumstances on my achievements and progress. Additionally, it includes a detailed list of references cited and utilized throughout this work. As the chapters progress, a critical analysis is systematically presented, followed by thorough discussions and conclusive remarks.

Chapter 2 - Literature Review

Decarbonizing the building sector is extremely important to mitigating climate change as industry contributes 40% of the overall energy consumption and 36% of the total GHG emissions in the world. NZEBs are one of the promising decarbonization attempts due to their potential to decrease energy use and increase the full share of renewable energy. To achieve a NZEB, it is necessary to reduce the energy demand by applying efficiency enhancement measures and using renewable energy sources. NZEBs can be classified into four models (Net-Zero Site Energy buildings, Net-Zero Emissions buildings, Net-Zero Source Energy buildings, and Net-Zero Cost Energy buildings). Various technical, financial, and environmental factors should be considered during the decision-making process of net-zero energy building development, justifying the use of MCA methods to design NZEBs. This chapter also discussed the contributions of renewable energy generation (hydropower, wind energy, solar, heat pumps, and bioenergy) to developing NZEBs and reviewed its role in tackling the decarbonization challenge. CBA and LCA of NZEB designs and their challenges were reviewed to shape future development priorities. Creating a universal decision instrument for the optimum design and operation of NZEBs is essential. In addition, the literature review section examined the latest academic research on waste-to-energy technology and assessed the current state of renewable energy supply for NZEBs. It analyzed various methods related to renewable energy and waste management. The insights gathered from this review will serve as a guiding framework for the design and configuration of the technology and system done in this study. The content within this chapter has already been published in the Energy and Buildings Journal.

2.1 Introduction

The building sector faces significant challenges concerning energy consumption, decarbonization, and a lack of access to modern energy services (i.e. energy poverty) along with the global pressure of fossil fuel depletion [7]. The sector is a major GHG contributor and energy consumer globally. For example, in the UK, it contributed around 40% of the total carbon footprint with 69% of these emissions attributed to heating [8]. Buildings consume about 40% of the entire energy within the EU [9]. In China, this sector accounted for roughly 50% of the national energy consumption which was expected by 2030 [10]. There is a worldwide urgency to take stringent measures to enhance building energy efficiency and decarbonize the sector [11].

Renewable energy plays a critical role in tackling the challenges of fossil fuel depletion and climate change and has gained an increasing percentage in the energy mix around the world. For example, in 2022, approximately 42% of electricity production in the UK was provided by renewables [12].

The aims of decarbonization, as well as increasing renewable energy generation in the building sector, stimulate the development of sustainable buildings or buildings with net-zero energy (NZEB) status. An NZEB is defined as a building or construction with zero-net energy consumption or zero carbon emissions over a set period (Figure 2.1) [13]. A two-way grid is a grid that can deliver energy to and receive energy from a building. The red arrow in Figure 2.1 shows the energy exported from the building to the grid, indicating either off-site or on-site grid. The green arrow refers to the energy delivered to the building from the grid, which could be either off-site or on-site renewable energy.

On-grid and off-grid NZEBs refer to two different types of NZEBs based on their connection to the electrical grid. On-grid NZEBs, these are NZEBs that remain connected to the electrical grid. On-grid NZEBs generate renewable energy on-site, such as through solar panels or wind turbines, to produce as much energy as they consume over a year. Any excess energy generated can be exported to the grid, while energy deficits can be met by importing electricity from the grid as needed. Off-grid NZEBs, these are NZEBs that operate independently of the electrical grid. Off-grid NZEBs generate all the energy they need on-site using renewable energy sources, such as solar panels, wind turbines, or micro-hydro systems, coupled with energy storage systems for times when renewable energy generation is insufficient to meet demand.

NZEB can be used to describe a building with traits such as having equal energy generation to usage, a significant reduction in energy demands, and the costs of energy being equal to zero or net-zero GHG emissions [14]. It can also be referred to as a building that generates sufficient renewable energy on-site to satisfy its energy requirements [15].

There are several ways in which buildings can achieve net-zero energy, including integrated building design, retrofits, and energy conservation [16]. For example, high-quality insulation is integral in helping achieve net-zero energy by effectively reducing energy demands [17]. Underfloor heating instead of radiators can reduce energy consumption, as the water does not need to be heated as much to achieve thermal comfort. Finally, renewable energy (i.e. wind, solar, geothermal, and bioenergy) generation and use play a central role in fulfilling NZEBs.

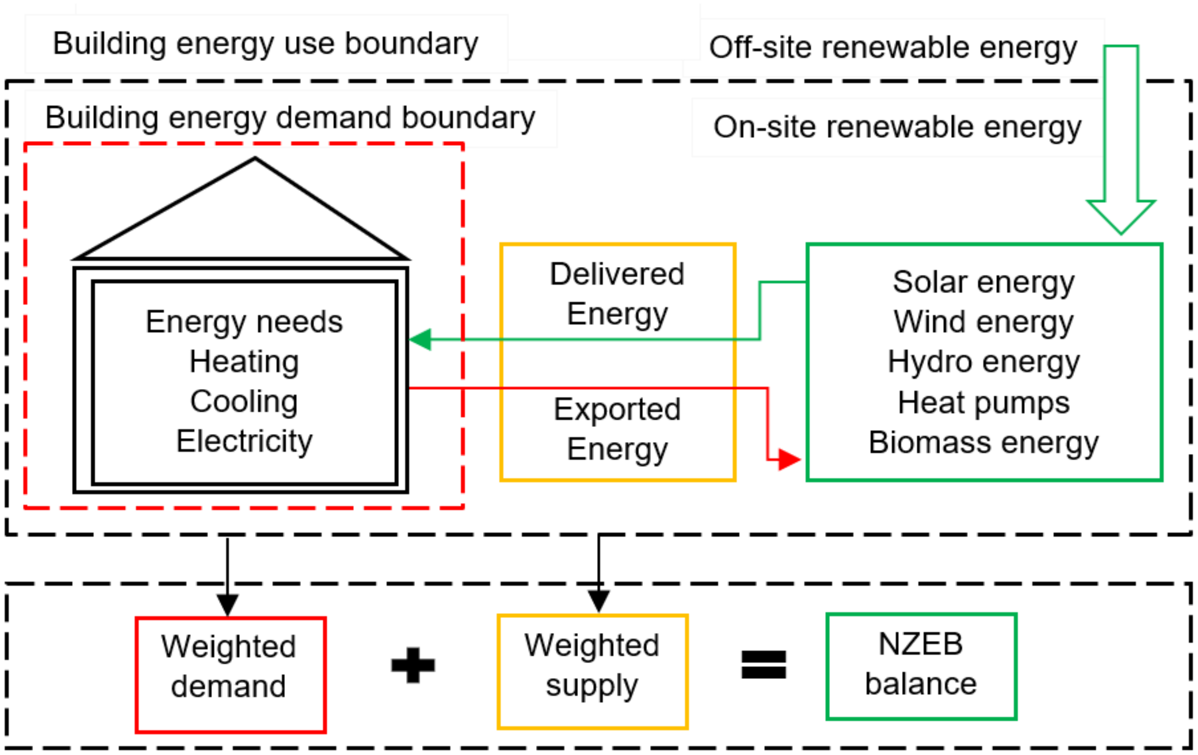


Figure 2.1 The definition of NZEB.

Extensive studies have been carried out concerning developing NZEBs with different types of renewable energy. However, the practical implementation of NZEBs is still in its early stages, particularly for the ones supported by distributed renewable energy supply. There are limited reviews that summarise the development of NZEBs in terms of renewable energy generation and the methods (considering various factors such as economic viability and environmental impacts) of designing NZEBs. Harkouss and Fardoun reviewed a comprehensive review of NZEB definitions and NZEB designs and their drawbacks. It examined the most used electric and thermal renewable energy applications which support NZEBs [18]. Feng, et al. presented features of current NZEB development, reviewed climate-responsive NZEB designs and analyzed building energy performance and technology options [19]. It is worth noting that, in addition to the concept of NZEB, there is a concept called “net energy” frequently used in the construction industry to account for the difference between the energy consumed by a building and its occupants and systems and the energy from renewable energy sources. Hernández and Kenny incorporated the “net energy” concept to aid the design of a built environment from a life cycle perspective [20]. NZEBs are a specific type of building designed to achieve net-zero energy consumption, whereas net energy analysis is a broader concept used to evaluate the energy balance of systems or activities beyond individual buildings.

2.2 Net-Zero Energy Buildings (NZEBs)

2.2.1 Classification

NZEBs are typically classified into four well-known models based on different modes of energy generation and usage: Net-Zero Site Energy buildings (NZ-site-EB), Net-Zero Emissions buildings (NZ-EB), Net-Zero Source Energy buildings (NZ-source-EB), and Net-Zero Cost Energy buildings (NZ-cost-EB) [21]. An NZ-site-EB produces a unit of energy for every energy unit consumed on the site itself. The origin of the energy is not considered as it assumes that one unit of energy is equal to that of another, regardless of source. This definition may prevent the identification of cost-saving prospects like peak and off-peak energy tariff rates [22]. An NZ-source-EB produces a unit of energy for every energy unit consumed on the site itself. The energy generation is quantified at the source itself [14]. This definition has an edge over the first one as it considers energy that may be lost or wasted during generation or distribution. However, it also prevents the identification of cost-saving opportunities. NZ-source-EB suggests that some energy produced can be from an off-site source. An NZ-EB defines a building that produces minimally as much emission-free energy as it consumes emission-producing energy [23]. It encourages emissions-producing energy if the same amount of energy is offset by emissions-free energy. For an NZ-cost-EB, the owner of the building has zero utility bills. However, utility providers usually charge certain fees for various reasons, such as maintenance. To meet obligations for maintenance and maintain the capacity to meet potential loads, the associated costs may make NZ-cost-EB not achievable. Also, it does not consider the energy production process and is affected by external factors such as fee variations.

Hierarchical steps have been proposed to develop NZEBs. Firstly, energy use should be reduced by restricting the quantity of loss and heat gain, considering building service systems such as cooling and heating. Secondly, renewable energy technologies can be used to supplement energy supply and to cover part of the energy use that cannot be reduced. Typical renewable energy technologies such as solar thermal, heat pumps, bioenergy, and wind turbines can be considered [24]. Table 2.1 shows different existing studies that used different renewable energies in the development of NZEBs. Because different renewable energy sources can be used to facilitate NZEB design models, critical parameters such as the location of the building, energy efficiency, and performance should be considered when designing the models and when selecting the renewable source of energy. Building orientation and good installation of insulation facilities also contribute to the efficiency of renewable sources in NZEBs. It is worth noting that, upon NZEB rating, only the operational energy intended for a building is used, while the energy linked to the building's construction (i.e. embodied energy) and commissioning is often ignored [25]. This is mostly due to a lack of data, a preference for traditional construction methods, and the difficulty of quantifying the energy incorporated [26].

Table 2.1 Renewable energy usage for NZEB development.

Reference	NZEB design	Renewable sources	Critical parameters	Major findings
[27]	On-site or off-site renewable energy supply NZEB	PV, micro combined heat and power, off-site windmill, purchase of green energy from the 100% renewable utility grid	Energy efficiency	• Energy efficiency should be the priority in designing a cost optimal NZEB with an on-site renewable energy supply. • It is more cost-effective to invest in renewable energy technologies than energy efficiency.
[28]	Renewable energy balance in environmental building design	All possible renewable sources	Maximizing the use of renewable resources	• Renewable energy balance can be used in environmental building designs to achieve higher levels of sustainability.
[29]	Solar energy for NZEBs	Solar thermal and PV	The total efficiency of the power source and the usage of space	• Using high-efficiency PV modules in construction helps to achieve an almost zero energy balance depending on the boundary conditions as well as the building's energy system design.
[30]	A classification system based on renewable energy supply options	Renewable sources on-site, off-site	Energy efficiency	• A classification system can be developed to distinguish NZEBs based on the source of renewable energy as well as the building’s utilization.
[31]	Net-zero energy (NZE) low-rise residential building	Solar energy	Energy performances	• The building orientation has little influence on the energy performance of the systems year-round. • The NZEB design can potentially be utilized in all new and old buildings to ensure low carbon production.
[32]	The impact of PV and solar thermal on net NZEBs	Solar energy	Percentage of energy provision	• Solar energy can provide more than 76% of the energy demands in NZEBs.

[33]	Multi-criterion NZEB renewable energy system	Conventional renewable energy sources	Annual energy balance reliability, the grid stress, and the initial investment	• NZEB's renewable energy proposal enhances the overall performance by 44% when compared with conventional methods.
[34]	Building-integrated solar renewable energy systems for NZEBs	Solar energy	Energy saving	• To meet thermal needs in buildings, using renewable energy with energy-saving measures like installing good insulation will be efficient.

2.2.2 Passive House (PH)

The PH standard has emerged as a critical enabler for the NZEB standard. A PH is designed to have an energy demand that is as low as achievable [35]. The PH concept could minimize the energy demand of buildings by enhancing building technology with low energy requirements [36]. It aims to deliver a satisfactory and even superior indoor environment concerning thermal comfort and indoor air quality at the lowest energy cost. The PH standard is a rigorous and voluntary standard for energy efficiency in buildings, aiming to significantly reduce the building's ecological footprint while providing high levels of comfort for occupants. The principles of the PH standard include: passive solar design, ventilation with heat recovery, high-performance windows and doors, airtight construction and superinsulation [37]. Consequently, when houses are built under the PH standard, the cost normally rises.

The PH concept aims to achieve clean indoor air, good thermal comfort, and a considerable decrease in the primary energy demand, e.g., saving more than 50% of significant energy consumption[36]. Based on the PH concept, a building should conform to certain requirements. For example, the demand for space heating energy should not exceed 15 kWh/m^2. The principal energy demand, i.e. the entire energy that domestic applications consume, should not exceed 120 kWh/m^2. Concerning airtightness, a maximum of 0.6 air changes per hour is allowed [38]. Comparatively, the NZEB standard demands that houses must consume on average less than 45 kWh/m^2 per year, including ventilation, fixed lighting, and space heating. The NZEB standard focuses solely on energy consumption, while the PH standard is defined based on the consideration of the indoor environment and quality thermal comfort.

When it comes to defining the sustainability of a building, the materials used in its construction are crucial [39]. Normally, NZEBs do not account for the embodied energy during the construction and production of the materials they use [40]. The energy embedded in the construction of a building includes the energy used in the manufacturing of the materials, their transportation, and the energy required by the machinery during the execution of relevant tasks [41]. According to Chastas et al., the share of embodied energy among the overall energy usage for passive buildings could range from 11 % to 33 % [42]. The share of embodied energy among the overall energy usage for passive buildings is important because it accounts for the energy consumed during the construction, manufacturing, and transportation of building materials and components. While traditional energy efficiency standards typically focus on operational energy use (i.e., energy used during occupancy), the PH standard considers both operational and embodied energy.

In some situations, the energy analysis of buildings showed that embodied energy accounted for 50% of all primary energy demand [43]. Ding found that the energy embodied in residential structures ranged from 3.6 to 8.76 GJ/m^2 [44]. Dascalaki et al. measured the embodied energy for a variety of buildings, which ranged from 3.2 GJ/m^2 to 7.1 GJ/m^2 on average [45]. Construction energy should be viewed as a tool that can be used to reduce the extraction and exploitation of non-renewable raw materials. Hence, it is desirable to develop a new NZEB rating approach to consider the variation of embodied energy.

Living Building Challenge is another common approach for designing NZEBs. In this approach, the premise is evaluated based on seven Petals including place, water, energy, health, materials, equity, as well as beauty. Certification of the framework looks at the actual performance and not anticipated outcomes. As a result, approaches must be operational for at least twelve months before being evaluated [46]. A building can earn living certification by achieving all imperatives assigned to a typology (renovation or new infrastructure) and Petal certification by satisfying the requirements of at least three Petals. Zero energy certification mandates that projects fulfil 100% of their energy needs with on-site renewables [47].

2.2.3 Energy Efficiency (EE)

The improvement of EE is critical for the development of NZEBs. The United Nations Development Programme (UNDP) illustrated three ways to decrease the energy consumption of buildings: (1) Reducing energy demand, (2) Improving ‘technical’ energy efficiency, and (3) Integrating renewable energy sources into a building system in supporting heating, and electricity generation [48].

Effective insulation can reduce buildings' energy requirements by not only preventing heat escape during heating months but also stopping unwanted heat from being transferred into the building during cooling months [13]. U-Values serve as an indicator of how effective the building’s material is at preventing heat loss. A case study on NZEBs in the UK found the lowest heating loads and total energy consumption were achieved when the external walls had a U-value of 0.1 [49]. In considering which models and concepts of energy efficiency to be applied in buildings, several factors need to be considered including renewable energy supply (e.g., wind energy and solar energy), energy demand reduction (e.g., lighting and heating, ventilation, and air conditioning), and technical energy improvement (e.g., insulation and natural ventilation).

2.2.4 Active House (AH)

AH is a goal-oriented framework for improving indoor and outdoor environments (e.g., active shading and switchable roofs) and efficient use of energy [50]. AH is creating new opportunities for the built environments. Responding to the issues highlighted in the UN Sustainable Development Goals, AH offers sustainable building solutions that balance energy, environment, and safety while cantering to the needs of a building's users. People are interested in sustainability while also demanding products and services that consider their health and well-being [51]. AH standards have been the subject of scientific investigations, covering daylight design, the sociological perspective of indoor comfort, energy-efficient, and user-focused building design. Lara Anne Hale, for instance, addressed the legitimacy of comfort criteria in the building sector and among policymakers, as well as the importance of user-centric designs of technologies in smart buildings [52].

2.3 Renewable Energy Systems Supply

Torcellini, Pless, and Deru categorized NZEBs based on the types of renewable energy supply and the configuration of renewable energy use [18]. The first category referred to an on-site supply option that tends to use renewable energy available within the building’s footprint. The renewable energy produced was linked to the building, which decreased distribution and transmission losses. The second category referred to an on-site supply option that aimed to make better use of renewable energy resources that are accessible at the building’s site boundary. These categories are related to the models (NZ site EB, NZ source EB). The third category referred to an off-site supply alternative that aimed to bring off-site renewable energy resources to the site. The fourth category referred to an off-site supply option that comprised installed renewable energy sources.

An on-site supply option tends to use renewable energy available within a building’s footprint. The produced renewable energy is directly used by the building, which decreases distribution and transmission losses. The option also serves to make better use of renewable energy resources that are available at the building’s site boundary for local energy production and distribution, as opposed to centralized systems, improving reliability and reducing distribution losses [53]. An off-site supply aims to bring off-site renewable resources to a building site to produce power on-site. Table 2.2 below summarises the supply options of renewable energy technologies with NZEBs.

Small-scale renewable energy systems, such as solar and wind turbines have been installed in homes. There are stand-alone systems that allow customers to generate a portion of their energy needs. In the grid-connected mode, the client can either feed excess power back into the grid or store it in storage systems for later use [54]. Specifically, wind turbines are divided into two categories: small-size wind turbines and large wind turbines. Small-size wind turbines are suitable for household and small business applications with a maximum capacity of less than 100KW, whereas large-size wind turbines are utilized for utility power generation in wind farms and are hundreds of times larger than small-size wind turbines [55].

There are three main energy system configurations including distributed energy systems, decentralized energy systems, and centralized energy systems [56]. Centralized energy systems refer to the large-scale energy generation units that deliver energy via a vast distribution network, far from the point of use. Decentralized energy systems refer to the small-scale energy generation units that are used in delivering energy systems to local customers. In the decentralized energy systems, the production units that are used could be stand-alone or they could also be connected to other energy systems through the shared resources. The networks and shared resources are used to share the surplus energy. In the case of connections, the systems can become decentralized energy networks that can be connected to the neighborhood systems. A distributed energy system can also be perceived as a small-scale energy generation unit that is near the point of use for the producers. The production units can also be in the form of stand-alone or in some cases can be made to form a network that shares the energy surplus. In the case of a connection in the networks, the energy systems can become locally distributed energy networks linked to nearby similar networks. The integration is perceived as an important step towards developing a smart grid and a reliable communication network is required to manage and control these systems.

Table 2.2 Supply options for renewable energy technologies with NZEBs [18].

Options	NZEB supply options	Examples
Energy efficiency improvement	Reduce site energy through low-energy building technology.	Insulation, efficient equipment, daylighting.
On-site supply	1. Renewable energy within the building footprint. 2. Renewable energy within the site.	PV panels, wind turbines, and ground-mounted solar thermal systems.
Off-site supply	1. Renewable energy off-site produces energy on-site. 2. Purchase off-site renewable energy sources.	Wastes, wood pellets, PV panels, wind turbines.

2.4 Energy Storage

Energy storage can always be essential when handling self-consumption and excess energy can be stored and used when there is a deficiency. Therefore, monetary benefits are realized when using these systems. Energy storage can be used in the generation of income. Energy storage can further be used to generate income by leveraging changes in energy prices; power is purchased during times of low demand and price and exported to the grid when the energy demand and market price are high [57].

When there is an extra renewable generation, energy can be stored in the form of heat, potential energy, chemical energy, etc., and discharged when renewable generation is deficient. To accommodate demand, short-term and seasonal storage might be used. Building owners must evaluate if the benefits of a storage system outweigh the higher initial cost and complexity of the system [58]. NZEBs can use a variety of energy storage methods. Specifically, excess power can be stored in batteries and transformed into thermal energy, or chemical energy [59]. Heat can be stored directly as thermal energy, turned into electricity stored in batteries, or converted into chemical energy [60].

Battery energy storage systems have been widely regarded as one of the most viable solutions, with various advantages such as rapid reaction, long-term power delivery, and less dependence on the grid [61]. In particular, battery storage can store and release energy at high frequencies, and offer frequency and voltage stability, making it an efficient tool for improving renewable energy system management. However, one of the most important challenges in implementing battery energy storage systems is the determination of the optimal battery size for managing the trade-off between its technological advantages and the extra cost. For the optimization of battery energy storage systems, a variety of performance indicators including financial, technical, and hybrid factors need to be considered (e.g., smaller systems are desired from a financial perspective [62]).

Electric power from renewable sources could be buffered using vehicle-to-home systems, which use idle electric vehicle battery power as a storage device. By charging during off-peak hours and discharging during peak hours, electric vehicles can modify or regulate the load and peak power profiles of the building system [63]. Hydrogen (H_2) fuel cell vehicles can convert fuels to electricity and heat with zero pollutant emissions and have been demonstrated in residential buildings [64].

On-grid NZEBs with partial storage are significantly less expensive than off-grid NZEBs. Partial off-grid energy storage is valuable for load shifting and improved usage of on-site renewable generation, but it does not necessitate the large investment required for a fully off-grid NZEB. The energy storage arrangement and associated energy conversion equipment increase the complexity of NZEB design and planning, incurring additional expense. Off-grid NZEBs, on the other hand, could be a feasible choice for isolated regions without grid connections. Off-grid, self-contained NZEBs require large energy storage systems [61].

2.5 Renewable Energy Sources

2.5.1 Hydropower

Hydropower is an important source of electrical energy around the world. It generates one-fifth of global power and is the sole domestic source of electrical generation in several countries (e.g., South Africa, India, and the US) [65]. It was estimated that hydropower provided at least 50% and 90% of national electricity for 63 and 23 countries, respectively [66]. There are two main types of hydropower turbines: reaction and impulse turbines. The level of standing water, "head" and the flow or water volume over time dictate the type of hydropower turbine used for a project. Other influential factors include the cost, turbine efficiency, and the depth of turbine installation [67].

Hydropower turbines are used to convert water pressure into mechanical shaft power which can subsequently be used to power a generator or other machinery. The power generated is determined by the pressure head and the flow rate volume. Modern hydropower turbines can convert up to 90% of energy into electricity; however, this decreases as the size of the turbine increases. The efficiency of micro-hydro systems is typically 60–80% [68].

The intake structure, the forebay, the penstock, and a short canal are the essential components of a hydropower plant [65]. An intake structure at the weir diverts water away from the main river's path and controls the flow of water via the intake. Water is filtered through a forebay to eliminate particulate particles before entering the turbine. In the forebay or the settling tank, the water has been sufficiently slowed to allow particle matter to settle. To safeguard the turbines from destruction, a protection trash rack is usually located close to the forebay. The top of the penstock is required to have a valve that is closable when the turbine is turned down and water emptied for proper maintenance. Water is diverted back to the river via a canal known as the spillway when the valve is closed [68].

2.5.2 Wind Energy

Wind turbines convert the kinetic energy of wind into electrical energy [69]. As the airflow from the wind hits the aerofoil blade section of the turbine the lift force is significantly greater than the drag force, causing the blades to turn to produce electricity [70]. The amount of power (P) generated in Watts by a wind turbine is given by the formula:

$$P=\frac{1}{2}C_p\rho Au^3 \tag{1}$$

where C_P is the coefficient of performance, ρ is the density of air (kg/m^3), A is the swept area of the turbine blades (m^3) and u^3 is the wind velocity (m/s) [71]. The Betz limit defines the theoretical maximum amount of energy that can be extracted from the wind by turbines and is defined as 59.3% [72].

For a standard wind turbine, the pitch bearings connect the rotor hub and the rotor blade and allow the blades to be adjusted so that the maximum amount of energy can be extracted from the wind [73]. Similarly, the yaw bearing is a structure that supports the process of aligning the wind turbine rotors towards the wind. Depending on the size of the turbine this can be an active or a passive system [74]. An active system makes use of a motor to turn the nacelle, whereas a passive system would see a tail fin fitted to the turbine and the nacelle would then be free to move according to the wind direction. Passive systems are generally only used on smaller wind turbines. Microwind turbines are suitable for taller buildings [75].

The main benefits brought about by wind power are low carbon emissions and low fuel requirements [76]. In China, the wind power potential in the northern regions constitutes approximately 78% of the nation's total wind energy capacity [77]. In the UK wind power accounts for 25% of total electricity generation in 2022 [78]. The total capacity of the installed utility-scale is 82 GW in America alone, meeting 6.2% of terminal demand. In Germany, wind power is an integral part of the electricity market with the installed capacity being 194.53 GW in 2016 [79]. Germany is the country with the largest installed wind power base in Europe, followed by Spain, the UK, and then France. Portugal, Denmark, Poland, Turkey, and Sweden have more than 5 GW of wind installations, and in particular, Denmark has the highest (41%) share of wind energy in its electricity demand [80]. However, the biggest drawback associated with wind energy is the inconsistency of yield [81]. Moreover, a potential issue with distributed wind turbines when located near dwelling houses is shadow flickering for which rotating blades periodically cast a shadow through openings such as windows [82].

2.5.3 Solar Energy

Solar energy can be harnessed through either photovoltaic (PV) panels or solar thermal panels. The amount of energy produced is largely dependent on the amount of sunshine incident upon them, which varies enormously across the globe [83]. The energy density of solar radiation at the upper levels of our atmosphere is around 1,368 W/m^2. The energy density at the earth's surface drops to about 1,000 W/m^2 for a surface perpendicular to the sun's rays at sea level on a clear day [84]. The average raw power of sunshine incident on a south-facing roof in the UK is around 110 W/m^2 [85]. The Middle East is located in the so-called 'Sun-Belt' of the earth; thus, it receives numerous terawatts of power from solar radiation. The everyday average solar radiation does differ from one month to another and reaches around 730 W/m^2 during March and drops to about 302 W/m^2 during August [86]. Spain stands out as a frontrunner in solar energy production within Europe, hosting several large-scale PV projects. Notably, the Núñez de Balboa solar park in Extremadura, Europe's largest operational solar plant as of 2023, boasts a capacity of 500 MW [87]. Spain is also home to concentrated solar power plants such as the 150 MW Andasol solar power station in Granada [88]. Italy similarly boasts substantial solar energy potential and a noteworthy installed solar PV capacity, with its largest solar PV plant located in Rovigo with a capacity of 70 MW [89]. Germany, despite receiving less solar irradiation compared to southern Europe, boasts one of the highest installed solar capacities due to supportive government policies and public acceptance. The UK, despite its often-cloudy climate, sees significant contributions from solar energy to its renewable energy mix, with large-scale solar farms like the Shotwick Solar Farm and Landmead solar farm playing key roles [90]. PV energy in Africa is around 470 and 660 TWh [91]. The US has estimated that solar energy potential is capable enough to provide 400 ZWh/y [92].

PV panels generally consist of two thin layers of semiconductor material, such as silicon, sandwiched together. One of the layers is doped with phosphorous to give a negative electrostatic charge, while the other layer will have a dopant such as boron, giving it a positive charge [93]. When light energy hits the cell, electrons are knocked loose from the negatively charged side and are captured by the positively charged side. This flow of electrons is an electric current that can be captured by metal contacts [94]. Efficiencies of PV panels have risen from around 1% conversion up to 46% in recent years [95].

Solar thermal panels differ from PVs is that they use solar energy to heat water, rather than generate electricity [96]. Solar thermal panels utilize solar energy to heat water directly, contrasting with PV panels, which convert solar energy into electricity. While the energy gained in this way is of a lower grade (can only be used for heating), solar thermal panels can achieve much higher efficiency than PV panels, with efficiencies of up to 70% [97]. Solar thermal systems can be used with an immersion heater, boiler, or collector. For a typical solar thermal system used for households, flat plate solar collectors are positioned on the roof at an optimum angle for gathering the most amount of solar energy [48]. The water inside the panels is combined with an antifreeze solution to prevent damage from occurring in colder months. The antifreeze solution is heated in the solar collectors and then passed through a heat exchanger to heat the water for the house; the antifreeze solution is kept in a storage tank with an auxiliary heater in case the water temperature is too low [98].

Solar panels are more effective in space cooling when integrated with a thermal-driven air-conditioner. Owing to the availability of a substantial amount of solar energy and lengthy daily sunlight hours, solar-powered cooling systems like thermoelectric cooling systems are considered an intriguing green cooling technology in the Middle East region [99]. The thermoelectric effect, in which refrigeration turns electrical energy generated by PV cells directly into a temperature gradient, can be used in these systems [100].

A PV system can power thermoelectric cooling systems directly without the use of an alternating current/direct current inverter, thus lowering expenses significantly. Working fluids are not used in thermoelectric cooling systems because there are no mechanical moving parts. Furthermore, these systems are eco-friendly and their GWPs were reported to range from 0.13 to 0.47 $gCO_{2\text{-eq}}$/Wh [99, 101]. Therefore, the combined technologies (e.g., thermoelectric cooling systems and PV) are beneficial for solar energy use and environmental protection, meeting the requirements of NZEBs.

2.5.4 Heat Pumps

2.5.4.1 Ground Source Heat Pumps (GSHPs)

GSHPs serve as a source of thermal energy that can replace a traditional gas boiler [102]. GSHPs make use of the relatively constant temperature of soils, rocks, and water below the surface of the earth to heat spaces and provide hot water for buildings [103]. This is achieved by placing heat-collecting pipes containing water and a small amount of antifreeze (refrigerant solution) in a borehole or shallow trench to extract heat from the borehole. Electrical energy is required to power the pump; however, a typical GSHP will return around three or four times more thermal energy than the electrical energy it consumes [104].

The input electrical energy drives a compression/expansion cycle that acts on the refrigerant solution. This cycle extracts heat energy from a low-temperature, high-volume body of water and transfers it to a much smaller volume of water at a higher temperature, which can then be used for heating, such as a refrigerator [105]. Just as a water pump can transfer water from a low elevation to a high elevation, a heat pump can transfer heat from a low-temperature surrounding to a high-temperature surrounding. If a renewable source of electricity is used to power the pump, then the system becomes even more environmentally friendly [106]. In Finland, the use of GSHPs for heating in single-family houses is growing and accounts for 38% of the heat supply (25% of homes are supplied by direct electric heating) [107]. One of the authors' previous studies that aimed at planning renewable energy use in Glasgow found that 3,382 units of 22.5 kW GSHPs were needed [108].

2.5.4.2 Air Source Heat Pumps (ASHPs)

ASHPs use heat from the air outside to heat underfloor heating systems, radiators, and water in buildings [109]. The benefits of ASHPs include delivering heat at lower temperatures over extended periods, increasing the overall heating efficiency (especially when combined with other renewable technologies), and eliminating fuel bills in NZEBs when the electricity required for an ASHP is powered by another renewable technology [110].

Two kinds of ASHP systems are available: air-to-air and air-to-water [111]. An air-to-water system dispenses heat through a central wet heating system [112]. Heat pumps perform much better at lower temperatures compared to a standard boiler system. They are thus more appropriate for underfloor heating systems or bigger radiators and can give out heat at lower temperatures of 20°C for a long time. Air-to-air systems, in contrast, generate warm air that is circulated by fans to heat a house. Such a system cannot generate hot water. Air-to-water heat pumps may be more suitable for recently constructed buildings [113]. It could be less costly if the heat pump is incorporated as part of the original building process, instead of having to retrofit underfloor heating afterward. An ASHP system can reduce carbon footprint since it utilizes a renewable, natural source of heat air [114]. ASHPs are easier to install compared to other pumps they do not need constant maintenance, and they can deliver both hot water and heating. However, they are not perfect systems because ASHPs have much higher emissions than GSHPs. Moreover, ASHPs cannot function very well in cold climate zones because of the problem of frost. Also, ASHPs commonly experience coolant leakage [115].

Heat pumps are receiving increasing attention because of their high performance in terms of efficiency. Many studies confirm that, despite different climatic conditions, heat pump rates are among the most cost-effective and energy-efficient systems for NZEBs [116]. For instance, in Switzerland, more than 90% of buildings are equipped with heat pumps [117]. In Italy, Germany, France, and Denmark, heat pumps are preferable when it comes to meeting NZEB requirements under minimum future building regulations [118].

2.5.5 Biomass

Bioenergy makes up approximately 9% of the total primary energy supply in the world [119]. In the UK, biofuels are a significant part of electricity generation, constituting 11% of total electricity generation in 2022. The UK Government has devised a comprehensive strategy to utilize biomass in various forms [78]. In Denmark and Finland, bioenergy represents more than 15% of electricity production, while for countries like Sweden, Austria, Estonia, Belgium, Italy, and Brazil, biomass-based electricity represents around 6 to 8% of total electricity production [120] Globally, the projected average biofuel production for the years 2023 to 2025 is estimated to be 182 billion liters annually [121].

Since NZEBs must have a reliable source of energy to achieve a stable energy supply, biomass tends to be one of the most appropriate renewables as it is not affected by climate conditions the way that wind or solar energy is, and a steady supply can be maintained as long as there is enough feedstock sustaining the system [122]. Also, biomass systems have a simple design and are easier to construct compared to the structures required e.g., for geothermal systems [123]. Presently, bioenergy contributes to a sustainable carbon-zero society in line with cultural and economic developments and issues [124]. Energy-efficient green buildings, such as NZEBs, reap more rewards from bioenergy than they do from other sources of renewable energy [125]. Economically, biomass, as a clean source of energy, attracts various tax benefits from the government. A study by D'Agostino and Mazzarella determined that, among all the NZEB alternative sources of energy, biomass is the most effective regarding energy supply [126].

Bioenergy could be derived from a variety of feedstocks including industrial residues of food and paper, agricultural by-products, sewage sludge, and woody biomass [127]. The process of bioenergy can be broken down into the steps of cultivating feedstock, processing, and then transporting the energy to the intended point of use [128].

The production cost of bioenergy can be significantly reduced if the feedstock is co-fired with pulverized coal. The gaseous fuels and bio-methane produced from the gasification of feedstock can replace natural gas used for heating households. The electric power generated from biomass can also be used as a source of power and heat in buildings [129]. There are two main routes for biomass conversion, either biochemical or thermochemical. The thermochemical route mainly encompasses four processes: pyrolysis, gasification, liquefaction, and combustion while the biochemical route encompasses two processes: AD and fermentation [130].

While bioenergy has several benefits, including its renewable nature and potential to reduce greenhouse gas emissions, it also has limitations that need to be considered [131]- [132]:

Land use and competition with food production: the production of bioenergy crops requires significant amounts of land, which can lead to competition with food crops and natural ecosystems. Large-scale cultivation of bioenergy crops may result in land-use change, deforestation, loss of biodiversity, and conflicts over land resources.

Resource intensive: the production of bioenergy often requires significant inputs of water, fertilizer, and energy for cultivation, harvesting, processing, and transportation. Depending on the feedstock and production methods used, bioenergy systems may have high resource and energy intensity, reducing their overall sustainability and environmental benefits.

Impact on soil and water quality: intensive cultivation of bioenergy crops can lead to soil erosion, nutrient depletion, and degradation of soil and water quality. Agrochemicals used in bioenergy crop production may also contribute to the pollution of water bodies and ecosystems, affecting biodiversity and human health.

Limited feedstock availability: the availability of sustainable biomass feedstocks for bioenergy production may be limited, especially in densely populated or environmentally sensitive areas. Competition for feedstock resources can drive up prices and lead to conflicts between different sectors, such as agriculture, forestry, and energy.

Technological and economic challenges: scaling up bioenergy production to meet significant portions of energy demand requires substantial investments in research, infrastructure, and policy support. Additionally, the economic viability of bioenergy projects may depend on factors such as feedstock costs, energy prices, regulatory frameworks, and market dynamics.

While bioenergy can play a role in transitioning to a more sustainable energy system, addressing these limitations and ensuring the sustainable and responsible production and use of bioenergy is essential to maximize its benefits and minimize its adverse impacts on the environment, society, and economy.

Bioenergy faces several limitations. These include limited feedstock availability, potential carbon emissions, resource-intensive production processes, technological challenges and competition with food production. Addressing these limitations necessitates careful feedstock selection, technological advancements, sustainable practices, and supportive policies [133].

2.5.5.1 Waste Management

There are four ways to manage waste: (1) waste generation reduction, (2) reusing required items, (3) recovery, disposal, and collection of recyclables, and (4) waste conversion into energy [134]. The conversion of waste into energy is crucial in the context of energy and can be a great avenue for renewable energy development [135]. The classification of strategies to manage waste through recycling, reusing, reducing, and recovery based on their effectiveness in minimizing waste is known as a waste hierarchy, it aims to generate minimal quantities of waste while extracting maximum benefits from the products [136].

Waste-to-energy comes before final disposal in the hierarchy of waste management. It is the waste processing into electricity, heat, or fuel through waste-to-energy technologies, such as gasification, pyrolysis, AD, and incineration. By applying appropriate and more efficient techniques, it is possible to convert diverse biomass types, such as agricultural, energy crops and forestry waste, animal and industrial residues, and domestic and household waste into different types of bioenergy products (e.g. biogas, biofuel, and biochar) [137].

The exciting aspect of the solution provided by waste-to-energy is two-fold, i.e. production of energy and management of waste. Increased adoption of waste-to-energy projects leads to the improvement of valuable energy provision, reduced health-related risks related to environmental pollution, and waste reduction [138]. In the past, waste incineration technology was used to significantly reduce the mass and volume of solid waste. For more than a century, Sweden and Denmark have been at the forefront of using energy from incineration. In Denmark, 13.7% of the total local heat and 4.8%, of the electricity consumed in 2005 were produced from waste incineration [139]. In the EU, 31% of waste was still landfilled compared to about 25% in the UK [140]. The EU government’s goals include no more than 5% of all waste being landfilled by 2025 and 70% of all waste being recycled, prepared for reuse, or composted by 2025 [141].

Waste-to-energy technologies facilitate the development of sustainable waste management practices. The amount of waste being sent to landfill has been a cause for concern in recent years. [142]. The energy generation from waste through the technologies is a promising solution for tackling the challenges of sustainable waste pile-up and renewable energy production [143]. A study conducted by the Sustainable Development Commission Scotland found that 3.9% of Scotland’s total heat demand could be provided through energy from waste [144].

Renewable energy, such as that recovered from waste, has become more competitive in the energy market through government incentives, the reduction of process costs, and advancements in technology [145]. The appropriate treatment of waste is crucial both to its disposal and to renewable energy production, thus ensuring its sustainability and contribution to increased energy demand [146].

Effective waste sorting leads to increased efficiency in energy recovery. To improve recovery and treatment operations, and minimize waste directed to energy recovery operations, separation of the different elements (e.g., solid waste and organic waste) is a necessity. This reduces greenhouse gas emissions and the cost of transportation due to the potential remoteness of processing and disposal facilities [147]. Waste is a valuable resource that supports the circular economy by reusing the material in self-sustaining production systems [148]. The energy generated from waste meets increased demand and reduces dependence on natural resources, contributing to the circular economy and increasing economic productivity.

2.5.5.2 Energy from Waste

Bioenergy-based NZEBs have the additional benefit of facilitating the development of sustainable waste management practices. The amount of waste being sent to landfills has been a cause for concern in recent years [149]. Generating bioenergy from waste through the technologies mentioned above is a promising solution for tackling the challenges of sustainable waste pile-up and renewable energy production [143]. A study conducted by the Sustainable Development Commission Scotland found that 3.9% of Scotland’s total heat demand could be provided through energy from waste [144]. Up to 300kg of CO_2 could be saved for every tonne of solid waste that is treated [150]. This is because when solid waste is treated, biogenic carbon is excluded. By selling the by-products, waste-treatment systems that generate biomass have a 68% to 98% chance of profitability. Finally, in each of the towns used in the study, bioenergy systems were able to meet 20–23% of the town’s electricity demands and 4–5% of its heat demands [151].

Using MSW as the main source of renewable technology for NZEBs would enhance the sustainability of the system at the community level [152]. In other words, dwellers would participate in providing sources for the system, and the energy suppliers would, in turn, produce power to sustain the buildings [153]. The amount of waste and its composition are vital factors for estimating energy potential. MSW is broadly classified into organic and inorganic compounds. The major chemical compositions of some typical wastes in the UK are listed in Table 2.3.

Table 2.3 Waste characteristics (UK) [154].

Composition	wt %	Moisture %	C %	H_2 %	O_2 %	Higher heating value kJ/kg
Paper and card	15.9	6.25	45.94	6.35	38.55	17445
Plastic film	4.5	11.31	44.77	6.08	32.45	33727
Dense plastic	9.2	7.5	73.81	11.90	4.83	33727
Textiles	4.3	7.04	47.64	6.30	35.46	8000
Combustibles	13.1	15.88	45.35	5.51	32.45	19771
Glass	5.5	2.25	0.50	0.10	0.40	151.19
Food/kitchen waste	3.3	66.38	44.77	6.08	32.45	19771
Garden waste	31.5	55.16	43.62	5.55	33.92	16282
Other organics	2.6	66.38	44.77	6.08	32.45	19771
Metal	1.1	5.50	4.50	0.60	4.30	1954
Hazardous items	4.1	13.00	0.50	0.10	0.40	12000
Electrical items	0.9	14.11	0.50	0.10	0.40	-
Fines	1.5	14.49	26.30	3.00	2.00	-
Non-combustibles	2.6	0.50	0.50	1.00	4.00	-

Biomass generates around ten times less CO_2 per MWh when compared to traditional fuels [155]. However, the utilization of biomass in urban areas might contribute to a city's fine-particle pollution [156]. The main advantages and disadvantages of biomass versus fossil fuels are summarised in Table 2.4.

Table 2.4 Advantages and disadvantages of biomass [157, 158].

Advantages	Disadvantages
• Biomass is a renewable energy source. • Non-edible biomass can be used. Climate change benefits from CO_2 -neutral conversion. • Biomass contains less ash, C, FC, N, S,	• Fuel uses may compete with edible biomass production. • There is a lack of global control over the production of biofuels and the certification of their origins.

Si, and most trace elements than fossil fuels. • The supply for producing biofuels, sorbents, fertilizers, and other materials is abundant and inexpensive. • Biomass consumption helps to reduce biomass residues and waste. • Ash aids in capturing and storing toxic components. • Biomass costs are lower than fossil fuels. • Biomass can be converted into many fuel chemicals.	• Biomass has a high moisture content. • Biomass has a low energy density. • Some technical problems occur during thermochemical processing, such as slagging and corrosion. • The investment cost is high. • Biofuels often need to be combined with small amounts of fossil fuels to make them more effective.

2.6 **Waste-to-Energy Technologies**

There are biochemical, physiochemical, and thermochemical technologies that can be used for waste-to-energy development [159]. Figure 2.2 summarizes the technologies for energy recovery from waste. Gasification, pyrolysis, and incineration are the three types of commonly adopted thermochemical technologies [160]. Biological agents are used in biochemical processes that are suitable for converting organic waste into energy in the form of liquid fuels or gaseous. AD is a typical biochemical technology [161]. Transesterification is one of the most common physicochemical processes where chemical agents are used to convert organic waste into energy [162]. Technology selection (e.g., process parameters and capacity) depends on the waste origin, capital and operational cost, technological efficiency, and complexity, and geographical locations of system implementation [163]. Energy recovery from waste tends to be one of the most appropriate renewables, as long as there is enough feedstock to sustain the systems [122]. Also, the waste-to-energy plants have a simple design and are easier to construct compared with tidal or geothermal system structures [123]. Waste-to-energy contributes to a sustainable low-carbon society that hinges on the definition of cultural and economic developments and issues [124].

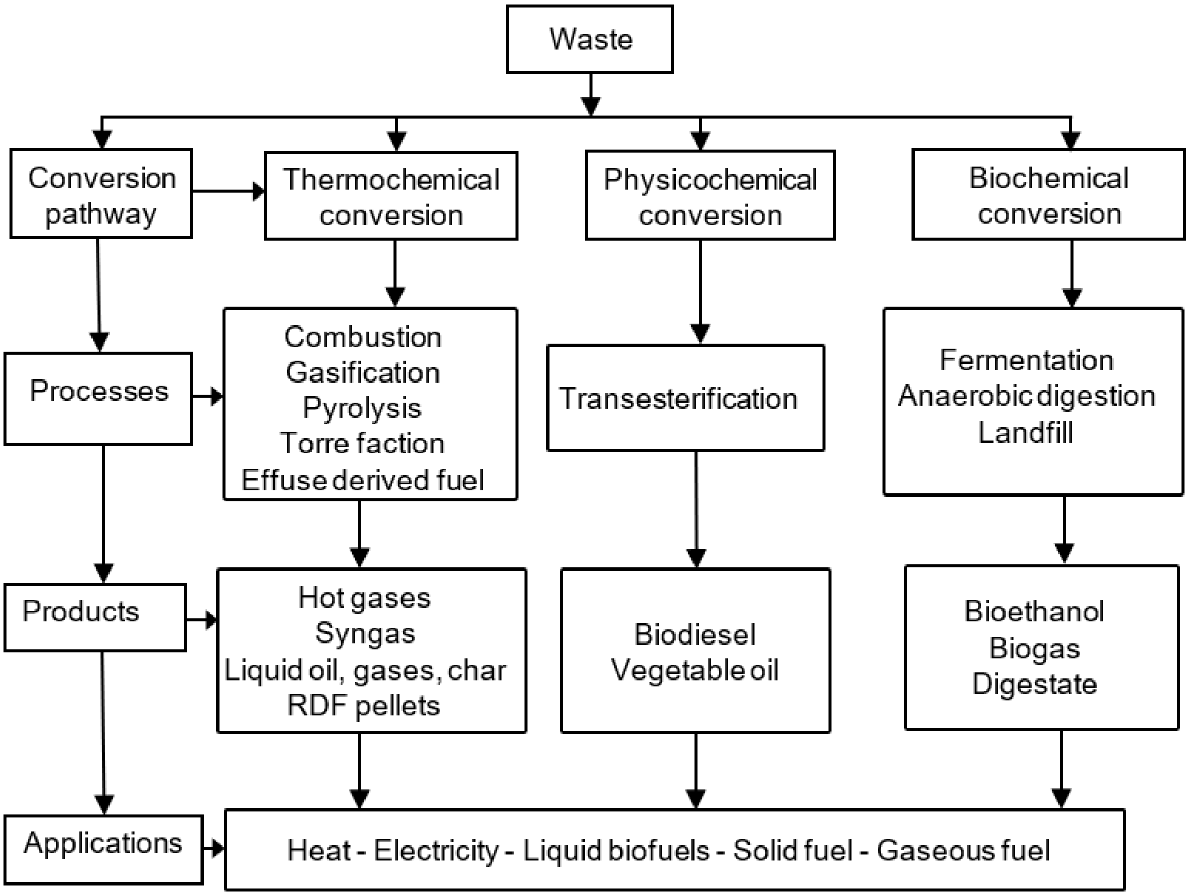


Figure 2.2 Waste-to-energy technologies.

2.6.1 Pyrolysis

Pyrolysis is the process of heating biomass without oxygen [164]. It results in the decomposition of chemical compounds into three main products: bio-oil, biochar, and gas. The specific quantities of these products depend on various factors, including process parameters and biomass composition [165]. Optimal conditions for bio-oil production involve a pyrolysis temperature of around 500°C and a high heating rate of approximately 1,000°C/s, leading to bio-oil yields of 60–70 wt%, with 15–25 wt% biochar and 10–15 wt% syngas [166]. Importantly, pyrolysis can be self-sustaining and economically viable on a large scale, offering advantages such as heat and electricity generation, soil enhancement, carbon sequestration, and waste volume reduction through biochar utilization [167, 168].

The resulting bio-oil, with its dark brown appearance, consists of oxygenated compounds, rendering it unsuitable as an engine fuel [169]. Biochar, a solid byproduct of pyrolysis, can exhibit varying properties depending on the pyrolysis conditions and biomass composition, with carbon content ranging from 53 to 96 wt% [170].

Pyrolysis processes are classified into three main types: slow, fast, and flash. Slow pyrolysis operates within the temperature range of 300–700 °C, utilizing biomass particles sized between 5-50 mm to produce charcoal. Fast pyrolysis, characterized by residence times of 0.5-10 s and heating rates exceeding 10–200 °C/s, favors the conversion of biomass into liquid products. Flash pyrolysis, with residence times below 0.5 s and heating rates ranging from 103-104 °C/s, facilitates biomass-to-liquid product conversion at moderate temperatures (350–500 °C) and biomass-to-charcoal conversion at lower temperatures [158-160].

2.6.2 Gasification

Gasification, the process of generating combustible gas from biomass, is accomplished by burning biomass at high temperatures of 700°C with a limited quantity of oxygen [143]. Gasification is a thermochemical process where carbonaceous materials are converted into syngas (mainly a mixture of CO, H_2, and CH_4) under oxygen-deficient conditions. The main influential factors of the gasification process include oxygen, pressure, and temperature [171]. The syngas can be used in gas turbines for the production of electricity [172]. The process can produce 1.9–3.8MW per ton of waste and reduce the volume of waste by 50%–90% [173]. Table 2.5 displays the gas compositions of diverse gasification processes [174]. Gasification is environmentally compatible with co-generation. It is also economically feasible to work at a high range of working temperatures [175]. Gasification is a more expedient energy production method due to its availability, simplicity of the technology in terms of operation and maintenance, and the high-quality gaseous and by-products produced.

Table 2.5 Gas compositions of different gasification processes [174].

Gases (%)	Gasifier types		
	Fluidized Bed	Updraft	Downdraft
Carbon monoxide (CO)	14	24	48
Hydrogen (H_2)	9	11	32
Carbon dioxide (CO_2)	20	9	15
Methane (CH_4)	7	3	2
Nitrogen (N_2)	50.0	53.0	3.0

The following are the key stages that happen inside a biomass gasifier [176]:

1. Drying: Biomass typically consists of 10–35% moisture. The moisture becomes steam when it is heated to 100°C. Biomass inherently contains moisture that must be removed before combustion occurs.

2. Pyrolysis: As the heating continues after drying, the biomass experiences pyrolysis. The biomass then decomposes.

3. Oxidation: Air is added to the gasifier when the biomass decomposes. During oxidation, charcoal reacts with oxygen in the air to generate CO_2 and heat.

4. Reduction: At high temperatures and as the oxygen supply becomes depleted, CO_2, H_2, and CH_4 are produced.

2.6.3 Liquefaction

Liquefaction, which is also known as hydrothermal liquefaction of biomass, is defined as the thermochemical process that converts biomass into liquid fuel by processing it under high temperatures and pressure in a water environment [177]. The typical conditions are 523–647K and 4–22MPa. This temperature is adequate to initiate pyrolysis of the biopolymers, and the pressure is sufficient for maintaining a liquid water processing phase. The duration of the process also has to be long enough to allow the solid biopolymeric structure to break down into liquid components [178]. The basic reaction mechanisms are [179]: depolymerization of biomass, decomposition of biomass monomers, and recombination of reactive fragments.

Since liquefaction is essentially pyrolysis in hot water, the resulting main product is a liquid crude. Up to 70% of the carbon is transformed into bio-crude, and some lighter products are attained depending on which catalysts are employed [180].

2.6.4 **Combustion**

Direct combustion is the most well-known and most commonly used technology for deriving energy from biomass [181]. In this process, biomass is burnt in extra air to generate heat [182]. There are three main stages involved in the combustion process [183]:

(1) Drying: Biomass inherently contains moisture that has to be removed before combustion occurs. The heat required for drying is provided by radiation emitting from both the flames and the heat stored in the combustion unit.

(2) Pyrolysis: When the temperature of the dry biomass ranges between 200°C and 350°C, the volatile gases are freed. The products are CO_2, CO, CH_4, and high molecular weight compounds like tar that become liquid when cooled. These gases react with oxygen in the air and generate a yellow flame. This is a self-sustaining process, and the heat coming from the burning gases is utilized to dry the fresh fuel to discharge more volatile gases. Oxygen must be provided during this part of the combustion process. When all the volatile substances have been burnt off, char remains.

(3) Oxidation: At approximately 800ºC, the char either burns or oxidizes; oxygen is required both at the fire bed for carbon oxidation and above the fire bed since it reacts with CO to form CO_2, which is discharged to the atmosphere. Allowing the fuel to remain in the combustor for a longer period allows it to be fully consumed. It is pertinent to point out that all the stages mentioned above can take place at the same time within a fire. It is vital to work towards 100% complete combustion of fuel to prevent wastage and improve the cost efficiency of the combustion process [184].

2.6.5 Anaerobic Digestion (AD)

AD is a biochemical process where anaerobic microorganisms decompose organic waste into a mixture of CO_2, CH_4, and small quantities of other gases, such as H_2 sulfide known as biogas. A biogas plant or biodigester is a reactor that provides an environment for AD to take place with the presence of anaerobic microorganisms digesting organic waste [185]. AD is the process whereby organic waste, such as waste or animal food, is disintegrated to generate biogas and bio-fertilizer. This process takes place when there is no oxygen in a sealed container and produces digestate, which can be used as organic manure in farms [186].

The generated biogas can be used to produce heat, electricity, or as a substitute for natural gas [187]. The process is carried out inside enclosed vessels (digesters), whose internal temperatures are maintained between 30 and 55ºC [188]. The process takes place in three stages, which are liquefaction or hydrolysis, acetogenesis, and methanogenesis. In the liquefaction process, fermentative bacteria convert complex and insoluble organic matter into monomers. In industrial operations, chemical reagents are used during liquefaction to produce high-quality CH_4 with a shorter digestion time. The second step of AD is acetogenesis, where products of the first reaction are converted to simple organic H_2 acids and CO_2 through the action of acetogenic bacteria such as lactobacillus. The third stage of the reaction is methanogenesis, where CH_4 is produced by the action of methanogens such as CH_4 bacillus [189].

AD can be classified into wet and dry ones with the wet technologies processing materials with a moisture content greater than 15% whereas dry technologies dealing with drier materials technologies are used for AD [186]. Wet AD technologies normally operate at mesophilic temperatures of between 30 to 40 ºC. Dry AD technologies on their part operate with high solid content and generally have a shorter operating time for CH_4 recovery and organic matter degradation at a higher temperature condition of ~55 0C [188]. In the United Kingdom, two-stage digesters are preferred as they also produce more biogas per unit of feedstock and have lower operating costs as compared to other types of AD systems [190].

2.6.6 Incineration

The incineration process can achieve a 25%–30% efficiency [191]. Non-combustible material, oxygen (O_2), flue gas, CO_2, and N_2 are the major components of the hot combusted gases of the incineration process [160]. Reduction of waste volume and weight by 70% and 80% respectively are the main advantages of the incineration process. To reduce air pollution emissions, modern incineration systems often utilize emission control systems. The solid residue (slag) of incineration is commonly removed from the bottom of the furnace into a quench tank. To promote resource utilization efficiency, slag of the process can be combined with fly ash to produce cement and other building materials [192].

2.6.7 Fermentation

Fermentation is an anaerobic biochemical process that breaks down organic compounds such as glucose into value-added products such as Ethanol (C_2H_5OH) and H_2. In a fermentation process, biomass is inoculated with yeast or bacteria, which act on the sugars and yield C_2H_5OH and CO_2. To achieve the high product purity required for fuel applications, C_2H_5OH can be distilled and dehydrated. The solid residue leftover from the fermentation process can be used as cattle feed to achieve additional environmental benefits. In the case of sugar, the resultant fiber known as bagasse can be used as a fuel in boilers or for further gasification [193].

The fermentation-based H_2 production can be divided into three categories: first, dark-fermentation, in which no light is used; second, photo-fermentation, in which light is used as a source of energy; and third, a combination of photo- and dark-fermentation [194]. When dealing with fermentation-based H_2 production, numerous factors should be examined including the types of feedstocks, microorganisms, and technologies (i.e. dark-fermentation, photo-fermentation, and photo- and dark-fermentation) [195]. Refined sugars, raw biomass sources like corn stover, and even wastewater can be used as organic matter for the process. Dark fermentation is a cost-effective and environmentally beneficial method of processing waste biomass. Dark fermentation, with a net energy ratio of 1.9, is thought to be the most promising and well-understood technique of biohydrogen production from biomass [196]. Many anaerobic microbes use H_2 as a primary energy source. If energy-rich H_2 molecules are available, such microbes can use the electrons produced by H_2 oxidation to generate energy. In the absence of external electron acceptors, organisms generate an excess of electrons in metabolic activities as a result of protons being reduced to H_2 molecules. Hydrogenases are the key enzymes that regulate H_2 metabolism [197].To improve the performance of dark fermentation (e.g., the yield of H_2) different types of bacteria such as *Bacillus amyloliquefaciens* and *Clostridium pasteurianum* have been tested and sophisticated co-culture fermentation techniques were also proposed [198].

2.6 Analysis Methods

The CBA, LCA, MOO, and MCA methods provide valuable insights into different aspects of decision-making, allowing stakeholders to make informed choices considering various economic, environmental, and technical factors.

The functionality of CBA, LCA, MOO, and MCA are:
CBA is a method used to evaluate the economic feasibility of a project by comparing its costs and benefits. It involves quantifying costs and benefits associated with a project, typically in monetary terms.

LCA is a comprehensive method used to assess the environmental impacts of a product, process, or activity throughout its entire life cycle, from raw material extraction to disposal. It considers environmental indicators to provide insights into the environmental performance of different options.

MOO is a mathematical approach used to find the best solution to a problem with multiple conflicting objectives. It involves optimizing multiple objective functions simultaneously, considering trade-offs between them, to identify a set of solutions known as the Pareto front or Pareto set, representing the best trade-offs between conflicting objectives.

MCA is a decision-making tool used to evaluate and compare alternatives based on multiple criteria or objectives. It involves systematically assessing alternatives against predefined criteria, which may include economic, environmental, and technical factors, to rank or prioritize them according to their overall performance.

2.7.1 Cost-Benefit Analysis (CBA)

One of the main factors decision-makers consider assessing waste treatment strategies is the economics of system development. CBA is one of the primary methods used for the evaluation of the economics of waste-to-energy technologies and systems [199]. It is used to assess and associate the benefits and costs of a project while considering the essential determinants (technical and environmental profitability). This tool is utilized in welfare economics to contrast the benefits and costs of option policies. For waste-to-energy development, typical benefits comprise the sale of heat, electricity, by-products (e.g., biochar and digestate), the gate fee revenues from waste disposal, and carbon taxes, whereas typical cost components include the operation and maintenance costs, capital cost, and waste collection and transportation costs [200].

The CBA comprises eight steps (Figure 2.3) [201]. The first step refers to defining the problem. The second step refers to identifying relevant policy options, and there could be more than one option available to address the issue. The third step refers to determining which stakeholder’s perspective the CBA will be applied to. The fourth step predicts the economics based on baseline conditions which could be the ones corresponding to the existing policy status. The fifth step predicts policy responses and involves a comparison of the impacts of the option selected against the baseline conditions. Two major impacts can be considered: financially and environmentally related. The sixth step is about estimating the costs and estimating the benefits. The seventh step refers to calculating the net benefits while the eighth step refers to estimating the distribution of impacts.

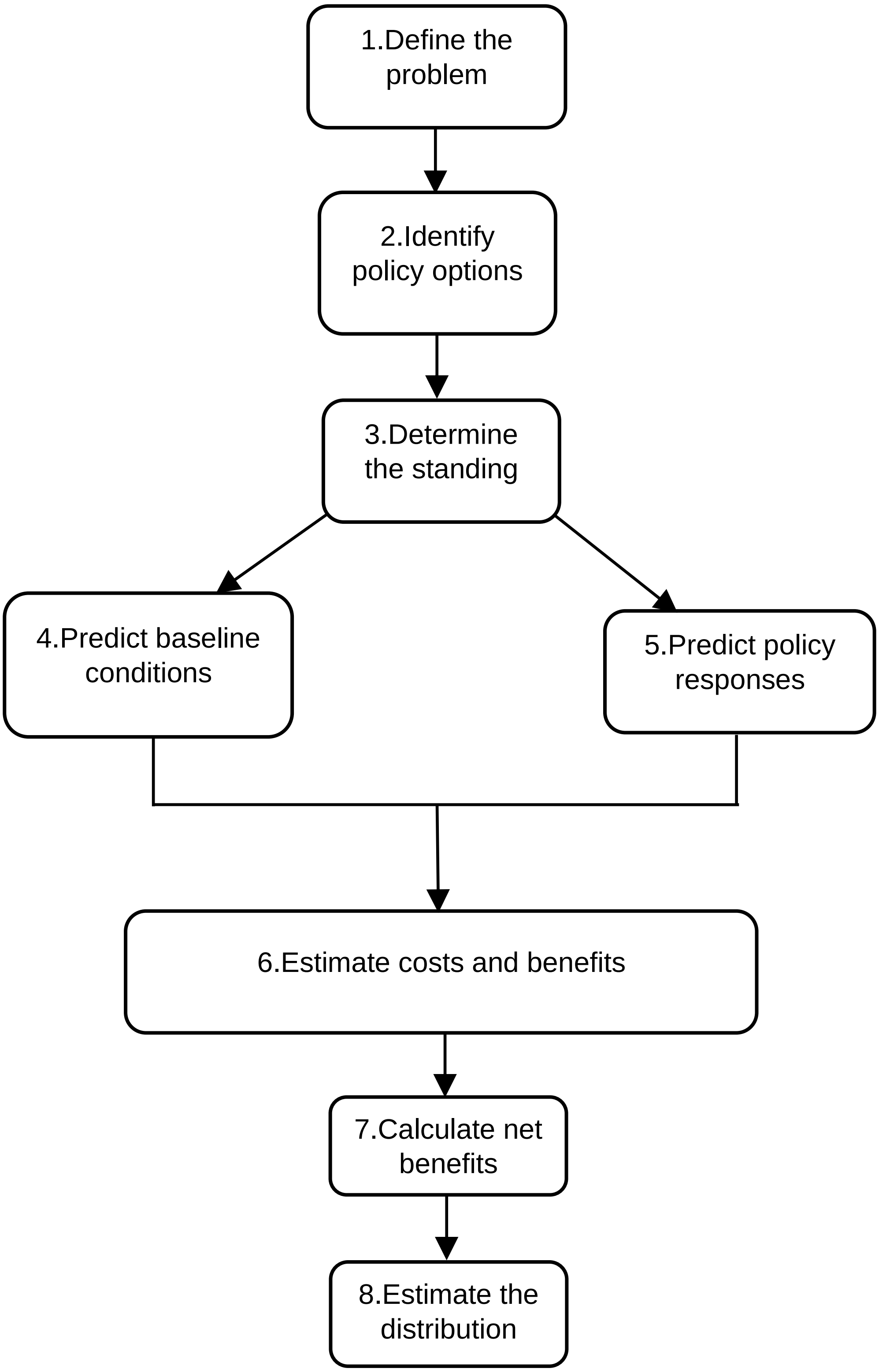


Figure 2.3 CBA framework.

The objective of CBA is to assess all financial costs, including operations, investments, anticipated revenues, and decommissioning costs. The major items for waste-to-energy facilities are plant costs (comprising of direct expenses such as land groundwork), equipment and building costs as well as indirect outlays (e.g., environmental impacts) [202]. In mainland Europe, the investment costs of waste incineration plants were €18–140 million for 50–400 kt/a [202]. In the UK, the investment cost for gasification plants and 32–360 kt/a pyrolysis plants ranged from €11–130 million [203]. In Finland, the Lahti plant is a 250 kt/ power plant based on gasification with an entire investment cost of roughly €160 million [204]. In the UK, the capital cost of a 5,000 kWe gasification-based combined heat and power unit had a capital cost of €201 million in 2015 [205]. AD plants in the UK with a power ranking of up to 100 kW have a unit cost of €7,500/kW [206]. The yearly O&M costs for gasification plants in the UK amount to around 17% of the capital cost [207].

For incineration in China, the unit capital cost amounted to 3.45 €/t waste (a currency exchange rate of 0.13 from CNY to €); the total operating cost was 14.67 €/t waste; the revenue from power generation was 13.73 €/t waste [208].

Anticipated revenues in waste-to-energy processes are mainly electricity and heat sales, gate fees, and the sale of recovered materials. The government pays gate fees to offset the treatment and waste disposal costs by the market conditions and national policies. In Europe, a major waste incineration plant charges a fee of approximately 100 €/t, compared with €50–77/t in the UK [203]. In Italy, the revenue from digestate sales amounted to 15 €/t [206]. For 2016, the worldwide average price of biochar was 2233 €/t [209]. In Australia in 2015, the average biochar price was about 674 €/t [210]. It is pertinent to point out that sales of by-products (e.g., biochar and digestate) can have a vital effect on the economic feasibility of waste treatment. When the by-products are sold, profits can increase by 68-98%. [151]. Table 2.6 presents the economic analysis studies of various waste-to-energy systems.

Table 2.6 A summary of existing economic analysis of waste-to-energy systems.

Design option	Economic results	Major findings	Reference
AD and gasification	Profitability chances from 68 to 98%,	• The findings were that carbon tax might be an adequate incentive to change to using green waste-to-energy technologies. • Considering the sale of the by-products, all technologies can be economically sustainable; additionally, they can generate profits in the future.	[211]
AD	A net present value (NPV) worth of £ 3.187 million.	• The system's major profit source was a form of gate fee. • Waste collection and transport constitute the highest cost factor within the system's life cycle.	[200]
Incineration, pyrolysis, and gasification, and landfill	Incineration, with an optimal electricity price of $ 3cents/kWh	• The best technological option is incineration followed by gasification and pyrolysis. • What makes pyrolysis a profitable option is an increase in the tipping fee.	[212]
Landfills	The NPV is $ 7.556 million	• The application of a small engine generator promotes feasibility. • The electricity sale Standard Reciprocating Engine-Generator Set project has made a breakthrough in the last six years.	[213]
Landfills and incineration	The NPV of 35,483,853 USD.	• It is likely to produce 227.1 GWh annually with 22.3% net electrical efficiency. • It has the potential to recover the investment in less than half the project's life cycle.	[214]
Gasification, organic Rankine cycle	Life cycle cost at $227.8 million	• The net power, the first and second law efficiencies, and the stack temperature of the plant are 219.94 MW, 62.3%, 55.5%, and 54 °C respectively. • The plant can supply electric energy to around 730,000 households.	[215]

CBA aims to supply decision-makers with a framework that can be used to assess economic attractiveness when there is an investment in renewable technology that will improve efficiency. CBA includes the benefit-cost-ratio (BCR), the NPV, cash flow balance, and internal rate of return (IRR) [216]. The NPV marks the dissimilarity between the current value of cash inflows and the value of cash outflows considered over some time as shown below:

$$\mathrm{NPV}=\sum_t^T \frac{C_t}{(1+r)^t}-C_0 \qquad (2)$$

where C_t is the net cash flow during the period t, C_0 is the total investment cost, T is the lifetime of the project, and r is the discount rate. The discount rate ranges from 5–10% depending on the ratio of equity financing and financing for projects.

It is noted that as the number of years (t) progresses, the discount rate diminishes. This means that the further away the cost or benefit is set in the future, the lower its discount factor becomes. A higher discount factor for renewable energy resources only means more preference for things now rather than in the future [217].

The discount rate is applied to the cash flows to account for the time value of money, due to factors such as inflation and interest rates. The IRR is calculated by setting the NPV equal to zero and solving for the discount rate.

The renewable technologies described above each have different capital, maintenance, and material costs, as well as varying feed-in tariff (FiT) incomes. The FiT scheme is a government program that promotes low-carbon electricity generation technologies and makes the uptake of small-scale renewable technologies more attractive [218].

2.7.1.1 Hydropower

Hydropower has been used for decades and is one of the most efficient and reliable renewable energy sources. Due to the high fuel prices, low-head micro-hydropower plants are a viable and cost-effective option to generate electricity in rural, isolated, and hilly areas [68]. The efficiency of the Turgo turbine can reach 91% at 3.5 meters head and 87 % at 1.0 meters head [219]. The efficiency of a Pelton turbine is 70–90%. Because of the uneven flow in the spinning buckets, the performance of a Pelton turbine is dynamic [220].

Another important turbine is a crossflow turbine. It's often used in both horizontal and vertical layouts. Unlike the Pelton and Turgo turbines, a cross-flow turbine is typically employed at higher flow rates and lower heads. [221]. For small and micro-power outputs, crossflow turbines have an average efficiency of around 80% but can achieve as high as 86 % for medium and large units. Micro-hydropower has an initial cost of nearly 6 cents per hour [222]. In the socio-economic development of isolated hills and mountain locations, micro-hydro power is a far more cost-effective option.

The cost of building a hydropower plant can be divided into four categories which are civil work, which was estimated to account for about 40% of the total cost, turbine, and generator sets (30%), control equipment (22%), and management costs (8%), in that order [223]. The overall cost per kilowatt of power capacity ranges from $1500 to $2500 [224].

2.7.1.2 Solar Thermal

Solar thermal panels capture energy from the sun to heat water, and the heated water is stored in an insulated cylinder and is controlled until required [225]. Solar thermal combines well with other renewable technologies to produce high-efficiency levels, and the system can last approximately 25 years [226]. The cost of the solar thermal system is found by scaling up costs per m^2. The estimated cost per m^2 is £700 (944 USD) [227, 228]. The generation tariff is 20.66 p/kWh (USD 0.028/kWh) for the UK [229], making solar the highest thermal tariff. Installing solar thermal with biomass CHP system collectors reduces the possibility of operating the CHP system for longer periods [107]. In Portugal, solar thermal collectors were designed to cover around 60% of DHW needs. Solar thermal systems should be replaced after 14 years [230].

2.7.1.3 Wind Turbines

Domestic wind turbines have a lifetime of 25 years and require regular maintenance checks [231]. Parts such as the inverter will need replacing at some point in the turbine’s lifetime, which costs approximately £1,500 (USD 2023) [232]. A 2.1 kW rated wind turbine cost is approximately £4,500 (USD 6,071) [233], and there is presently a generation tariff of 8.24 p/kWh (USD 0.11/kWh) [234]. The corresponding fixed O&M cost is £22.5/kW/year (USD 30.4/kW/year) [235]. The level of profitability of wind turbines is dependent on the average wind speed.

2.7.1.4 Solar (PV)

The worldwide solar PV capacity increased from 0.7 GW in 1996 to 139 GW in 2013 [236]. Solar PV turns solar energy into electricity with a lifetime of around 25 years [237]. The findings demonstrate that PV technology decreases the consumption of non-renewable main energy to a level below the approximate zero-energy threshold value, which is expected to be 15 kWh/($m^2 \cdot y$) [238]. The results show that, at present, based on electricity charges and solar PV system capabilities and production levels, single-family houses, apartment buildings, and other building types need 0.044 €/kWh (USD 0.050/kWh), 0.037 €/kWh (USD 0.042/kWh), and 0.024 €/kWh (USD 0.027/kWh), respectively [239]. Statistics revealed that in Estonia in 2015, the nationally established PV capacity amounted to 6.5 MW, representing an increase of about 50% from 2014 [240].

2.7.1.5 Heat Pumps

Heat pumps could be both cost-effective and energy-efficient [241]. They can play a significant role in high-performance buildings planned to meet future NZEB requirements, not only owing to the energy and cost considerations but also because of the ability of demand response to back the process of associated energy grids [116].

When evaluating the balance of building technologies, heat pumps combined with PV are the most cost-effective systems for single-family buildings based on a 25-year life-cycle analysis of energy efficiency and annual cost [242]. Most NZEB projects opt for a GSHP as the core device of an HVAC system owing to its excellent performance. GSHPs can provide 30% more energy-efficient than ASHPs [243]. GSHPs can be activated professionally in cold winters. In certain areas where the air is not very cold in winter but is very hot in summer, an ASHP might be more sensible, particularly for limited uses [244].

GSHPs can last 25 years with regular maintenance, so they can be considered a long-term investment. The capital cost of a GSHP (4 kW) is approximately £14,000 (USD 18,891) [245]. ASHPs generally last for 15 years, although with regular maintenance they can be expected to last for much longer. The capital cost for an ASHP (10 kW) system is approximately £6,000 (USD 8,097) [246]. Their capital costs are comparatively much cheaper than GSHPs, and the system provides a reliable and sustainable energy source during most parts of the year [246].

In the UK, the revenue of GSHPs is 9.36 p/kWh (USD 0.13/kWh). The cost of installation is £1,000/Kw (USD 1,349/Kw), and the O&M cost is £5/Kw (USD 6.8/Kw) [108].

2.7.1.6 Bioenergy Technologies

Each of the waste-to-energy technologies and their selection (e.g., process parameters and capacity) depends on the waste origin, technological efficiency, capital and operational cost, and geographical locations of the plants. In the UK, the average capital costs of gasification (2MW) are £16,708 million (USD 22,643 million). The O&M costs for gasification plants in the UK are around 17% of the capital cost [207]. The average O&M cost of gasification is £ 2,860 million (USD 3,857 million) and the AD cost is £ 11,329 million (USD 15,287 million). In Europe, the investment costs of waste incineration plants are £18–140 million (USD 24- 188 million) for 50–400 kt/a [202]. In the UK, the investment cost for pyrolysis plants ranged from £11–130 million (USD 14- 175 million) [203]. In Finland, the Lahti plant is a 250 kt/ power plant based on gasification with an entire investment cost of roughly £160 million (USD 216 million) [204]. In the UK, the capital cost of a 5,000 kW gasification-based combined heat and power unit has a capital cost of £201 million (USD 271 million) in 2015 [205]. AD plants in the UK with a power ranking of up to 100 kW have a unit cost of £7,500/kW (USD 10,119/kW) [206]. Anticipated revenues in waste-to-energy processes are mainly electricity and heat sales, and the sale of recovered materials. In Europe, a major waste incineration plant charges a fee of approximately 100 £/t (USD 135/t), compared with £50–77/t (USD 67-104/t) in the UK [203]. In Italy, the revenue from digestate sales amounted to 15 £/t (USD 20/t) [206]. In Australia in 2015, the average biochar price was about 674 £/t (USD 909/t) [210]. When the by-products are sold, profits can increase by 68-98%. [151].

Biomass boilers can last 20 years, leading to major savings in CO_2 emissions throughout the lifetime of a boiler [247]. Pellet costs are approximately £255/t (USD 344/t) across the UK, but this depends on the size of the order and method of delivery [130]. The estimated capital cost of a biomass boiler is £4,218 (USD 5,690), and the generation tariff is 6.74 p/kWh (USD 0.09/kWh) for the UK [248]. In Austria, the price of pellets was €232/t (USD 262/t) in 2016, while in France, due to an increase in the VAT rate on pellets from 5.5% to 10%, the cost was €272/t (USD 308/t) [249]. Additionally, on-demand heat is essential to creating an NZEB that can always produce thermal energy throughout the year. Table 2.7 shows the cost components for a gasification system with combined heat and power generation.

Table 2.7 Gasification plus combined heat and power generation (2 MWe) cost [250].

Items	k€
Capital costs	
Consultancy/design	650.4
Civil works	1409.3
Fuel handling/preparation	617.7
Electrical/balance of plant	433.6
Converter system (gasifier)	6753.8
Prime mover (CHP)	2732.7
Annual operating costs	
Personnel	120
Power consumption	91.8
Initiation system	26.5
Water treatment	182
Waste disposal	171.5
Consumables	35
Maintenance	629.9
Unit of hourly cost	232.0

To consider the effect of inflation, the following equation can be used [250]:

$$C=C_0\times\left(\frac{P}{P_0}\right) \tag{3}$$

where C is the current cost, C_0 is the original value referred to its reference year, and P/P_0 is the fraction of producer price indices calculated based on the actual inflation rate. To consider the potential effect of scale, the following equation has been used:

$$C=C_0\times\left(\frac{S}{S_0}\right)^f \tag{4}$$

where C is the scaled cost referred to as the commercial-scale S and C_0 is the reference cost referred to as the reference scale S_0. In general, biomass-based energy generation has four main income sources: electricity, gate fees, metal recycling, and carbon credits.

It's critical to examine component interactions, such as on-site and off-site renewable energy supplies upon the design of NZEBs. Marszal et al. used cost analysis to ascertain the optimal levels of energy efficiency and renewable energy generation, including on-site (PV - micro combined heat and power) and off-site (windmill and purchase from a 100% renewable energy electrical grid) choices [251]. The findings revealed that for designing a cost-effective NZEB with on-site generation, energy efficiency should be prioritized over renewable power.

Meanwhile, it is more cost-effective to invest in renewable energy systems rather than energy efficiency for off-site choices. Table 2.8 compares the overall costs and payback periods of typical renewable energy systems.

Table 2.8 Economic performance (cost and payback period) of different renewable energy systems [252-254].

No.	Renewable energy generation type	The average cost		The average payback periods. (Year)
		(£/kw)	(USD/kW)	
1	Hydropower	(1,800- 2,000)	(2,428- 2,699)	4-7
2	Heat bumps	(6000-14,000)	(8,095-18,888)	5-15
3	Wind turbine	(4,500-6,000)	(6,071-8,095)	13-19
4	Solar	(3,000-5,000)	(4,047- 6,745)	7-10
5	Biomass	(7,500-9,000)	(10,118- 12,142)	12-13

The payback period of a renewable energy system is defined as the length of time it takes for the cumulative financial benefits generated by the system to equal the initial investment cost. This metric helps assess the economic viability of the investment by indicating how long it will take to recover the initial capital outlay through savings or revenue generated by the system. Typically, payback periods are calculated by dividing the initial investment cost by the annual financial benefits generated by the system. Shorter payback periods indicate faster returns on investment.

2.7.2Life Cycle Assessment (LCA)

LCA involves the analysis and assessment of the environmental effects of a specified product or service based on the energy and material inputs and the emissions released into the environment [255]. It is an iterative process that comprises the following stages: (1) the definition of the goal and scope, (2) the inventory of the life cycle, (3) the impact of life-cycle analysis, and (4) the interpretation of the result (Figure 2.4) [256].

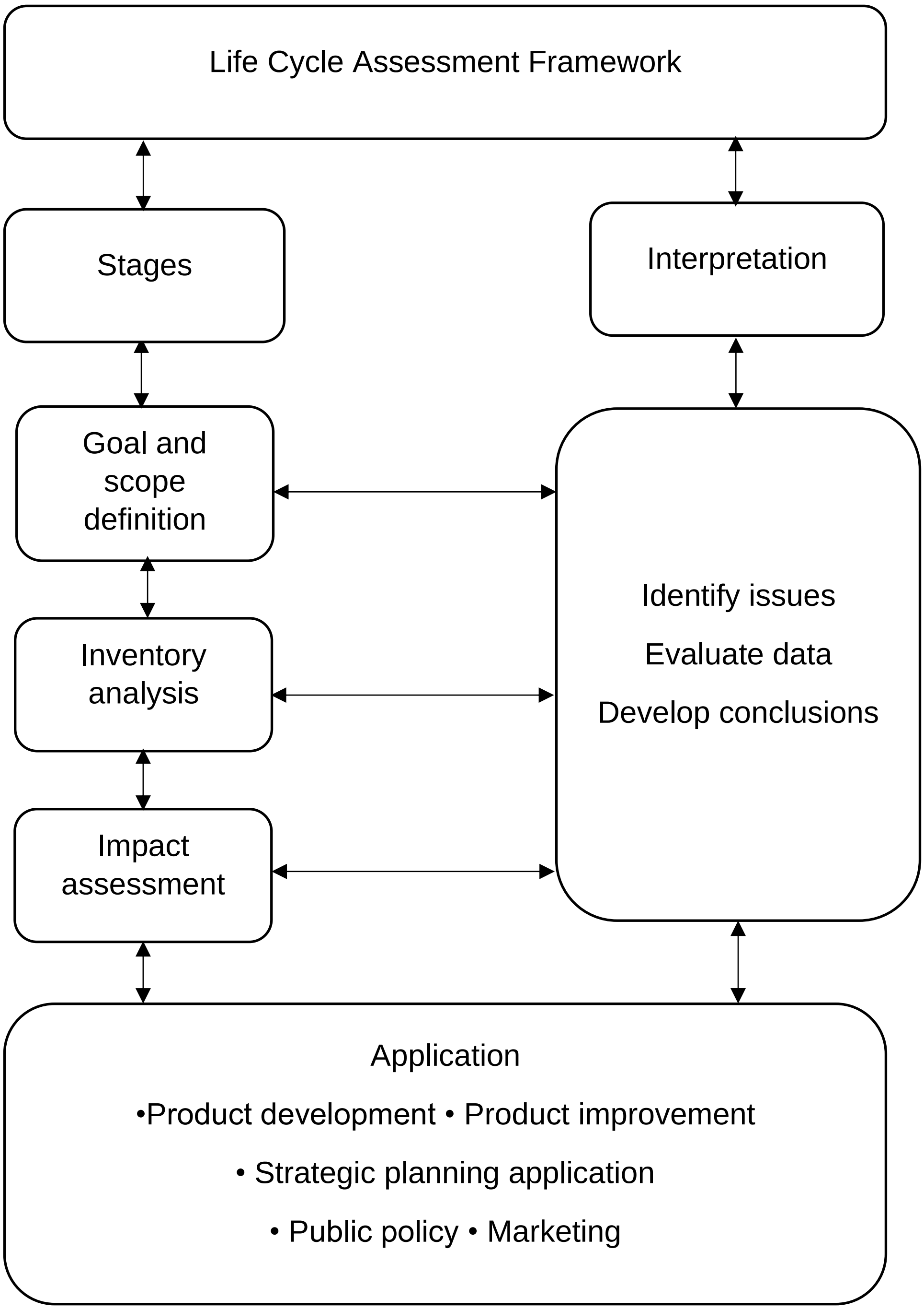


Figure 2.4 LCA methodology.

In stage 1, the goal definition includes information such as the planned use of the study, the reasons for conducting the study, and the targeted audience. Defining the scope involves providing information such as the system boundary, functional unit, data sources, data requirements, and suppositions used. In stage 2, data is gathered for each unit process incorporated within the system. The data can be calculated or estimated and are used to measure the inputs and outputs of a unit process. In stage 3, the potential environmental impacts are evaluated. This is done to highlight the significance of all environmental loads attained in stage 2 by analyzing their effect on defined environmental loads. In the final stage, the aim is to analyze the findings based on the scope and goals and to draw conclusions from all the information gathered.

Biomass produces approximately ten times less CO_2 per MWh compared to conventional fuels and is almost on par with renewable sources such as wind [257]. Matthews and Mortimer stated that the approximate life cycle of CO_2 emissions for wood pellets is 7 kg/GJ. Their definition of life cycle covers the entire process of utilizing wood pellets, beginning from the original resource to its final disposal. Using this value, the total amount of CO_2 that will be released per annum for a domestic building is 608 kg [258]. Kang, Sim, and Kim carried out experiments on wood pellets and discovered that after gasification, the mass of the biomass was reduced by 37% from a starting mass of 0.8065 g [259]. This suggests that for every 1kg of wood pellets, 370g of emissions will be produced [260]. Table 2.9 summarizes the emissions levels of sources of energy.

Table 2.9 Sources of energy generation and their respective emission levels [260].

Electricity generation	kg CO_2/MWh
Wind	6.9 - 14.5
Biomass	15 – 49
Coal	547-733
Hydroelectric	2-26
Nuclear	2-29
Solar PV	13-85
Lignite	1.06-1.69
Industrial gas	0.86-2.41
Space heating	**kg CO_2/MWh**
Biomass (Woodchip)	10 – 23
Natural gas	263 – 302
Oil	338 – 369

Table 2.10 shows the LCA of NZEBs using different approaches. NZEB designs that have high thermal insulation and airtightness have low levels of embodied energy and do not affect the environment. Appliances and office equipment contribute to global warming as does building

construction, depending on the type of material used. Besides, the type of material used in constructing NZEBs determines the factors that can influence their GWP.

Table 2.10 LCA of NZEBs.

Reference	NZEB design	Functional unit	GWP impact ratio	Major influential factors	Findings
[261]	NZE in poultry housing	Cradle-to-farm gate environment	34%	Most emissions and embodied energy are associated with the construction of housing and renewable energy generation systems	• Based on the life cycle impacts, NZE poultry housing with solar PVs can generate net environmental benefits in most impact categories in provinces with greener electricity grid mixes.
[262]	The convergence of LCA and nearly zero-energy buildings	German thermal insulation ordinance	-	Raw materials for construction	• The reduction of energy consumption has progressed in building construction.
[263]	Energy life-cycle approach to NZEB balance	Operation and embodied energy	-	-	• Adopting the life cycle perspective and the concept of embodied energy has transformed the NZEB targets. • The demand for primary energy increases twice when compared to demand in conventional primary energy cases.
[264]	Environmental impacts of appliances in NZEBs	Furniture and appliances	Appliances: 30%, non-renewable energy: 15%	Office appliances and computer equipment make up 30% of greenhouse gas emissions	• Appliances contribute to GWP. • Labels describing the energy efficiency of appliances should include the life cycle perspective and the user's point of view.
[265]	Nearly zero-energy multifamily buildings	Building materials and energy production devices	Building structures: 50%, system: 12%	The pre-use phase of the building contributes 56% of the environmental impacts and	• The consumption of operative energy affects only one-third of the buildings' environmental impacts.

					the operation energy contributes 31%	
[266]	Materials LCA	Meet living building criteria	10%		The largest environmental impacts are the building materials, structural steel, and PV panels	• The environmental impacts associated with the use phase are very low relative to standard structures.
[267]	Integrated assessment framework	Integration of LCA and MCA	31%		Environment, human health, and energy efficiency	• The approach can be used for entire buildings or components and assemblies in buildings.

LCA is a standard protocol that can be applied to determine the environmental potency and weaknesses of waste management technologies [268]. LCA is an evaluation and compilation of inputs, outputs, and potential environmental effects involving a product system during its life cycle [269].

An LCA consists of four stages, i.e. definition of the goal and scope, impact assessment, inventory analysis, and interpretation [256]. The stages of LCA need to be performed sequentially to ensure that goals, methods, and conclusions are internally consistent, comprehensive, and relevant. The inventory and impact assessment phases include the collection and assembly of data that informs both the refinement of the goal and scope definition. To assess whether or not a treatment system is better when compared to another, one needs to measure at least two waste-to-energy technologies using the same method while dealing with an equal waste fraction [270].

LCA by itself cannot exhaustively assess different waste-to-energy alternatives. In the meantime, sustainability which represents the new standard and demand for products or services receives more attention [271] and is based on the consideration of social, environmental, and economic impacts. Numerous expansion methods within the LCA framework have emerged, such as life cycle costing, the environment–energy-economy models, or the energetic life cycle and social LCA [272].

In the waste-to-energy field, the functional units of LCA could efficiently be grouped into two classes: input and output. The input-based method consists of a specific quantity (e.g. 1 kg) of waste or it might have a spatial and temporal indication (a fixed quantity of waste treated in a year). In the output, the LCA outcomes are stabilized towards a definite number of valuable products (e.g. 1 MJ of energy) [270].

The system boundary of LCA identifies and defines all input- and output-streams [273]. However, several studies excluded certain waste management life phases, for instance, transportation and waste collection, because transportation would not affect the comparative assessment of different waste-to-energy technologies. It has a limited effect on strategy studies comparing different waste treatments [274]. On the other hand, some LCA studies simplify the system by not including final disposal in the system boundary with the incorporation of relevant waste avoidance activities [275].

Table 2.11 lists the LCA results for waste-to-energy systems. It reveals that AD and gasification result in considerably lower CO_2 emissions than landfills. It has also been demonstrated that landfilling results in significantly higher CO_2 emissions than gasification.

Table 2.11 A summary of LCA from existing studies of waste-to-energy systems.

Design option	GWP	Major findings	Reference
AD and gasification	300 kg CO_2	• Conveyance has a negligible impact. • AD and gasification offer a better option than traditional treatment methods, such as landfilling and incineration.	[211]
AD	92.27 kg CO_2	• The most significant contributor was electricity displacement. • Emissions that are related to waste collection and transport as well as emissions that result from the CHP unit resulted in lower emissions.	[200]
Landfill, incineration, and AD	GWP reduction ranging from 75.7–93.3% for integrated incineration and AD compared to landfill without energy recovery	• The GHG emissions from Landfilling are the highest. • AD technology has the highest environmental value which decreases the potential of global warming.	[276]
Grate firing	637 g CO_2	• The heat from the waste-to-energy sector is a climate-friendly option for the fossil fuel heat energy system. • The addition of challenging novel waste fractions as an alternative to address the excess capacity of the waste-to-energy sector and to realize environmentally friendly energy systems.	[277]
Incineration- and gasification	107.9 kg CO_2	• Gasification has displayed the highest unsurpassed environmental performance, and growing degrees of proficiencies. • The gasification exhibited lower environmental effects on the acidification potential categories	[278]

Gasification, mechanical-grate incineration, and circulating fluidized bed incineration	186 kg CO_2	• The general environmental operation of gasification is better than that of incineration. • Gasification and incineration can achieve extraordinary advantages by capitalizing on general energy effectiveness.	[279]

2.7.3Multi-Criteria Analysis-Based NZEB Design (MCA)

MCA is an effective solution to assess uncertainty systematically impacts [280]. MCA housing various assessment criteria (e.g., technical, economic, environmental, and social) are commonly used for analyzing thermal comfort and energy performance when designing NZEBs [281]. It can be used to evaluate the energy performance of a particular building [282] and the thermal comfort it offers occupants [283]. MCA approaches help assess the state of buildings and compare them with alternatives such as NZEBs. The comparison permits the best refurbishment approaches to be selected and even procedures that can be used to achieve NZEB requirements. It compares the general performance of different options to determine the best one by evaluating the possible advantages, costs, and hazards [284]. They help people to have a better understanding of how a particular building can operate using different designs [285].

The MCA approach is helpful to guide pre-design and preliminary design stages [286]. The pre-design stage generally involves selecting the most efficient strategies for conserving energy, while the preliminary design is about choosing the best design for the building [176]. In many cases, MCA becomes essential because it determines the sustainability goals of buildings in addition to energy performance goals [287].

In Athens, a study compared several architectural solutions to create additional volumes on existing buildings considering the NZEB standard. Maximizing comfort conditions for the occupants and minimising economic impacts were considered. The results highlighted that living space was increased by 22%, with an energy-saving and polluting reduction of around 90% [288].

MCA was applied in the Isle of Wight to determine the disposal options and wastepaper management procedures. It has been suggested that the best options were gasification and recycling, whereas the least preferred options were landfills or exporting to the mainland for incineration [289]. An MCA method was initially utilised in Turkey to rank renewable energy supply. The results showed that the priority technologies were hydropower and geothermal power [290]. Table 2.12 summarizes existing studies that used MCA to design NZEB.

Combining CBA and LCA factors into an MCA effectively supports decision-making for waste-to-energy development [291, 292]. MCA is an efficient procedure for assessing the general performance of every option and for identifying the most favourable opportunity by evaluating the possible costs, benefits, and risks [284].

In Japan, it was determined that the suitable choice for processing biodegradable and food waste was through AD [293]. MCA was used in a study by Yap and Nixon to evaluate the opportunities, benefits, risks, and costs of waste-to-energy technologies in the UK. The considered technologies are gasification, mass-burn incineration, landfill gas recovery, and AD. It was found that the gasification technology was preferred for the treatment of waste because it had high government funding opportunities, required fewer land areas, and lower environmental risk in comparison to other technologies [294].

Table 2.12 MCA-based NZEB designs.

References	Design option	NZEB composition	Criteria considered	Criteria values of optimal options	Major findings
[280]	Design optimization for NZEBs	Performance preference in NZEB system design	Initial cost score, thermal comfort score, and grid stress score	Sizing of the air-conditioning system	• The peak cooling load uncertainty approximately follows a normal distribution. • The renewable system size combination plays an important role in the grid stress
[295]	Early stages of zero-energy building	Using a simulation-based decision support tool	Usability testing	Local benchmarking, building components, comfort conditions	• Aid engineers in increasing the speed and flexibility of assessing thermal comfort and energy performance in early design alternatives.
[296]	A genetic algorithm-based system sizing method	Using the users' multi-criteria performance requirements as part of the design constraints	Energy balance, thermal comfort, and grid independence	60%	• The uncertainties of the NZEB models need to be described better to improve system efficiency.
[297]	Simulation-based multi-criteria optimization of NZEBs	Using building simulation, optimization process, MCA making (MCDM), and testing the solution's robustness	Wall and roof insulation levels, window glazing type, cooling, and heating setpoints, and PV system sizing.	Annual thermal loads 6.7% for Beirut and 33.1% for Cedars	• Regardless of the climate, it is essential to minimize a space's thermal load through passive strategies that are ensured by a building envelope with high thermal performance.
[33]	Multi-criterion NZEB renewable	Using Monte Carlo simulations to determine an estimate of the annual energy balance and the	Annual energy balance reliability, the grid stress, and	Overall performance 0.78	• The multi-criterion renewable energy system design method improved the overall performance. • The model is effective in the optimization of the size of renewable energy systems under

	energy system design method	grid stress that results from power mismatch	the initial investment		uncertainties.
[298]	Net Zero Energy Village	A residential multi-energy system where energy and transport are sectors contemplated simultaneously	Technical, economic, and social analysis	1.0 MW PV, 5.8 MW wind	• To plan energy systems, the population needs to be involved to speed up the realization of the infrastructure. • A cost-effective and reliable multi-energy system can be developed for a net-zero energy village by integrating volatile energy sources.
[299]	Integrated systems	Through Monte Carlo simulation and statistical analysis (conventional separated design and integrated design)	Initial cost, grid friendliness, and indoor thermal comfort	The initial costs of the air-conditioning, PV, and wind turbine systems were reduced by 14.4%, 13.7%, and 11.8% respectively	• When considering system sizing, conventional separated designs should be replaced with an integrated design approach to improve grid economic friendliness.

2.7.4Multi-Objective Optimization (MOO)

Diverse waste management technologies are currently used, each designed for specific tasks [300]. The suitability of these technologies depends on factors such as the collection scheme, mass composition, and imposed policy goals. No universally dominant technology is applicable to every case, making it essential to explore various technology combinations. Given the issue's complexity, a systematic approach is necessary to identify the "most appropriate" solution. The optimization process helps find the optimal or best solution, addressing problems seeking maximum or minimum values and utilizing single or multi-objective approaches [301].

Mathematical Programming (MP) is valuable for optimizing complex systems like waste management. Over the last twenty years, MP has become one of the most popular tools in operational research for solving real problems. MP aims to optimize a system and has been widely employed in various sectors, including energy, industry, finance, supply chain, agriculture, and water management [302]. MP models describe the system using decision variables, parameters, and constraints. The optimization criterion is the objective function of one or more decision variables. MP, especially in Linear Programming (LP) or Mixed Integer Linear Programming (MILP), has become increasingly applicable in real case studies due to vast improvements in computer speed and algorithmic effectiveness.

MOO aims to provide optimal decisions when dealing with conflicting objectives simultaneously, generating non-dominated solutions such as the Pareto Optimal Front [303]. Each Pareto solution compromises design functions based on set goals. Solutions above the Pareto curve are sub-optimal and can be refined further, while those below the curve are deemed infeasible. Optimized results assist decision-making by identifying solutions that best suit input values and operating conditions. Genetic algorithms, rooted in evolutionary theory, play a role in MOO, offering a broader search space and terminating when a final population set of points is determined [304].

The steps of MOO involve designing the objective function, defining decision variables, and setting bounds and constraints. Various constraints, including bound, linear inequality, linear equality, and nonlinearity, can be applied. Combining effective optimization schemes with MCA becomes essential for balancing environmental quality and economic objectives and navigating the inherent trade-offs in these diverse scenarios. MCA aids decision-making with different criteria, choosing the best alternative as a compromise from available solutions. This analysis, tailored to specific situations, relies on various weighting factors and criteria, with outcomes depending on the decision maker's intentions, whether a policymaker, climate advisor, or company investor [305]. Figure 2.5 shows MOO prosses.

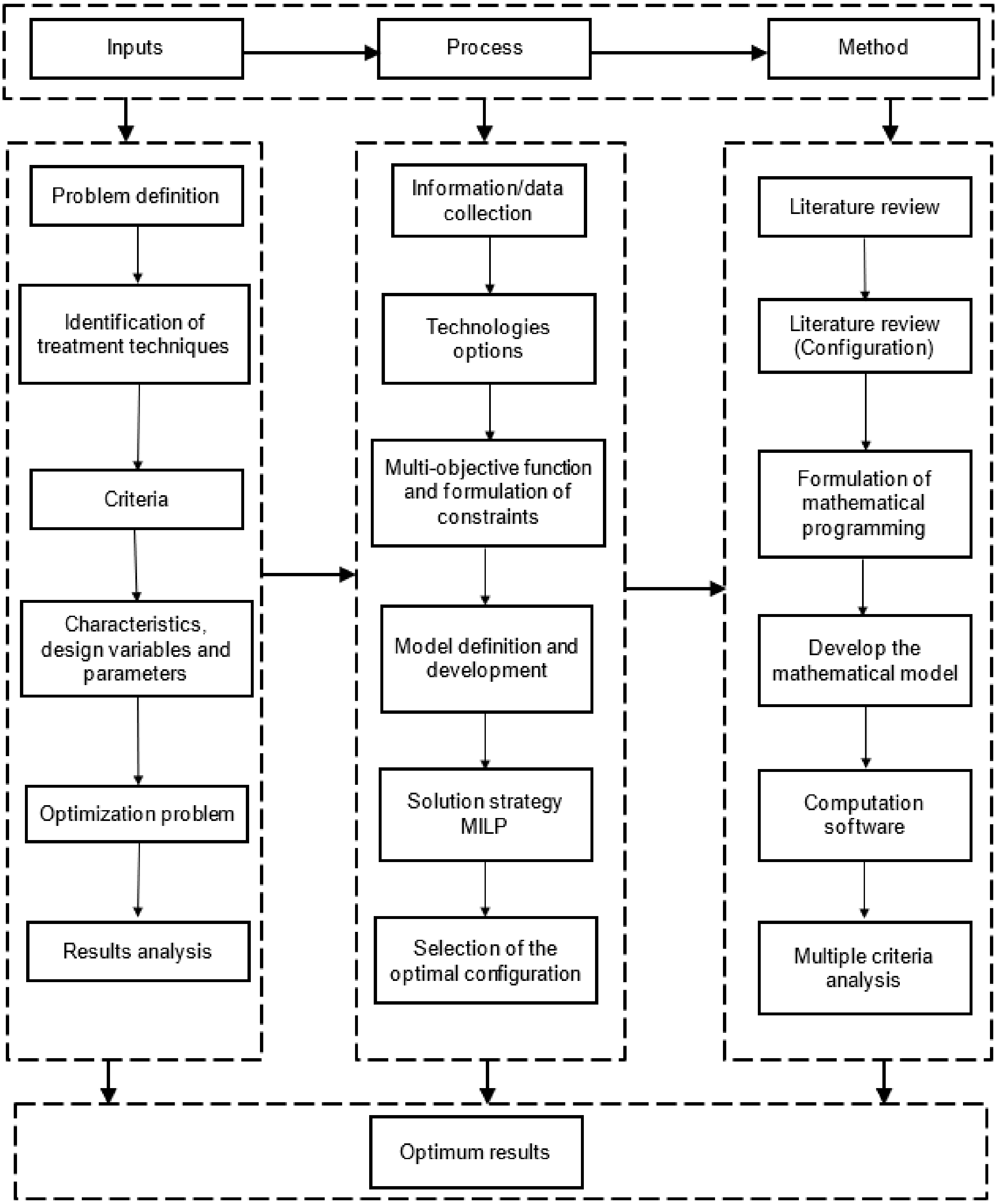


Figure 2.5 the optimization process.

System analysis tools, including optimization models, are essential in designing effective and sustainable waste management strategies. It involves applying mathematical techniques to solve problems based on MILP characteristics, a mathematical framework designed to optimize energy systems. This system can effectively determine the optimal approach to managing waste, and various optimization models have been formulated focusing on the management of solid waste based on economic and environmental assessment. For instance, Khan and colleagues designed a model to assist in making decisions when establishing waste management facilities [306]. Rizwan and coworkers developed a superstructure-based optimization framework using MILP to ensure optimal use and conversion of waste to maximize the economic benefits [307]. Yu et al. presented a multi-objective model designed to look for optimal waste management solutions and optimize cost and risk concurrently [308]. Santibanez et al. created a framework model to optimize the supply chain management of waste to optimize waste consumption and economic advantages concurrently [309]. On the other hand, Levis designed an optimization framework to conduct the life-cycle-based evaluation by focusing on an integrated system for waste management [310].

2.8 NZEBs Case Studies

Currently, the concept of NZEBs is quite new, and there are limited cases of practical applications in Europe [311]. In a detailed report on 32 NZEBs in the European region, four buildings had service systems powered by biomass boilers, and a total of six buildings used direct biomass heating [312]. For example, a building in Belgium used a biomass boiler together with PV panels, solar thermal panels, and a gas boiler. The energy use of the building showed a 78% improvement compared to national requirements. Another building in Ireland used biomass heating with a combined heat and power system based on natural gas and PV electricity production. The energy use of the building showed a 50% improvement compared to national requirements. However, one must also consider the costs involved in using bioenergy. The difference in the initial investment cost compared to current legislation for the building in Belgium versus a reference building that uses biomass heating is 6% higher. Also, the difference in NPV over 30 years is €7,100 (USD 8,036) less than the reference building [313].

In Cyprus, the first regulation concerning the energy performance of buildings was presented in 2007, and the Energy Performance Certification for buildings was advanced in 2010, making energy conservation in buildings relatively new [314]. Despite numerous shortcomings, the regulations and legislation for NZEBs in Cyprus are heading in the right direction. One drawback is that there are no guidelines regarding thermal comfort within a building. Also, there are no strict calculation methodologies applied to normal buildings or NZEBs for construction engineers to use for reference [312]. Thus, one can infer that practical experience and knowledge of NZEBs are still missing in Cyprus. The NZEB design here is also challenged by humidity and condensation, thermal insulation methods, mold growth, air-tightness issues, and the question of how to use renewables in combined systems [314].

In Greece, NZEB adaptation is in its infancy. No definition has been provided for the minimum energy efficiency threshold for NZEBs about either primary energy or end-uses. No bounds have been established for CO_2 emissions. There are also no records of any NZEB restorations for any buildings in Greece [314]. There are currently no indicators for using renewable energy systems in NZEBs, either. Solar energy is most commonly utilized and is regarded as the most effective renewable energy system. The chief obstacle to more widespread use in urban areas is the cost and the inadequate space allowed for solar access [315]. Another cause of concern for NZEB development in Greece is the quality of the construction materials, due to the lack of essential equipment and components. Furthermore, similar to the case of Cyprus, building professionals in Greece lack knowledge about the construction and design of NZEBs [314].

In Portugal, sustainable engineering is part of the energy revolution that applies the principles of NZEBs. The country regards NZEB principles in its architectural drive to comply with the implementation requirements of the European directive of 2010/2013 [230]. Despite achieving milestones in the creation of energy-efficient homes, some obstacles still hinder the move towards NZEBs. Some of these obstacles include financial constraints and legal as well as professional confines [316]. For NZEBs in Portugal, the cost-optimal solution is to make use of green energy that is tapped and used on-site or nearby to ensure the fulfillment of significant extra energy use [317]. There is a gap in the law and the requirements regarding upgrades or redesigns of energy systems in already existing houses or architectural designs. It is also impractical in Portuguese cities to optimize solar orientation, the layout of internal spaces, and the window-to-floor areas in ways that make NZEBs most effective and efficient. The consequence of such obstacles is that they limit the scope of passive building design elements [318].

In Romania, there are no limits specified for cooling, heating, or total energy demand for a building to be considered as an NZEB [319]. There are no renovations associated with NZEBs so far. The supply chain is also split between the market for products and construction materials and marked by poor quality and limited product performance categories, making it difficult for engineers to choose good quality NZEB components. A method to standardize product quality is required to overcome certain monopolistic practices and allow easy access to good quality products at reasonable prices [314].

In Spain, every building that can satisfy the least requirements of the present technical building code will be regarded as an NZEB [320]. However, the latest Spanish technical building code is not yet available, and, at present, only a draft of the future building energy indicators exists [321]. One major challenge of NZEB operation in Spain is the huge variation in climate zones. This necessitates several indicators that are flexible enough to evaluate different approaches to achieving NZEB status. The obstacles to NZEB application comprise the slow process of providing a definition and the problematic economic market situation. Concerning energy-saving building restorations, large socio-economic obstacles restrict the process of key renovations in the housing sector [314].

Because of the numerous technological possibilities, it is critical to choose an "optimal" configuration to maximize the overall economic and environmental benefits. It is also important to accommodate local climates and other circumstances in the optimization for greater design flexibility. As shown above, although several countries have made headway in establishing national standards, the effort to incorporate the concept of NZEBs into international standards and national codes needs to be strengthened. How to incorporate the idea of NZEB into building processes and routines, particularly for renovated buildings, is still an open question. Table 2.13 summarizes the NZEB development and challenges in Europe.

Table 2.13 Summary of NZEB status in Europe [314].

Regions	Status	Opportunities	Challenges
Europe	• Large-scale deployment of NZEB.	• The EU can benefit from future innovation and grow the market. • in NZEB.	• Requiring a large turnover of existing buildings.
Belgium	• Belgium set a definition for NZEB in 2009.	• Biomass boilers together with PV panels can be	• The high costs involved in using bioenergy should be considered.

		used for NZEB.	• The diffusion of NZEBs is complex due to regulatory, economic, social, and technological barriers.
Ireland	• New labels regarding positive energy building and low carbon are set up.	• Biomass could be a dominant renewable energy source for residential NZEBs.	• Bioenergy must be combined with other renewable energy systems, like PV to generate electricity.
Cyprus	• A National Plan is in place. The definition of NZEB has been set for the design of NZEB.	• The regulations and legislation for NZEBs are heading in the right direction	• No guidelines regarding thermal comfort within a building. • No strict calculation methodologies were applied to NZEBs for construction engineers to use for reference.
Greece	• No National Plans are yet available.	• Solar energy is most utilized and is regarded as the most effective renewable energy source.	• The cost and limited space available for solar access.
Portugal	• The definition of NZEB depends on numerous variables including technical viability, climate, type of construction, traditions, etc.	• Energy revolution applied in the creation of energy-efficient homes.	• Financial and legal constraints as well as limited professional support.
Romania	• The National Plan is under development.	• The easy availability of renewable energy.	• No guidelines are specified for cooling, heating, or total energy demand for a building to be considered as an NZEB.

Spain	• A draft of NZEB indicators for Spain was published in 2016.	• The design of buildings complying with the basic criteria and the current regulatory framework meets the requirements of NZEB.	• Large socio-economic obstacles restrict the process of renovation in the housing sector, no building code for future building energy indicators.
UK	• The UK has made significant strides in promoting energy efficiency. • Several NZEB projects have been completed.	• Government incentives and funding schemes. • Advances in renewable energy systems present opportunities to improve NZEB performance.	• Cost remains a significant barrier to NZEB adoption. • Integration of renewable energy sources into existing building designs can be challenging due to space constraints and aesthetic considerations.

2.9 Challenges

NZEB development faces a variety of challenges during the decision-making process [314]. One of the major challenges stems from the limited tools for guiding the decision-making process regarding different aspects of NZEB development such as technical, policy, and financial [322]. For example, an NZEB needs to meet yearly energy consumption with a varied renewable energy system to guarantee supply in different weather conditions [323]. Financially, it is critical to determine the optimal renewable energies and efficiency improvements to minimize capital costs and maximize income. Policy-wise, it is necessary to ensure that NZEB designs are consistent with government regulations to receive export and generation tariffs [14]. Detailed information is summarised in Table 2.14.

These challenges occur at different stages throughout the project life cycle and have to be considered to ensure the long-term success of an NZEB design. For example, Marszal and Heidelberg selected a multi-story residential property in Denmark as a case study to identify the necessary lifetime analysis involved in an NZEB design. They explored the issues from the building owner's perspective, which generated valuable information for prospective homeowners looking to invest in an NZEB [324]. Their results have shown that investment in energy efficiency is made more cost-effective by reducing the energy used to deliver the NZEB's design.

Table 2.14 List of barriers in the decision-making of new construction and retrofitting processes [325].

Field	Barriers to decision-making	Retrofitting processes	New construction
Technical	• The building's structure and design limit the choice of technical solutions and NZEB-related renovation. • There is no one-size-fits-all solution since every building is different. Solutions have to be highly customized. • Personnel with a high level of knowledge are required to carry out NZEB renovations. • An NZEB needs to ensure the security of renewable energy supply in different weather conditions throughout the year.	• The existing building's structure and design limit the choice of technical solutions and NZEB-related renovation. • There are insufficient proven and cost-efficient solutions for NZEB renovation.	• There is a disparity between the different energy needs, due to the challenges created by climate change, dense urbanization, noise pollution, air pollution, and population aging. • Fulfilling NZEB requires changing the rules of the building's design.
Financial	• Investment costs can be high. • The payback period is long and may require long-term ownership of the building, which is not always possible. • Greater financial	• Building owners are probably unable to make money from investments in NZEBs. • It is difficult to ensure that the project is financially justifiable without public funding.	• Unawareness among investors and citizens about the multiple benefits and feasibility of NZEBs (energy costs over the lifetime) • Financial incentives are needed for

	incentives are needed for higher energy-efficiency goals. • It is critical to figure out the optimal renewable energies and efficiency improvements to minimize capital costs and maximize income.		renewable energies to support NZEB.
Social	• Residents and owners lack the knowledge or interest needed to improve energy efficiency. • Architectural and cultural values restrict the extent of NZEB renovations that can be done.	• There is a need to communicate and provide information early in the renovation stage to increase acceptance among residents. • Architectural and cultural values restrict the extent of NZEB renovations that can be done.	• More attempts are needed to raise awareness about energy-neutral buildings and to discuss the strategic approach of enterprises to develop a suitable conceptual model for NZEBs.
Organizational	• If the building is owned by several parties, all or the majority of the stakeholders have to agree before renovations can begin.	• Planning and preparation are needed to reduce the impact of the renovation process on the building’s occupants. • Communication should take place between all involved parties early in the process.	• Need new and different building design concepts that are geo-climatically developed and respect climate sensitivity and technological state. • Need to harmonize actions between countries and consider the knowledge transfer between countries as a good starting point to increase the knowledge uptake and accelerate the implementation of NZEB.
Environmental Health Policy	• It is necessary to ensure that NZEB designs are in line with government regulations to	• If the residents stay in the building during renovation, issues such as noise and dust need to be	• Making energy neutrality of buildings desirable, and using it as a self-esteem and social

	receive generation and export tariffs.	taken into consideration. • There is a risk of increased moisture when making a building more airtight.	status perspective. • Legislation is subject to extreme uncertainty.

2.10 Discussion

This section summarises the development of the main renewable energy technologies for NZEBs, focusing on renewable energy supply, energy storage, CBA, and LCA to help the priorities of future development. Solar energy has long been the most popular renewable energy source for NZEBs, owing to its widespread availability, relatively low cost, and unit cost that is generally unaffected by installation size. When there is limited installation space for solar energy, a wind turbine could be used to augment the solar energy or to lessen the dependence on a single energy source. Wind energy is often less accessible and feasible compared to solar energy, although it has the advantage of more availability during cloudy days and nights. However, the deployment of wind energy for NZEBs is limited by its relatively high cost. Biomass energy is weather-independent, making it appealing, especially when biomass sources such as locally generated waste, are easily accessible. CHP generation can be exploited to achieve higher process efficiencies. ASHPs are appealing for home applications because of their simple setups, low maintenance, and their expense. High-efficiency, low-temperature ASHPs must be designed to work in very cold climates to compete with the operating costs and major fuel consumption of fossil fuel systems. GSHP systems are also appropriate for residential NZEBs, particularly in colder locations, due to their higher efficiency. However, GSHP systems are expensive which continues to be a significant barrier to their widespread adoption.

It is worth noting that the weather has an impact on the applicability of various energy-saving strategies. For example, in heating-dominated buildings, higher insulation and airtightness usually result in greater savings. For cooling-dominated structures, these efforts are less efficient, and they may also be unproductive in case the insulation hinders natural cooling during lengthy periods of lower external temperature [326].

Smart controls, energy-efficient lighting, and energy-efficient appliances, among other things, all contribute to NZEBs by lowering building energy consumption. Furthermore, energy-efficient lights and appliances can reduce the cooling load on HVAC systems. Smart controls can result in a net-zero building if the residents have relatively energy-efficient behaviors.

Energy storage can be used to boost process performance while also lowering resource costs and minimizing environmental impacts if properly designed and configured. The fundamental components of energy storage include energy generation, storage, and supply. NZEBs become more complex due to all the energy storage systems and accompanying energy conversion equipment, which requires further expenditure. On the other hand, off-site NZEBs could be a good choice for isolated regions without grid connections. Off-grid, self-contained NZEBs necessitate large energy storage systems.

CBA is used to assess economic attractiveness when there is an investment in renewable technology. In the UK, the estimated capital cost of a biomass boiler is £4,218 (USD 5,690), and the generation tariff is 6.74 p/kWh (USD 0.09/kWh). The estimated cost of a solar thermal system is £700 (USD 944), with a generation tariff of 20.66 p/kWh (USD 0.027/kWh). A 2.1 kW rated wind turbine costs £4,500 (USD 6,070), and there is a generation tariff of 8.24 p/kWh (USD 0.11/kWh). The capital costs for an ASHP system are approximately £6,000 (USD 8,094). The cost of a GSHP is approximately £14,000 (USD 18,887). The capital costs for an ASHP are much cheaper than a GSHP, which has the highest implementation and maintenance costs and, therefore, is one of the least attractive renewable technologies.

LCA involves the analysis and assessment of environmental effects based on the energy and material inputs and the emissions released into the environment. Combusting biofuels does not contribute to the greenhouse effect because biomass is renewable, leading to CO_2-neutral conversion. Biomass produces approximately ten times less CO_2 per MWh compared to conventional fuels. It has been found that for every 1kg of wood pellets, 370g of CO_2 emissions will be produced. The average emissions levels of wind energy and solar PV are 10.7 and 49 kg CO_2/MWh, respectively. Table 2.15 summarizes the characteristics of waste-to-energy technologies.

The growing number of technologies and the diverse array of potential disposal methods add substantial complexity to the quest for an "optimal" solution. Moreover, waste management holds significant importance not only for environmental reasons but also from an energy perspective. Waste management and the energy system are intricately interconnected, capitalizing on this synergy's economic and environmental advantages. Furthermore, a substantial portion of energy produced from waste is recognized as a renewable energy source.

2.11 **Conclusions**

This chapter reviewed renewable energy sources and the economic and environment analysis of renewable energy systems. Economic and environmental factors affect the design of renewable energy systems and are linked to various parameters, such as feedstock and technology selection, policies, and regulations. The efficiency of renewable energy technologies is measured by sustainability, where waste-to-energy development can play an important role. Waste-to-energy could contribute efficiently to the sustainable energy supply and mitigation of climate change.

This chapter has presented an inclusive review covering the crucial issues related to NZEBs, the contributions of renewable energy generation to the development of NZEBs, and the role of NZEBs in tackling the problems of reducing CO_2 emissions and saving energy. NZEBs minimise energy use through two strategies: diminishing the need for energy use in buildings via energy-efficient measures and embracing renewable energy technologies to meet the remaining energy needs.

Although no single "best" configuration can be suggested, this review aims to highlight potential design methods and renewable energy options for NZEB development. Different NZEB configurations are available for varied climate and building codes, and building industry practitioners need to choose the technologies and architectural components that conform to local conditions and limitations. It is essential to develop a universal decision instrument that directs the management and design of NZEBs. Future research should also focus on better integrating renewable energy generation technologies into the design and analysis of NZEBs. For example, the ability to use waste-to-energy technologies to support the development of NZEBs and facilitate sustainable waste management can be considered an additional benefit. Using waste in energy generation minimizes the environmental impact of uncontrolled disposal, and the decomposition of organic wastes often encourages ecological sustainability.

Few studies have reviewed the contributions of renewable energy generation to the development of NZEBs and the techno-economic feasibility and environmental impacts of renewable energy technologies in supporting NZEBs. Specifically, there are rare studies systematically summarizing the potential of different types of renewable sources to help NZEBs and the methods that can be used to design NZEBs. This project will fill these gaps by clarifying how renewable energy technologies (waste-to-energy) can support NZEBs and their techno-economic and environmental impacts in helping NZEBs.

This study employs a comprehensive approach to assess waste-to-energy technologies' environmental and economic viability in Glasgow. The methodology involves the integration of CBA, LCA, MOO, and MCA. Subsequent chapters provide detailed insights into the method, results, discussions, and conclusions from each analytical aspect.

Chapter 3 - Techno-Economic Feasibility of Waste-to-Energy Technologies-Based Net-Zero Energy Buildings

This chapter begins by outlining the types of input data, parameters, and the CBA methodology employed. The data presented here is derived from Glasgow's waste statistics, shaping the foundation for the calculations. Ten distinct scenarios have been devised, incorporating annual waste types for energy production calculations. The variations in energy yield are attributed to the varying waste available for conversion and the efficiencies of the associated plant technologies.

The outcomes generated in this chapter serve as crucial values for the subsequent chapters, forming a comprehensive understanding of the environmental and economic aspects of waste-to-energy technologies in Glasgow.

3.1 Introduction

There are a variety of waste-to-energy technologies that suit different types of waste technically. Each of the waste-to-energy technologies and their selection (e.g., process parameters and capacity) depends on the waste types and origin, capital and operational cost, technological efficiency, complexity, and geographical locations of deployment [163]. In particular, the performance of waste-to-energy development is contingent upon the types of feedstocks. For example, 120 kWh of electricity could be recovered from 1 tonne of gardening waste using the pyrolysis technology [327]; 448 kWh could be produced from 1 tonne of food waste with the AD technology [200]; 363 kWh could be recovered from 1 tonne of wood waste using the gasification technology [328]. Hence, it is essential to identify the appropriate combination of waste feedstock and waste-to-energy technology for optimal planning of waste-to-energy for NZEBs.

CBA is extensively applied throughout the energy industry and has become increasingly popular in waste management to assist decision-makers in comparing and assessing technologies [329]. It is an efficient procedure for determining design candidates' economic performance to identify the most economically favourable opportunity by evaluating the possible costs, benefits, and impacts [284]. CBA is a valuable tool for making reasonable decisions about resource allocation and technology selection. Nonetheless, there is a lack of CBA on systematically comparing the different types of waste waste-to-energy technology combinations for waste management and NZEB. Such analysis will be valuable for policymakers and investors to make viable judgments on deploying these systems.

High financial costs are a significant impediment to the extensive implementation of renewable energy to support NZEBs. Hardly any studies compare the economic viability of different waste-technology combinations used to support the NZE development of an individual building. This work adds value to existing works by systematically comparing the economic feasibility of various types of prominent waste technologies for guiding the design of bioenergy-based NZEB development. Specifically, this chapter will address the knowledge gaps and evaluate the economic feasibility of different waste-to-energy technology and feedstock combinations, which will project insights into the waste-to-energy system designs for developing NZEBs in Glasgow and beyond. A framework was proposed to compare the economic viability of different scenarios of bioenergy technologies, *i.e.*, pyrolysis (thermochemical), gasification (thermochemical), and AD (biochemical), considering three different types of feedstocks (gardening waste, food waste, and wood waste). A total of ten scenarios were evaluated based on the three main types of waste and the technologies analyzed. Waste treatment technology's overall appropriateness serves as the scenario design's foundation. For example, wet waste with high moisture content is well suited to biochemical treatment from an energy efficiency perspective (more details in Section 2.3). Overall, this study is novel and is different from previous studies, including the author’s work [108]. For instance, previous studies considered Glasgow’s entire power production through various types of renewable energy generation (wind turbines, heat pumps, solar, and biomass). They evaluated its sustainability, whereas the current work considers different combinations of waste-to-energy technologies and feedstocks to support NZEBs. This study demonstrates how implementing waste-to-energy technologies could provide an alternative waste management option to generate renewable energy for developing NZEBs in Glasgow. In addition, the present research indicates how waste-to-energy technologies can support NZEBs, and the proposed methodology is valuable for decision-makers who deal with waste-to-energy and waste management planning.

3.2 Methodology

AD, gasification, and pyrolysis are environmentally friendly methods for recovering energy from waste upon their development to support NZEBs in Glasgow. These technologies have been chosen for the sustainability assessment because they are comparatively well-developed in the waste management sector worldwide [330]. Other technologies were not considered, as many previous studies found this is the least sustainable waste-to-energy conversion technique [191], [331]. A detailed description of these technologies can be found in recent literature, such as [332], [333]. The other consideration for selecting these technologies for sustainability assessment was electricity generation opportunities. In contrast, ‘incineration and landfill’ were not considered because numerous prior studies revealed that it is the least environmentally friendly method for converting waste-to-energy; for instance, see refs. [191], [331], [332], [333] provide a thorough overview of these technologies.

Technical and economic criteria were considered to assess the relative priority of waste-to-energy technology scenarios, as shown by the research framework (figure 3.1). This work's data (e.g., waste generation in Glasgow, process parameters, technology procedures, and cost and benefit components) were collected from recent studies, existing reports, and government statistics and are detailed in the next section. The scale of the technologies used is determined by the volume and composition of waste generated in Glasgow.

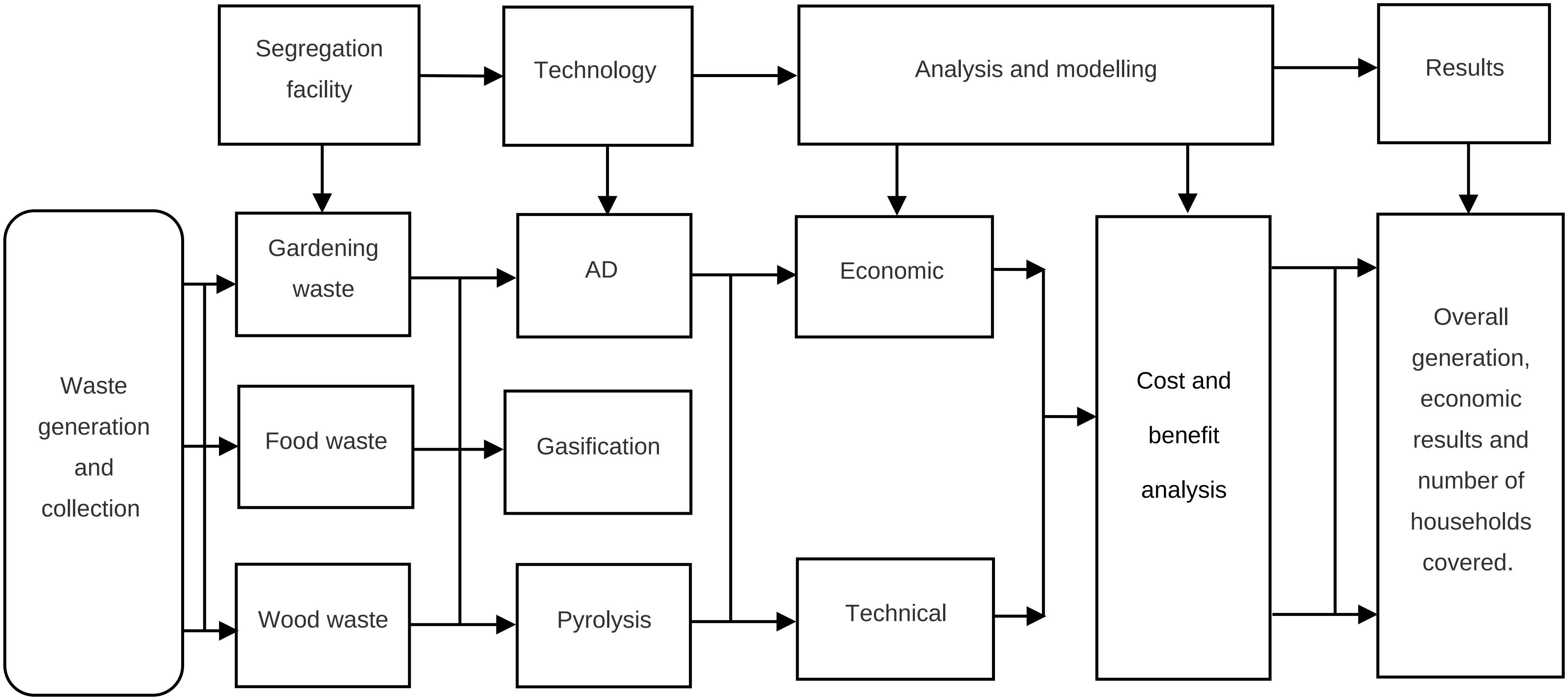


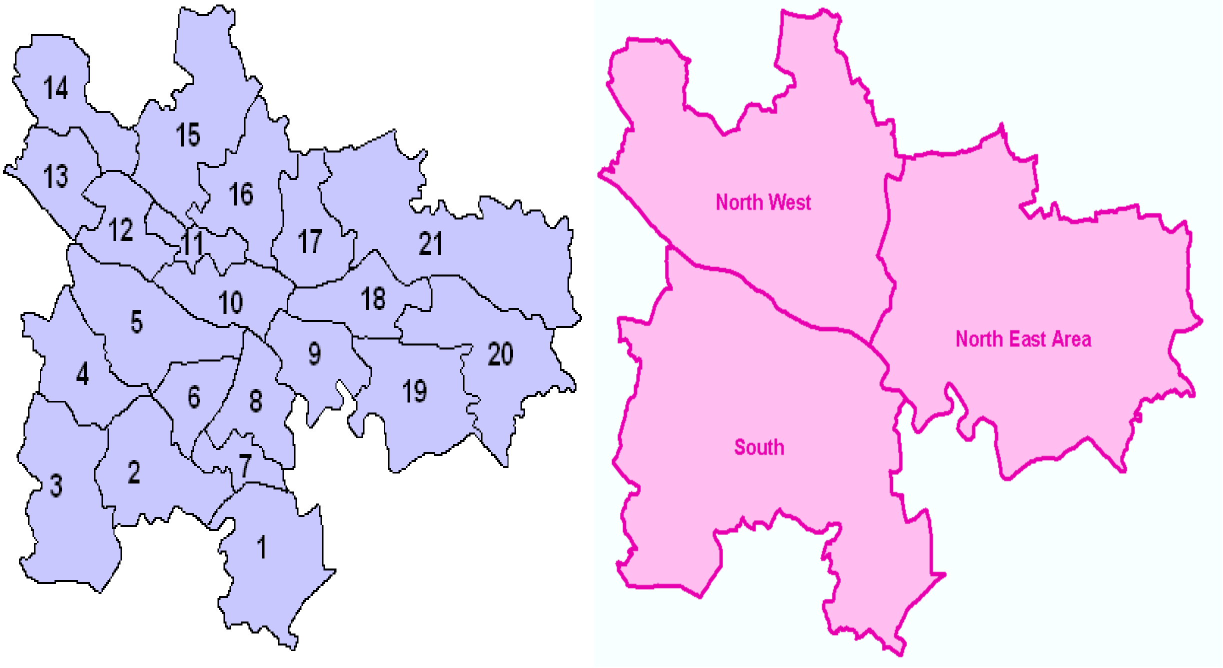
Figure 3.1 Research framework.

3.2.1 General Information About Studied Region (Glasgow)

Since Glasgow is considered a base case for applying the existing waste production, relevant information in the city is reviewed. Glasgow is located on the banks of the River Clyde in West Central Scotland. According to [334], Glasgow has the potential to generate enough bioenergy from wastes alone to power buildings. The city had 303,108 homes, and household waste generation is 245,318 tonne/y. This corresponds to 390 kg/y per capita [335]. The town also produces another 21,000 tonnes of garden waste and 32,000,000 kg of wood waste. There are 23 wards within Glasgow City's perimeters (Figure 3.2 a). In this work, a decentralized deployment concept as to the study by Simon et al. [211] was adopted: several districts are clustered together, as shown in Figure 3.2 b, as a deployment area to install a decentralized system that generates decentralized renewable energy from the waste generated in the regions. It has been shown that decentralized waste-to-energy systems have advantages in terms of GHG emission reduction, transportation reduction, and fertiliser production with a lower carbon impact [336]. Table 3.1 summarizes the general information about Glasgow.

Table 3.1 General information of Glasgow [335].

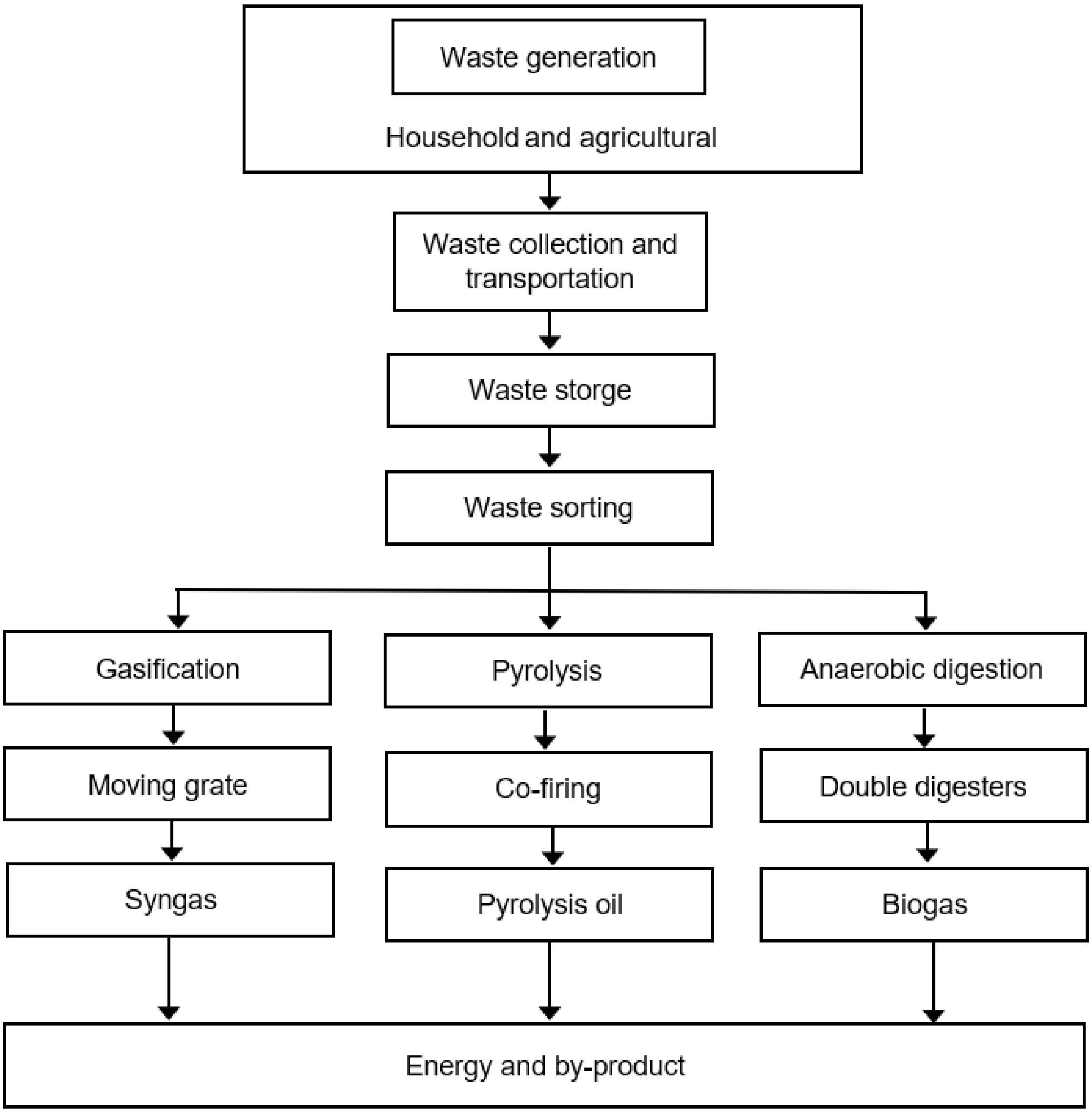
Local Authority Housing Stock of Glasgow and Energy Demand						
	Housing Stock					Energy demand
Category	Total	Fats	Terraced dwellings	Semi-detached dwellings	Detached dwellings	Energy
Unit	Houses	%	%	%	%	kWh/y
Value	303,108	74	12	11	4	3,315
Waste Generation						
Category	Population	Waste per person	Food waste	Garden waste	Wood waste	
Unit	-	kg	Tonnes	Tonnes	Tonnes	
Value	626,410	390	365,000	21,000	32,000	



a b

Figure 3.2 The city of Glasgow [337].

The technical parameters of gasification, AD, and pyrolysis systems considered in this work are shown in Table 3.2, and Figure 3.3 summarizes the process conditions of the three technologies. The analysis in this work was based on treating 418,000 tonnes of waste in all districts. A model for selecting suitable waste-to-energy technologies (comparing the economic viability of technology-feedstock combination) was developed based on the identified technologies (gasification, pyrolysis, and AD), and the system is composed of waste segregation along with waste treatment technologies.



Technologies	Processes	Feedstock	Temperature	Final product
Anaerobic digestion	Biochemical	Food waste, gardening waste and wood waste	35 - 55°C	Energy
Pyrolysis	Thermochemical		300 -800°C	
Gasification	Thermochemical		700-900°C	

Figure 3.3 Schematic diagram of the three main bioenergy production processes.

Table 3.2 Parameters for pyrolysis, gasification, and AD technologies.

Parameter	Unit	District									Reference
Districts	-	A			B			C			Estimated
Technologies	-	AD	Gasification	Pyrolysis	AD	Gasification	Pyrolysis	AD	Gasification	Pyrolysis	Estimated
Volatile solids content	wt. %	76	-	79	76	-	79	76	-	79	[338], [339]
Biogas yield	m^3/t	105	-	100	105	-	100	105	-	100	[340], [341]
CH_4 content	%	60	-	64.7	60	-	64.7	60	-	64.7	Estimated
Energy of CH_4	MJ/m^3	36.47	-	60	36.47	-	60	36.47	-	60	Estimated
Biogas energy density	MJ/m^3	21.88	-	13	21.88	-	13	21.88	-	13	Calculated
Digestate production rate	t/t	0.5	-	-	0.5	-	-	0.5	-	-	[342]
CHP electrical efficiency	%	32	34	30	32	34	30	32	34	30	[343]
CHP thermal efficiency	%	50	30	40	50	30	40	50	30	40	[343]
Electricity demand	%	7.5	20	3	7.5	20	3	7.5	20	3	[343]
Heat demand	%	25	20	10	25	20	10	25	20	10	[343]
Average lower heating value	MJ/kg	-	22	13	-	22	13	-	22	13	Calculated
Average higher heating value	MJ/kg	25	51	18	25	51	18	25	51	18	Calculated
Biochar production	%	-	10	-	-	10	-	-	10	-	Estimated
Electrical efficiency	%	30	40	40	30	40	40	30	40	40	[344]
Thermal efficiency	%	50	30	45	50	30	45	50	30	45	[345]

3.2.2 Scenarios Design Modelling

The scenario design considers the specific processes involved and assesses the overall appropriateness of the technologies for managing various types of waste. The pathways depict the utilized feedstocks, the associated technologies, and the core steps to ensure the finished biofuel is obtained. In Table 3.3, conversion pathways are matched by colouring the scenarios. For example, scenario one is black to illustrate the conversion to a suitable technology. Table 3.3 shows that the technology routes are not the only way to utilise each feedstock. Therefore, the processing of feedstock involves several conversion technologies.

Moreover, the flexibility of technology varies, where some conversion processes utilize various feedstocks while others have controlled requirements. The feedstocks lack homogeneity, which indicates that there are those feedstocks that cannot be used for given technologies. A good example is where waste wood cannot be subjected to AD. The suitability of the feedstocks is highlighted in figure 3.4 based on the core components.

Gasification entails a wide range of reactor designs and temperatures. Nevertheless, gasifier choices are limited by the ability to transform syngas into suitable gaseous or liquid biofuel. The requirements for the feedstock also vary between the gasifier designs. The down-to-entrained flow gasifiers are associated with stringent criteria of uniform and small particles, while plasma gasifiers are tolerant to heterogeneous feedstocks. Wet feedstocks produce more CH_4 and energy and less CO_2 and CO in syngas. Such feedstocks also lower the gasification temperatures and efficiency, depicting higher possibilities of generating tars. Feedstocks ideal for gasification have limited ash and moisture, and the matter content is highly volatile. As shown in Table 3.3, all the involved feedstocks apply to the gasification system.

AD technology can be used in several feedstocks, including garden and food waste. The design of the AD plants is such that they can utilize a mixture of various feedstocks. Nevertheless, there should be consistency in feedstock composition and conditions for optimal fermentation, as is the case with feeding rate. The engineering of the AD systems focuses on creating climatic conditions suitable for anaerobic bacteria. Such designs also ensure that valuable product streams (digestate and CH_4) are efficiently isolated. The system configurations for AD are dry and wet digestors. Systems of wet digestors focus on taking high water content for the feedstock, while dry ones are utilized for energy grasses, straws, and silage crops. The costs of AD technology depend on the scale and infrastructure required for processing wastes.

Pyrolysis conversion involves different reactor designs and temperatures. However, the usual selection for maximization of liquid yields within the shortest residence time and minimizing gaseous and solid by-products is fast catalytic pyrolysis. The suitable feedstocks for this process are the ones that have a high content of volatile matter and are low in ash and moisture. The reaction dynamics are improved by the easiness of reduction or chipping to small particle sizes. All feedstocks, i.e., wood, food, and garden waste, are suitable for pyrolysis.

The description above and the analysis show the conversion of waste-to-energy technology and waste-dependent. To evaluate the feasibility of waste-to-energy technologies to support NZEBs, it is necessary to assess economic and technological parameters covering the range of possible technology-feedstock combinations.

3.2.3 Economic Analysis

CBA is an effective tool used in analyzing economic feasibility due to its ability to examine uncertainties and risks in investment. CBA was applied to determine whether the benefits of using bioenergy to support NZEBs outweigh the costs. Uncertainties in the CBA are inevitable due to the availability and variety of the factors in consideration. In this case, Monte Carlo simulation-based CBA and variable parameters are assumed to follow triangular distributions to account for their potential uncertainties [274].

This study considers expenses comprising operation, maintenance, and capital costs as negative cash revenues and flows. In contrast, energy and bio-product sales are regarded as positive cash flows. The BCR is calculated by dividing the equivalent uniform annual benefits (EUAB) by the comparable yearly consistent cost (EUAC).

$$\mathrm{BCR} = \frac{\mathrm{EUAB}}{\mathrm{EUAC}} \tag{6}$$

Where:
EUAB = the benefits of the project × an annual worth and
EUAC = the capital cost of the project + operation and maintenance cost.

Annual Capital Expenditure (CAPEX) refers to the upfront costs associated with starting the project.

$$(\text{CAPEX}) = \text{CAPEX} \times \frac{r(1+r)^{T}}{(1+r)^{T} - 1} \tag{7}$$

Where r is the effective interest rate, in this work, 6% has been used [346], and T = 20 years, which is the lifespan of the systems [347].

The IRR estimates the profitability of projects with a higher IRR value, suggesting a more desirable investment. It is a comparison tool that is used in investment decisions.

$$0 = NPV \sum_{t=1}^{T} \frac{C_t}{(1+IRR)^{t}} - C_0 \tag{8}$$

The NPV determines the project's worth over the lifetime.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^{t}} \tag{9}$$

Where i is the discount rate or return that could be earned in an alternative investment. R_t is net cash inflow-outflow during the period. t is the number of periods.

The Levelized Cost of Energy (LCOE) measures the average net present cost of electricity generation for a generating plant over its lifetime. It can be used for investment planning and consistently comparing different electricity generation methods.

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{10}$$

where I_t is investment expenditures in year t, M_t is operation and maintenance expenditures in the year t, F_t is fuel expenditures in the year t, E_t is energy generated in year t,r is the discount rate, and n is the expected lifetime of the system.

The capital cost is determined by a plant’s capacity or scale, which was selected using a power-sizing method, as shown in the study of You et al. [274]. For all circumstances, the scaling factor is set to 0.8. The upper boundaries of triangular distributions are assumed. Each technology is estimated to be operational for 335 days each year. The operating and maintenance expenses for AD, pyrolysis systems, and gasification are roughly 7%, 10%, and 17% of the capital cost, respectively [207]-[348]-[274]. For the O&M cost, a triangle distribution with a lower mode and higher capital cost limit is assumed. The government developed the Feed-In Tariff system to promote the generation of renewable and low-carbon electricity, even in small-scale production (Table 3.4). The income from the bio-product sale was considered and reported in the UK market at £389/t. A gate fee value of £50 /t was used in this study [349].

It was reported that collection and transportation are part of the cost of the waste-to-energy technologies process [350], and its phase significantly contributes to the overall cost of waste handling systems [351]. It is crucial to consider these aspects, and a waste-collection model has been employed in this study because it accurately predicts the energy and time requirements of a waste-collection scheme. The model's accuracy was compared to the Organic Waste Recycling (ORWARE) and Waste and Resources Cost (WRCM) models, revealing that the waste-collection model outperformed the other two models [352]. Initially, various sub-systems were modelled, and all necessary input data were gathered. Subsequently, the primary model was developed, and interim results were computed. These interim results were aggregated and converted into diesel and truck time requirements per tonne of waste collected. This study determined the total capital cost of procuring all necessary trucks, the O&M cost of the trucks, expenses associated with hiring staff for truck operation, and the costs of diesel consumption. The capital cost of acquiring all required trucks was computed using information from the waste collection model, incorporating cost data and other relevant parameters. The variable truck time needed per tonne of waste collected, as determined by the waste collection model, was utilized to calculate staff wages for operating the trucks.

Economic information for all modelled technologies is derived from published articles, research papers, and online governmental resources. Assumptions and input parameters for the economic evaluation and the waste collection and transportation model are provided in Tables 3.4 and 3.5.

Table 3.4 Summary of parameters for the economic evaluation.

Parameter	Unit	Technology			Reference
		AD	Gasification	Pyrolysis	
Lifetime	y	20	20	20	Estimated
CAPEX	£/kw	2,500	1,605	3,400	Estimated
Operate system	day/y	335	335	335	Estimated
O&M cost	%	7	17	25	[353], [207]
Biochar price	£/tonne	-	389	-	[349]
Feed-In Tariff	p/kWh	1.57	1.57	1.57	[108]
Renewable Heat Incentive	p/kWh	2.68	2.68	2.68	[354]
District heating CAPEX	£	40	40	40	[355]

Electricity tariff	p/kw	1.6	1.6	1.6	Estimated
Heat tariff	p/kw	1.4	1.4	1.4	Estimated
Digestate price	£/t	5	-	-	[356]

Table 3.5 Parameters used in the waste collection and transportation model.

Parameter	Value	Unit	Reference
Average distance between stops	0.08	km	Calculated
Average truck time requirement	0.827	h/tonne	Calculated
Diesel requirement	10	l/tonne	Calculated
Average haul speed	50	km h-1	[2]
Average transport distance	20	km h-1	[2]
Average number of trucks	24	-	Calculated
Average speed during round trips	8	km h-1	[2]
CAPEX per truck	160,000	£	[357]
O&M cost per truck	2500	£	[358]
Average staff per truck	3	-	Estimated
Average paid wage per hour	10	£	Estimated
Average diesel price	1.30p	l	[351]

3.3 Results and Discussion

This section will discuss the economic feasibility results for the selected pathways to explore which way of technology-feedstock combination is the best.

3.1 Comparison of Total Energy Production

The selection of the best appropriate technology-feedstock combination to support NZEBs for Glasgow is dictated by the economic assessment of energy recovery from waste and the energy production and energy efficiencies, technically. Figures 3.5 to 3.6 show the system efficiency, energy generation, and the number of households all scenarios with AD, G, and P technologies can cover. Based on the average annual household energy consumption 3,315 kWh/y, the number of households that can be powered was calculated and shown in Figure 3.5 for each scenario.

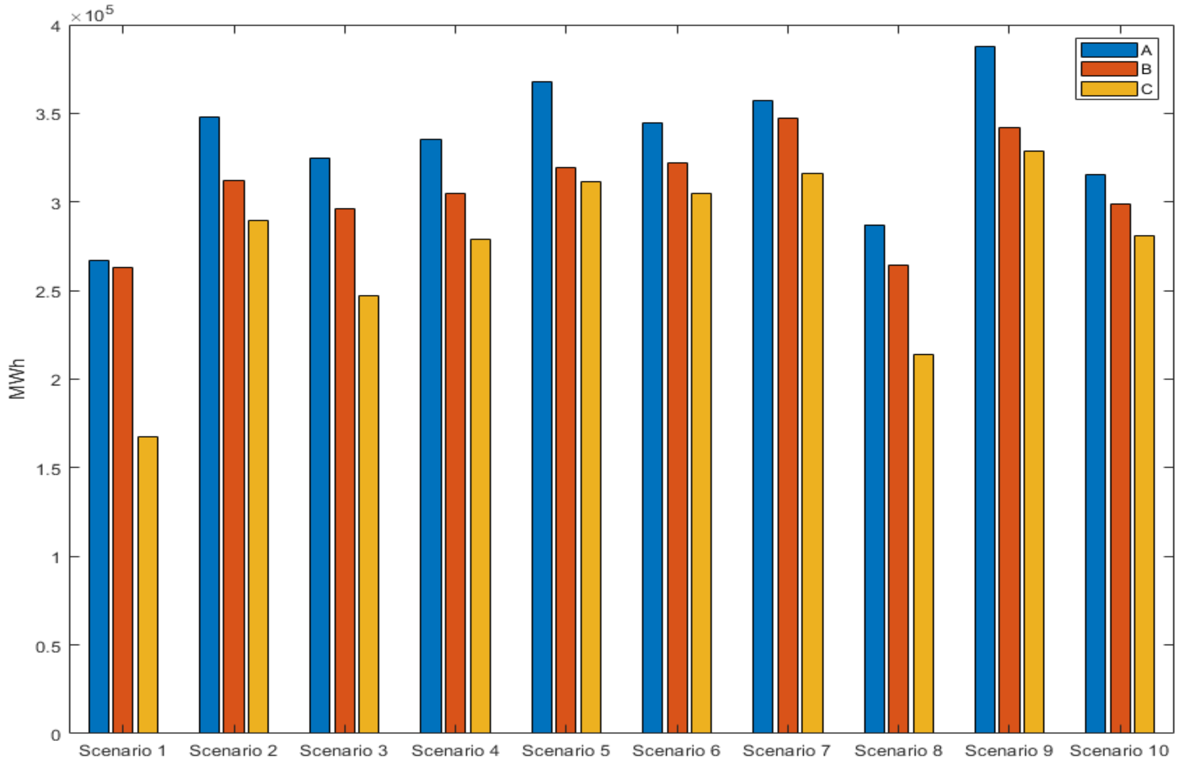


Figure 3.5 Energy generation for all scenarios for A, B, and C districts.

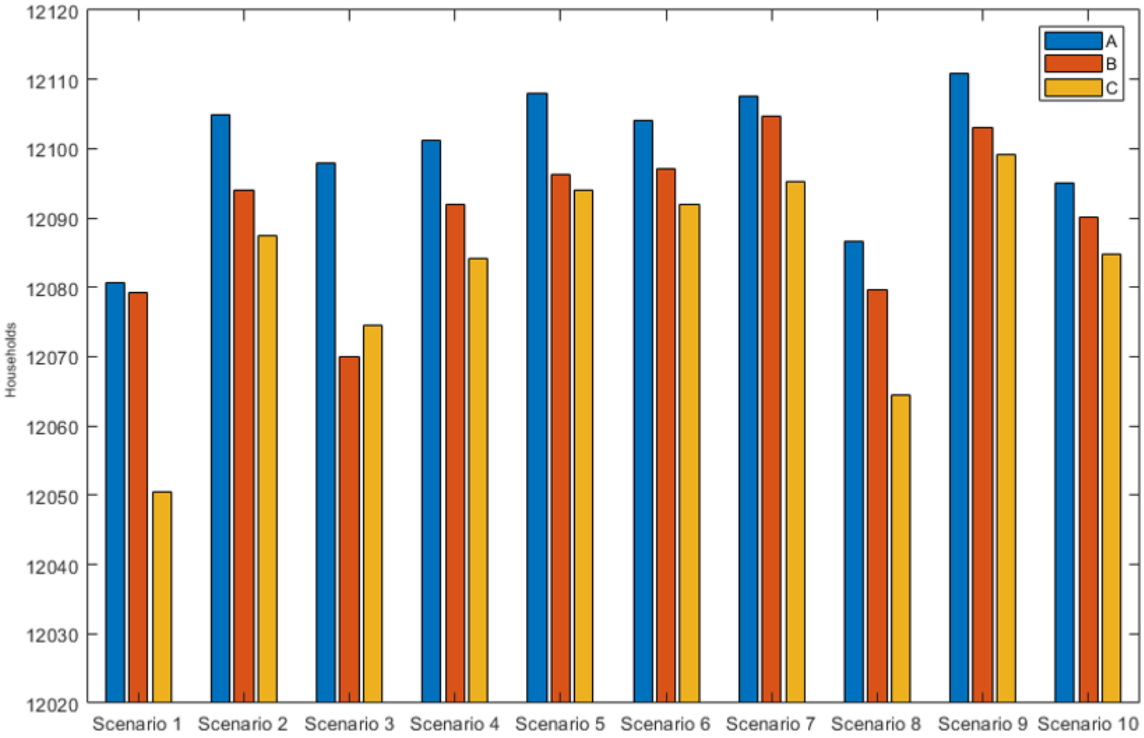


Figure 3.6 Households supplied for all scenarios for A, B, and C districts.

The findings show variations in energy yield according to the technology-feedstock combination. Figure 3.5 displays the yield of energy calculated for each scenario. The total energy produced in scenarios 5 and 9 generates the most energy. In scenario 5, the total energy production could cover the average annual energy of 12,117, 12,096, and 12,094 households in districts A, B, and C, respectively. Scenario 9 powers the most significant number of families. In addition, it exhibits the highest efficiency, reaching 70%, as shown in Figure 3.7. As a result, gardening waste is more favourable than food and wood waste for gasification and AD in terms of the total energy produced. Scenario 1 and scenario 8 have the lowest energy yields. Overall, in terms of energy output, scenario 9 is the most appropriate technology-feedstock combination for NZEBs in the city of Glasgow.

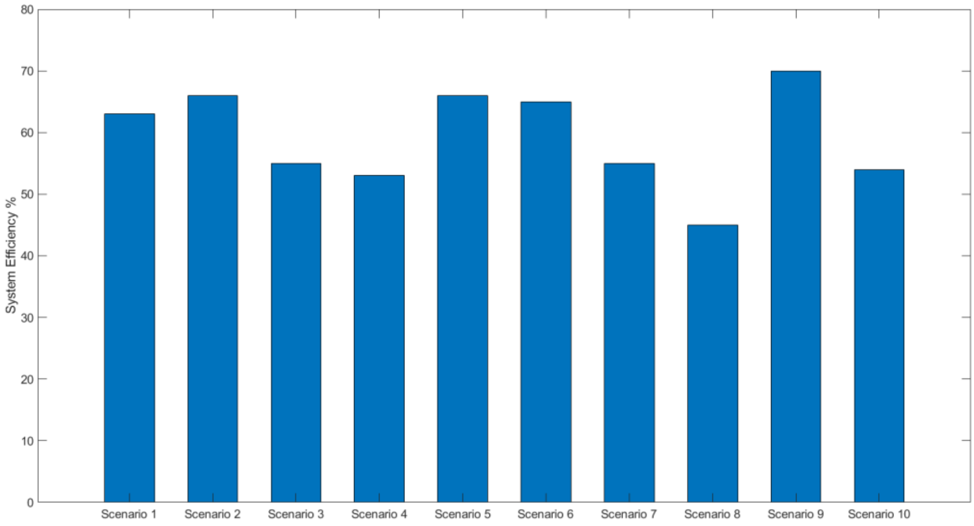


Figure 3.7 System efficiency for all scenarios.

3.2 Economic Assessment

Figure 3.8 illustrates the detailed breakdown of the CBA outcomes involving expenditures and incomes. The profits associated with each waste management technology encompass earnings from energy and bio-product sales. The project's overall profit amounted to £ -4.756 million. Waste collection and transport emerged as the predominant cost factor, totalling £ -20 million. The distinct components constituting the collection and transport element, such as Diesel costs, CAPEX of the trucks, Staff costs, and O&M costs for operating the trucks, are also included.

The average capital expense of gasification was found to be £ −17,118 million (− denote a cost). The average price of AD was £ −11,410 million. The average capital expense of pyrolysis was found to be £ −19,784 million, similarly representing substantial costs. Despite relatively modest profits, totalling £12,011 million, sourced mainly from energy and bio-product sales, they remained overshadowed by the considerable cost elements.

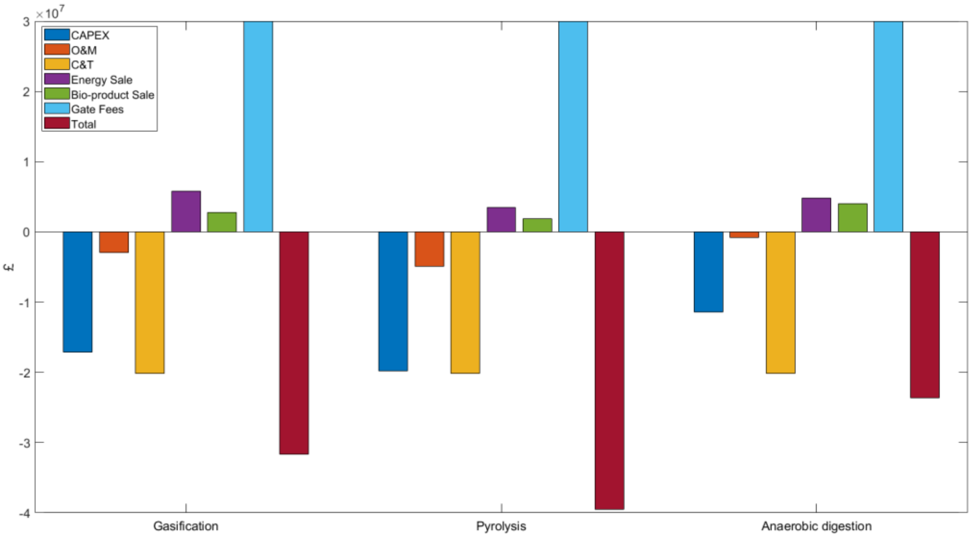


Figure 3.8 Detailed breakdown comparison for CBA.

The BCR, IRR, and LCoE for each scenario are shown in Table 3.6. From the results, the BCR of Scenarios 1, 5, 6, 8, and 9 is greater than 1, which makes the economic feasibility positive. On the other hand, scenarios 2, 3, 4, 7, and 10 have less than 1, meaning they are not making a profit. Also, the IRRs are above 22% for all the scenarios, which suggests that all the scenarios are potential investment projects. Scenario 9 is the most economically viable; it powers the most significant number of households in terms of the total energy produced and has the highest efficiency.

Table 3.6 Summary of the average results of the Levelized cost of energy, BCR, and IRR for all scenarios.

Stage		Scenarios									
		1	2	3	4	5	6	7	8	9	10
5% discount rate	BCR	1.6	1.1	0.8	0.9	1.7	1.2	1.1	1.4	1.9	1.2
	IRR	22.4	22.2	22.4	22.4	22.5	22.7	22.1	22.6	22.9	22.4
	LCoE	2.14	2.64	1.25	1.64	2.45	2.84	1.06	2.29	2.74	1.45
10% discount	BCR	2.3	1.6	1.2	0.7	1.4	1.2	0.9	1.3	1.6	0.9
	IRR	22.3	22.4	22.1	22.1	22.4	22.5	22.7	22.4	22.8	22.2
	LCoE	2.32	2.29	2.34	1.42	2.45	2.47	1.76	2.15	2.61	2.02

15% discount rate	BCR	1.3	0.9	0.6	0.6	1.2	1.1	0.8	1.1	1.3	0.8
	IRR	22.6	22.1	22.4	22.4	22.6	22.1	22.2	22.1	22.9	22.3
	LCoE	1.35	2.48	2.95	2.18	2.19	2.22	2.31	1.09	2.48	2.41

3.3 Sensitivity Analysis

Sensitivity analysis was conducted to examine the effect of selected model parameters on the economic results of the different waste-technology combinations. During the sensitivity analysis, the value assigned to each parameter is varied by 20 independently, while other parameters are kept constant. According to the above findings, scenario 9 is used for the sensitivity analysis, as it is the most economically viable option. The sensitivity of NPV to several parameters (syngas yield, bio-product selling price, and feed-in tariff) is shown in figures 3.9 – 3.15.

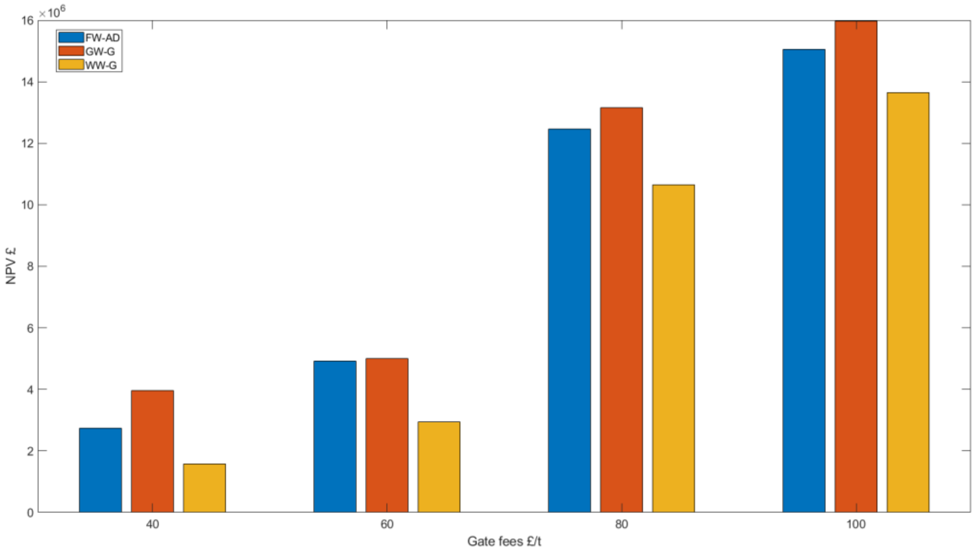


Figure 3.9 Influences of gate fees.

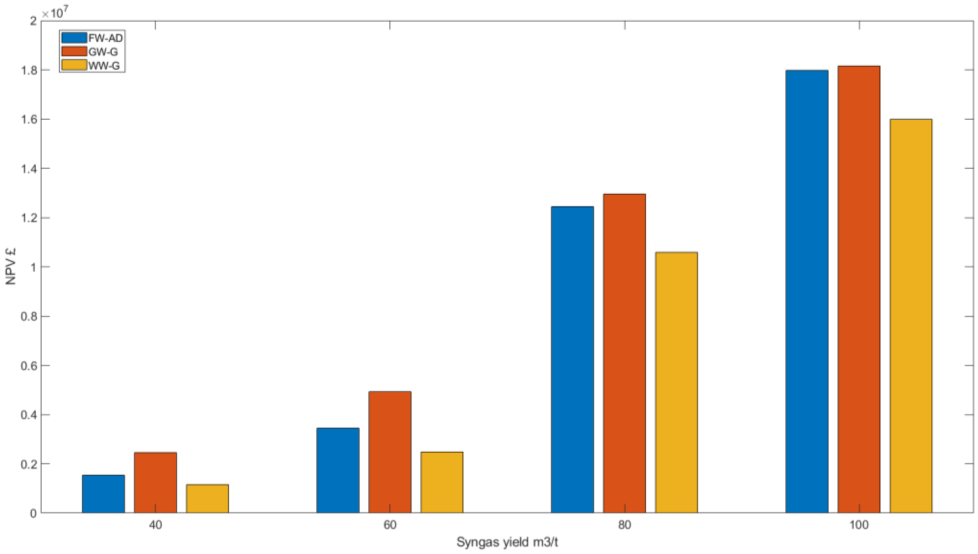


Figure 3.10 Influences of syngas yield.

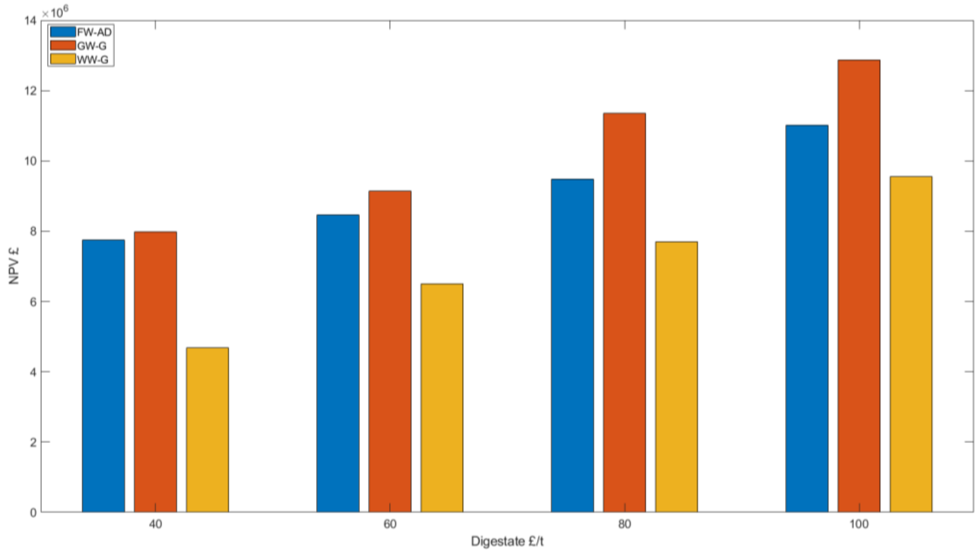


Figure 3.11 Influences of digestate.

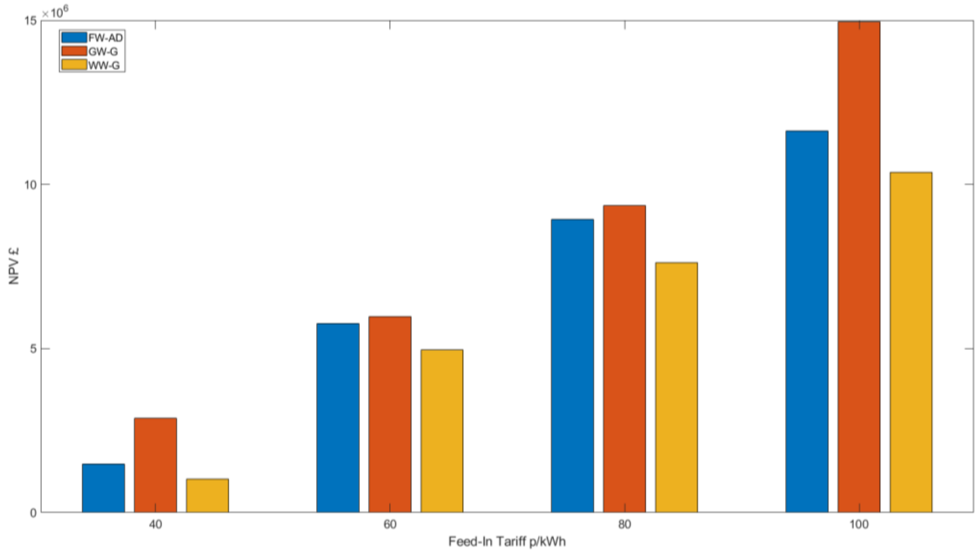


Figure 3.12 Influences of feed-in-tariff.

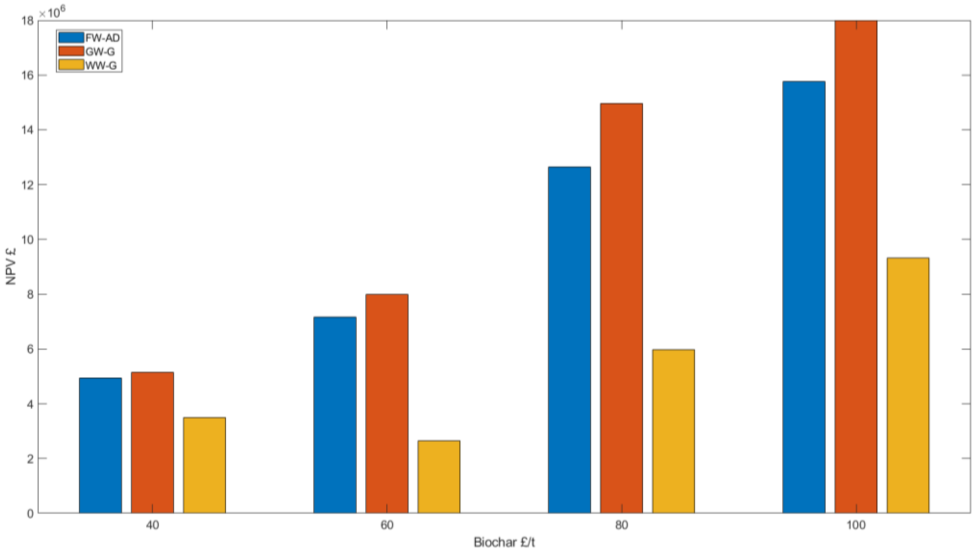


Figure 3.13 Influences of biochar.

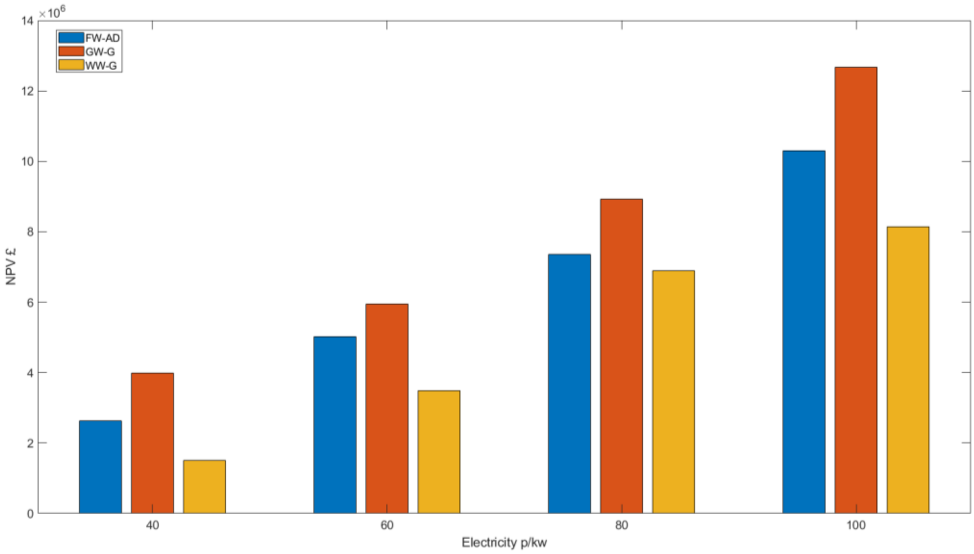


Figure 3.14 Influences of electricity.

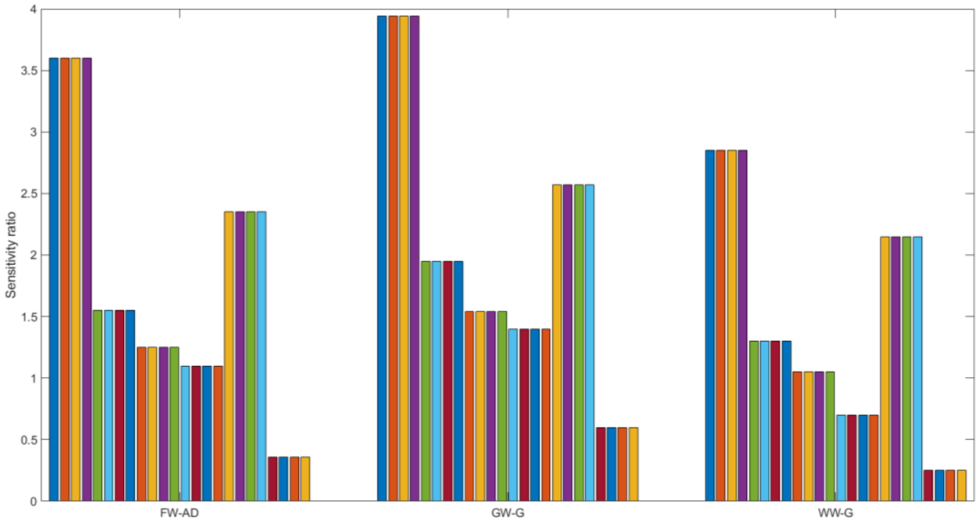


Figure 3.15 Influences of sensitivity ratio.

It is shown that NPV is most sensitive to commodities' selling prices, followed by the yields of technologies. The NPV increased by 120% with 40% in the selling price of energy—a 60% increase in the yield of technology results in a 75% increase in the NPV.

The lower syngas production of garden waste gasification compared to waste wood gasification reflects the influence of greater energy density feedstock and the susceptibility of the waste garden to decreased conversion efficiency. The NPV is most sensitive to syngas yield, followed by the Feed-In Tariff and the selling price of bio-products. The impact of energy prices on the NPV is less significant. The results reveal that changes in input parameters have a considerable effect on the profitability of the development. The analysis indicates that the economics of waste-to-energy developments are directly linked to technological improvement and the appropriate combination of waste and technology. Improving these parameters can increase economic benefits while achieving sustainable waste management.

3.4 Conclusion

This study sets out to develop waste treatment by applying the most recent energy technologies that consider economic and technical criteria to support NZEBs. The developed model has been applied to a case study based in Glasgow. The compositions of various combinations of waste-to-energy technologies and feedstocks were compared. Scenario 9 was proposed to dispose of the waste in Glasgow. The highest yield of energy is observed in scenarios 5 and 9. The CBA was conducted to compare the proposed Scenarios. It was found that Scenario 9 is considered the best appropriate technology-feedstock combination for implementation to support NZEBs in the city of Glasgow. The extent to which waste-to-energy technologies can contribute to supporting NZEB was also identified based on the status of waste production. The scheme successfully fulfilled the average annual energy requirements of approximately 12,085 households in Glasgow. However, achieving economic viability posed significant challenges, mainly attributable to high CAPEX and the associated waste collection and transport costs.

Transportation logistics contribute significantly to the overall expenses of waste management processes. One approach to improve economic viability involves excluding transportation logistics from the CBA if existing businesses handle waste collection and transportation. Another option is introducing government subsidies, which may be necessary. This incentive could address the economic challenges of such projects, ensuring their feasibility and long-term success.

Chapter 4 - Waste-to-Energy Technologies to Support Net-Zero Energy Buildings in Glasgow: Life Cycle Assessment Perspective

This chapter presents the feasibility of the proposed scheme from an environmental viewpoint to identify the appropriate technology–feedstock combination of the waste-to-energy technologies Scenarios introduced in Chapter 3 (Scenarios 1-10). The primary focus is utilizing LCA to calculate carbon emissions associated with each scenario. Further details on the LCAs are provided in this chapter.

This chapter studies the selected technologies as renewable energy sources for realising and developing NZEBs according to the conversion pathways based on environmental performance to identify the most appropriate method for distributed bioenergy-supported NZEBs. This model is developed based on the emissions from the technologies and the energy recovery from waste; such processes will be valuable for tackling the city's waste and energy challenges.

4.1 Introduction

Due to growing concerns about the environmental consequences of various products and manufacturing processes, environmental impact assessment tools are becoming more critical to achieve continuous development within the industry. Numerous environmental assessment tools exist, but LCA might be regarded as the most inclusive [359]. Documenting the ecological aspects of the project life cycle, service, or item is a valuable tool for making decisions that will contribute to sustainability and reduce environmental impact. Since the entire life cycle from the cradle to the grave (from procurement of raw materials to production, use, and disposal) is considered, LCA evaluates the primary environmental factors and their implications from exploitation through power generation, use, and end-of-life stage [360]. LCA plays a vital role in preventing the issue of shifting throughout the various phases of a product system by considering both downstream and upstream functions and expanding the emphasis outside the physical barriers. It includes numerous effect categories for each product's life cycle stage and measures all related emissions, such as wastes, used resources, and depleted resources. The LCA function aids in locating weak areas and the steps for improvement. Policymakers can opt to reach a high level of sustainability using the LCA results, which is a significant addition to the techno-economic measurements [361].

The LCA methodology has recently been applied to evaluate the sustainable development of waste-to-energy systems. For instance, the LCA was used in Brazil to examine sustainable waste management options for Rio de Janeiro. It was discovered that including AD was the most environmentally friendly option [362]. Similar findings were obtained for the Brazilian metropolis of Sao Paulo using the same methodology in a different study [363]. In the UK, a waste-to-energy assessment was carried out, and using the LCA methodology, landfill-burning waste and biogas collection was investigated [191]. In Sakarya, Turkey, a waste management system environmental susceptibility evaluation was conducted using the LCA [364]. Approaches have also been employed in numerous other studies to evaluate the effectiveness of waste management programs in countries including China, Italy, Belgium, and Greece [365]-[366].

The literature review shows potential differences in the waste composition and environmental framework conditions. Based on the researcher's existing knowledge, no studies have examined the utilization of alternate waste-to-energy technologies to support NZEBs (such as anaerobic, pyrolysis, and gasification). Few studies have been conducted that combine the concepts of distributed, community-based bioenergy generation with those of NZEBs. There is limited understanding of the technological routes and configurations of waste-to-energy technologies supporting NZEBs. There is a lack of relevant models that can be used to optimize and make strategic decisions about appropriate technology–feedstock combinations, particularly considering the increasing number of recently developed technological options. Therefore, choosing one waste-to-energy technique over another in terms of environmental performance constitutes research gaps.

This chapter will fill these gaps in knowledge; it focuses on the LCA concept of the selected waste-to-energy technologies that support NZEBs' development. This concept aligns with the UK's energy and GHG emissions reduction policies that promote renewable energy use, energy savings, improved energy efficacy, and decentralized energy generation that a building can utilize [367]. Choosing the best waste-to-energy technique is not easy. A thorough evaluation of various waste-to-energy process designs is required to determine whether pyrolysis, gasification, and AD-based waste-to-energy could be viable alternatives.

Due to the potential differences in waste composition and environmental framework conditions, this study investigated waste-to-energy technologies to assess the environmental competence of each approach and provide a comparison. Selecting a particular technique for sustainable waste disposal decisions or policy-making procedures is challenging without understanding the various technologies and their environmental effects. Indeed, waste-to-energy via these advanced bioenergy technologies will generate renewable energy and mitigate the challenge of increasing the pile-up of solid waste positively associated with economic growth and population expansion [274].

This chapter provides a thorough life cycle assessment of ten Scenarios of waste-to-energy technologies and a theoretical analysis of the potential configuration of these Scenarios. A sensitivity study was also conducted to identify the factors responsible for environmental damage. This study will better understand how more environmentally friendly technology could help the current waste-to-energy process.

This work explores the environmental impact and determines the carbon footprint of ten diverse scenarios encompassing various bioenergy technologies employed to support the development of NZE residential buildings based on life-cycle assessment using the methodology further explained in Section 2; its contribution is that it facilitates informed decisions for NZEBs' development.

The proposed methodology is valuable for decision-makers who deal with waste-to-energy systems. The outcomes will enable policymakers to make informed decisions to fulfil waste-to-energy technologies. This project will be a feasibility study of the futuristic waste-to-energy systems route. It will provide data support for the design of pilot-scale NZEBs in the future. The developed model can be applied to other types of renewable energy for NZEBs. The results will be valuable for guiding the development of waste management and NZEB-related decarbonization roadmaps in the UK and beyond.

4.2 Methodology

The research framework is shown in Figure 4.1. It compares the environmental impacts of ten scenarios involving various combinations of bioenergy technologies (AD, gasification, and pyrolysis) applied to waste as feedstock resources (gardening, food, and wood waste). The quantity and presence of waste feedstock is the primary benefit of offering numerous waste-to-energy technologies, as this heavily influences the energy input needed in the conversion procedures. It also affects the volume of energy produced.

Waste is collected and transported by trucks to treatment facilities. Local combustion of the produced gases produces energy that can be added to the area's electrical grid. The analysis considered the system’s capability for generating electricity and the environmental impacts of the emissions. The present study investigates the viability of the suggested plans from an ecological standpoint. The proposed system accomplishes two key goals: (i) waste treatment and (ii) energy production for Glasgow's NZEBs.

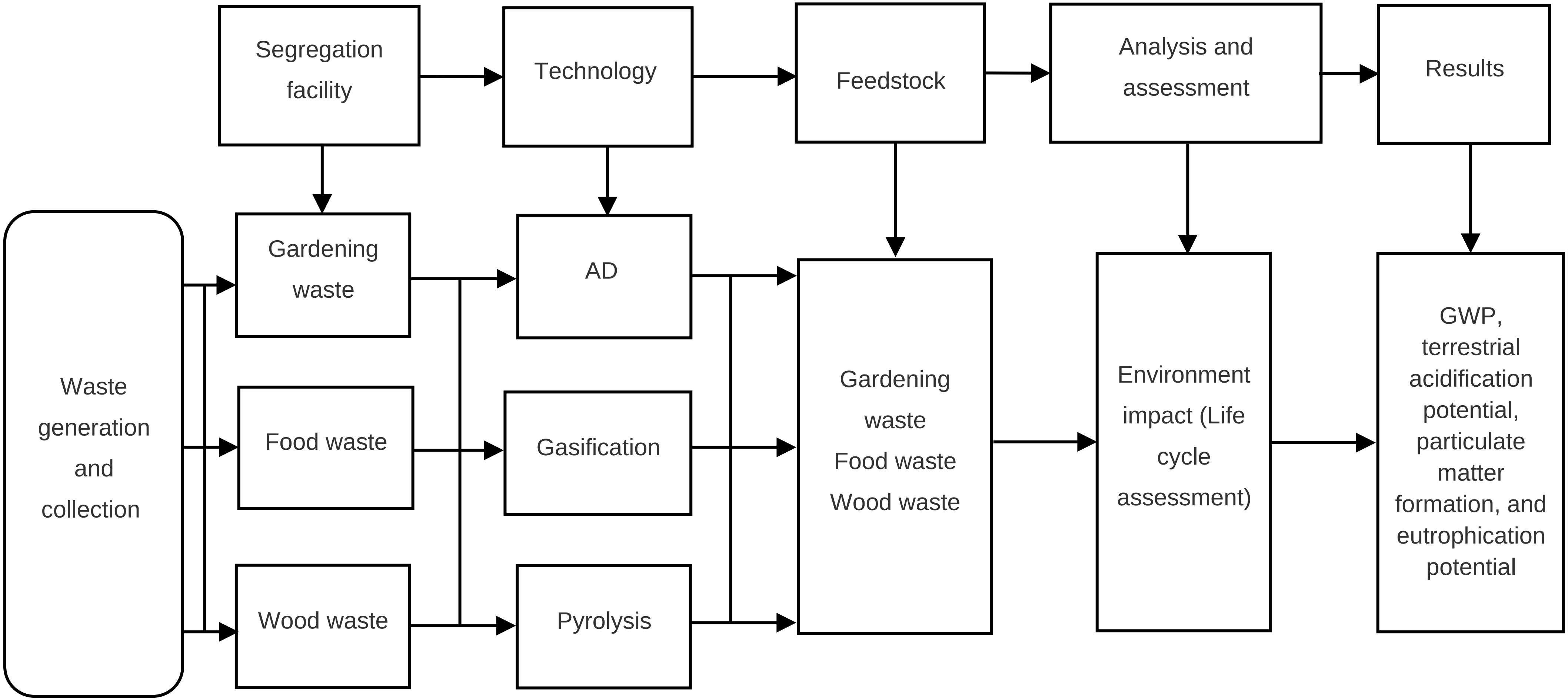


Figure 4.1 Research framework.

4.2.1 Framework Model Analysis of the Scenarios

The analysis parameters are achieved when the waste reaches the waste-to-energy system. There are three fundamental processes: pre-treating waste, converting waste, and using acquired products. Advanced bioenergy technologies can recycle waste. Syngas can generate energy in various ways, such as combustion in a boiler, combustion in a gas turbine, or combustion in an internal combustion engine. The bio-products can be sent into a separate boiler to generate more energy. The solid residues produced by the systems may be landfilled or concrete aggregate.

4.2.2 Waste Collection and Transportation Scenarios

The transportation and collection of waste might significantly influence the suggested plan's environmental element. Therefore, it is crucial to use a precise model for calculating the environmental impact of a particular waste collection strategy. This study derived the LCA analysis inputs using the waste-collect model [352].

The required amount of diesel was modified based on the ratios of the wastes to be collected. The modelling process involved creating models for various sub-systems and gathering all necessary input data. Subsequently, a primary model was constructed, and interim results were computed. These interim findings were then aggregated and transformed into diesel and truck time requirements per tonne of waste collected. Waste collection and transportation emissions are calculated based on the diesel requirements per tonne of collected waste. The collection and transportation emissions modelling is conducted through an open LCA process. In this modelling process, the "Diesel mix at refinery" process is initially utilized to assess the environmental impacts of diesel production. Subsequently, employ the "Truck - Dump Truck" process to simulate diesel combustion in waste collection vehicles. For the transportation phase from the waste collection point to the treatment facility, a Euro 6 truck with specific characteristics, a gross weight of 14–20 t, and an average transport distance of 20 km (round trip) is consistently employed across all scenarios. A truck time requirement of 0.8275 h tonne was required for every tonne of waste collected. Based on the amount of diesel needed to move one tone of waste – computed using the collection and transportation model, emissions from the waste collection were calculated.

4.2.3 Life Cycle Assessment

LCA methodology is a standardized method for tracking and reporting a product's or process's environmental impacts throughout its life cycle. An LCA has five primary stages: goal definition, scope definition, inventory analysis, impact assessment, and interpretation [256]. An LCA of an NZEB usually considers environmental impacts in lifecycle phases for the building itself as well as the system that generates electricity and heat for the building. In this work, however, the focus is on the system that realizes two purposes: the treatment of waste (evaluate distributed waste-to-energy systems scheme regarding three different impact categories, namely GWP, terrestrial acidification potential, and particulate matter formation) and the energy generation as a source of green energy for NZEBs, the assessment is based on avoided GHG emissions. Figure 4.2 summarises the LCA methodology.

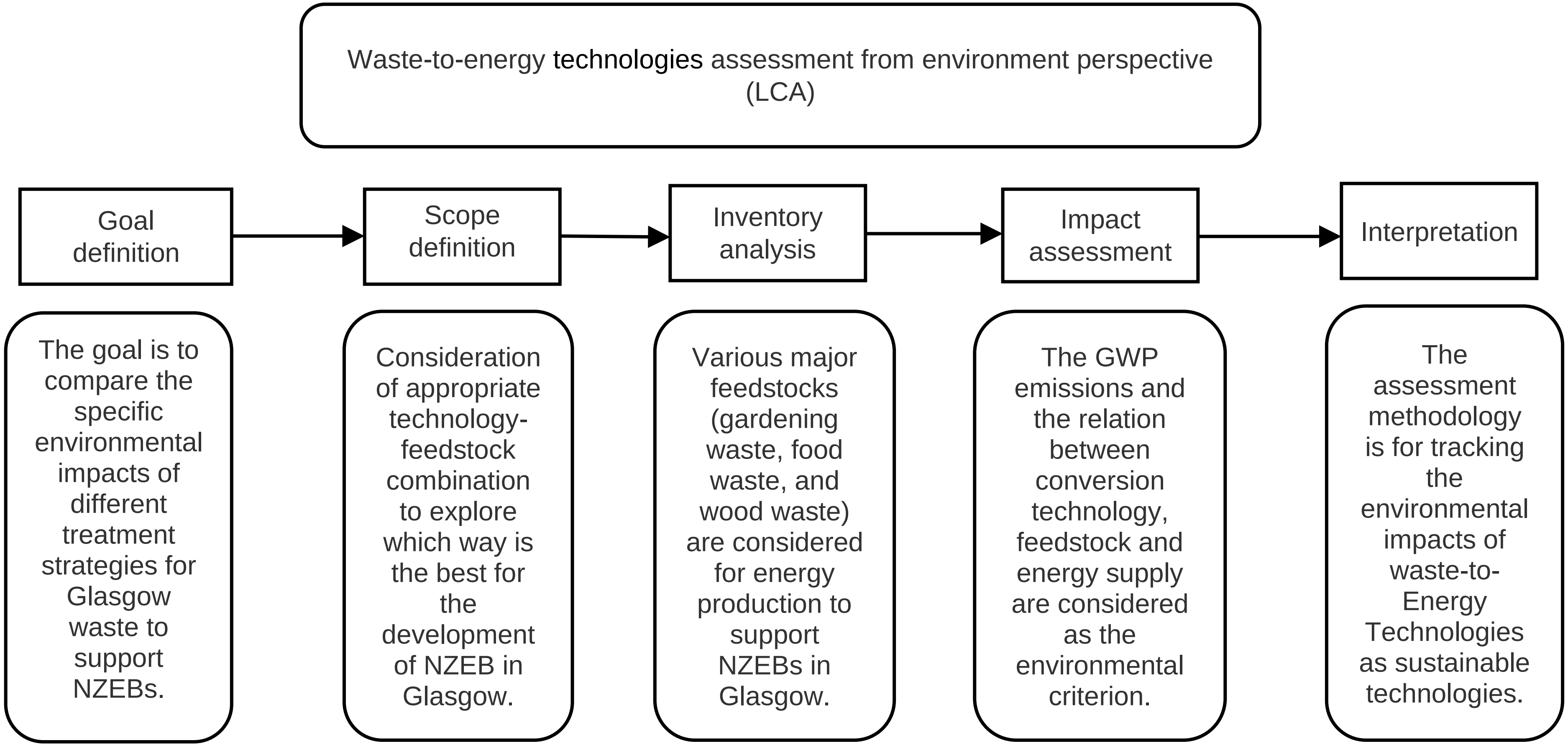


Figure 4.2 Life cycle assessment methodology.

4.2.3.1 Goal Definition

The study aims to assess specific environmental effects related to waste treatment. As a novel waste management system that prevents waste from ending up in landfills in the future, this study’s case scenario analyses various techniques (gasification, pyrolysis, and AD). The rationale behind this model is that a fair comparison of these multiple systems can be made by assessing waste treatment's potential advantages and drawbacks.

4.2.3.2 Scope Definition

The functional unit (FU) establishes the quantification of product functions, incorporating performance characteristics. It is crucial to choose an FU that captures the primary variable(s) relevant to the assessment, serving as a benchmark for result evaluation. FUs link the calculated carbon emissions and the technology, facilitating meaningful comparisons. This approach enables a nuanced understanding of how waste management and energy production objectives influence result interpretation, informing policy decisions. The overarching goal of LCA is to determine the role of waste-to-energy in advancing decarbonization efforts in energy production and waste management. The system boundary, encompassing all relevant processes and parameters, remains consistent across scenarios.

For analysis, the FU is the treatment of 3000 kg of waste, which goes into three systems for each scenario. Each system can deal with 1000 kg of waste to directly compare various processes and scenarios. The flow chart and system boundary of the waste-to-energy processes scheme are shown in Figure 4.3. The current investigation did not involve facility construction, infrastructure, and treatment of the products from feedstock end-of-life. Secondary materials application is not regarded as recycling, which ensures that environmental impacts are avoided and end-of-life treatment is replaced. It has been noted that the by-products have a positive environmental effect [368].

4.2.3.3 Life Cycle Inventory Analysis

The production of energy involves the application of the whole feedstock that is considered. The energy and feedstock supply inventory data was obtained from available databases. Using 1 tonne of waste feedstock as the initial value, the data sourced from the software database remains consistent, with accompanying references enhancing the reliability of the software. However, to ensure validation, comparative research methodologies are employed. Process simulation is adopted to generate data to ascertain that production pathways can be compared and that there is uniformity in the quality of data. An Open LCA is utilized as the core mechanism for inventory data integration. The applicability and availability of the datasets for the inventory determine detailed simulation of the processing steps and feedstock supply. The energy generated is presumed to replace the power generated by natural gas. The input parameters for the conversion pathways have been summarized in Table 4.1, while emissions resulting from the systems are presented in Table 4.2.

The qualities of waste vary greatly based on socioeconomic status, socio-political climate, and culture. As a result, the UK's waste representing the standard waste component is chosen as the comparison standard. Table 4.1 overviews the analyzed wastes' elemental composition and calorific value. The functional unit is 1 tonne of waste, with the average characteristics of the waste generated in the city shown in Table 3.2.

Table 4.1 Elemental analysis and calorific value of the wastes [154].

Category	C %	H_2 %	O_2 %	N_2 %	Ash %
Garden waste	43.6	5.5	33.9	2.2	7.1
Food waste	47.2	7.0	37.6	1.94	5.1
Wood waste	49.5	6.0	42.7	0.2	1.5

The quantity of CO_2 equal to each tonne of total waste was calculated. The energy needed to heat and energize each unit was added, and 0.15 kWh is estimated to be the energy required for one tonne of feedstock. Additionally, it was estimated that biogas leakage would be 3% of the production. Avoidable emissions are calculated by dividing the pollutants from biomethane generation by the contaminants from natural gas production. For this research, it is assumed that one unit of natural gas is comparable to about one unit of biofuel regarding the energy content. The CH_4 yield and its energy density were used to calculate the power of the gases generated from one tonne of waste. Statistics showing the emissions from the chosen technologies will be analyzed. The effect on the evaluation criteria is calculated using these emission levels. The corresponding emission variables for the three systems are listed in Table 4.2.

Table 4.2 List emission factors used in pyrolysis, gasification, and AD technologies.

Technology	Emission	Unit	Value	Reference
AD	CO_2	kg/t	354	[369]

	CH_4	g/t	15	[209]
	NOx	g/t	211	[209]
	CO	g/t	21	[209]
	N_2O	g/t	0.17	[209]
	SOx	g/t	8	[209]
Technology	Emission	Unit	Value	Reference
Gasification	CO_2	kg/Nm^3	0.814	[369]
	HCI	mg/Nm^3	4	[370]
	HF	mg/Nm^3	0.03	[349]
	SOx	mg/Nm^3	20	[349]
	NOx	mg/Nm^3	43	[370]
	CO	mg/Nm^3	3	[370]
	Hg	mg/Nm^3	0.004	[349]
Technology	Emission	Unit	Value	Reference
Pyrolysis	CO	mg/Nm^3	10	[209]
	SO_2	mg/Nm^3	8	[371]
	NO_x	mg/Nm^3	167	[370]
	HCI	mg/Nm^3	6	[372]
	PM	mg/Nm^3	1.5	[371]
	Hg	mg/Nm^3	0.012	[371]

4.2.3.4 Life Cycle Impact Assessment

Process modelling only considers airborne emissions, which limits impact assessment categories as determined by the emissions. GWP, terrestrial acidification potential (AP), particulate matter formation (PMF), and eutrophication potential (EP) were the core categories that were involved in the investigation. There will also be a discussion of the relationship between energy supply, feedstock, and conversion technology. The LCA in this study is conducted using the ReCiPe 1.08 Midpoint impact category methodology.

4.2.3.5 Interpretation

The study's primary objective is to assess the prospective most efficient technology that could be developed in Glasgow as a sustainable technology that could play a role as green energy supporting NZEBs in the long term. The environmental criteria denote the GHG emissions of relevant technology–feedstock combinations. The mechanisms that make up the complete scheme are modelled using data from previously published literature, as shown in Chapter 3.

The study also investigated the influence of specific pivotal parameters on environmental impacts in the sensitivity analysis. Reducing the energy utilization rate by half may lead to a corresponding 50% reduction in the environmental impact of displacing energy that natural gas would otherwise generate.

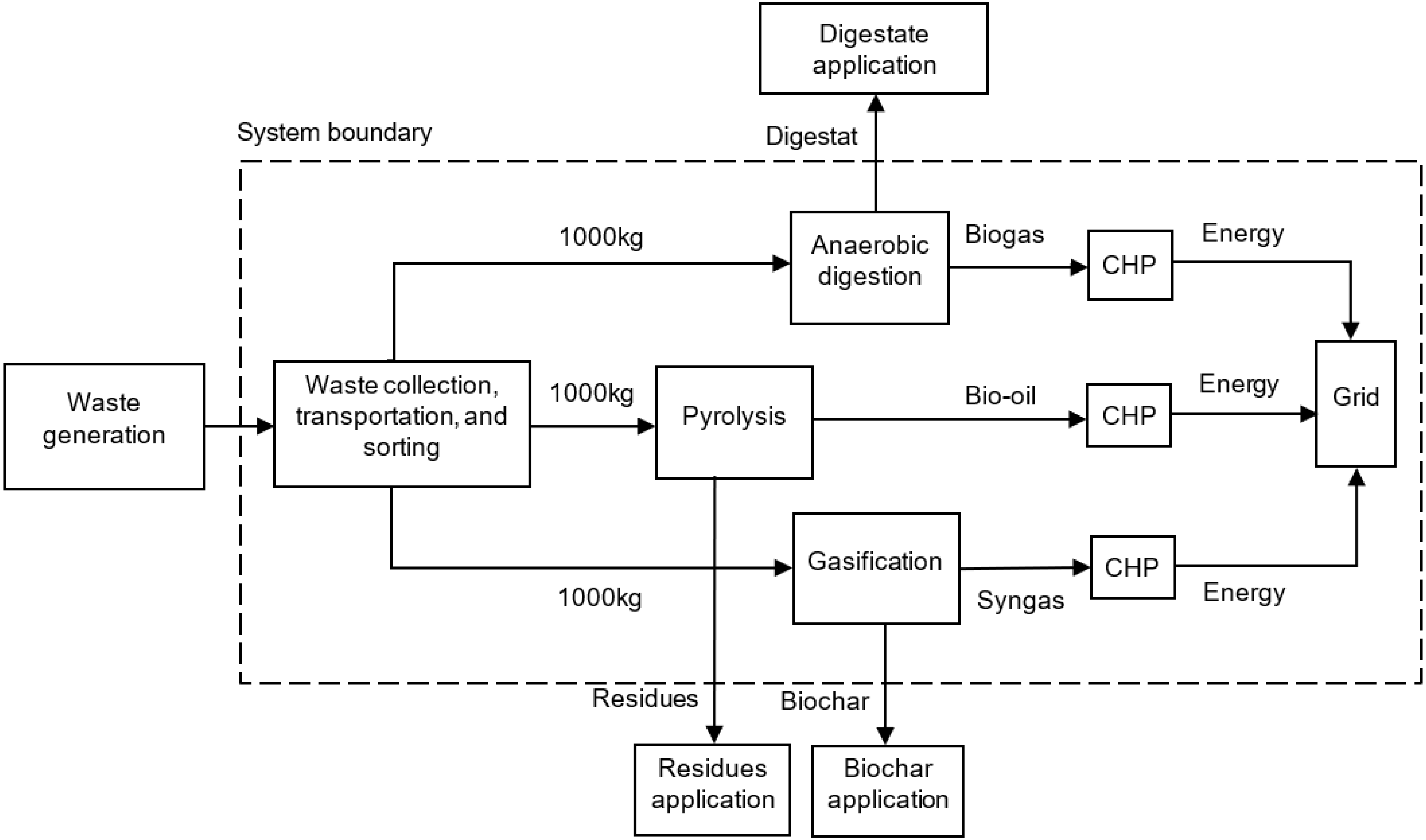


Figure 4.3 Flow chart and system boundary of waste-to-energy processes scheme.

4.3 **Results and Discussion**

This section discusses the environmental impact results for the selected systems to assess which technology-feedstock combination is the best. The research illustrates that waste-to-energy technologies have significantly fewer GWP quantities, which combine their evident merits when perceived as a dual-purpose scheme to eliminate waste and generate clean energy. The commendations from the outcomes emerge from comprehending the systems and disparities in outcomes, with demerits and merits between the situations evaluated. The LCA outcomes for the four impact classifications GWP, terrestrial acidification potential (AP), particulate matter formation (PMF), and eutrophication potential (EP) for all Scenarios are illustrated in Figures 4.4 to 4.7.

A breakdown of the GWP outcomes for each situation outlines the relative contribution of carbon-intensive procedures for every scenario, as shown in Figure 4.4. The outcomes reveal that, across diverse systems, transportation has a low influence on GWP. During transport and collection, the emissions produced amounted to 10 kg CO_2-eq per tonne of feedstock. In contrast, a range of 10 to 25 kg CO_2-eq per tonne of feedstock was obtained by powering the plants with diverse technologies. In every scenario, the emission levels from transportation and collection were similar. Concerning disparities, the most significant positive influence came from emissions resulting from fugitive biogas due to losses amounting to 40 kg CO_2-eq. A complete carbon saving span from 250-850 kg CO_2-eq per tonne of feedstock was obtained during the scheme. Nevertheless, the most evident negative contributor was waste treatment. The outcomes illustrate that Scenario 9 is significantly more suitable than other conditions from an environmental perspective.

This study compared the results obtained from Ascher et al. (2020), who conducted an LCA of gasification and AD plants processing 216,873 t/y of MSW for Glasgow. Regarding the impact category of GWP, the results reveal that transportation minimally affects GWP across various scenarios. Scenario 6A&G showed a similar impact to Scenario 3A&G, while Scenario 6G had a significantly more detrimental effect on global warming, emitting 911 kg $CO_{2\text{-eq}}$. One key difference between this study and Ascher et al. is the decentralized nature of this work. Ascher et al. focused on different plants, while this study examines various scenarios. Additionally, their study did not include pyrolysis in their assessment and cannot be compared.

These outcomes illustrate the essence of evaluating technology–feedstock amalgamation to obtain a complete opinion of the chosen technologies in this work and related GWP. It has been reported that pyrolysis, AD, and gasification lead to significantly fewer CO_2 emissions than traditional treatment processes [373].

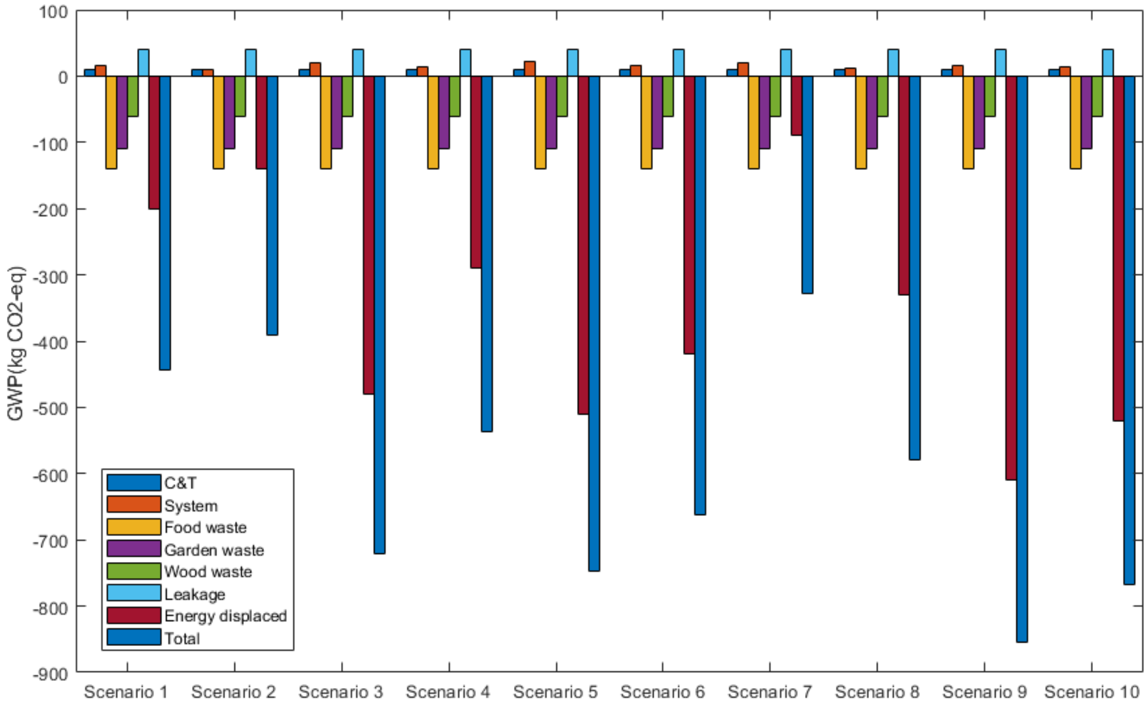


Figure 4.4 The GWPs breakdown results for t for all scenarios.

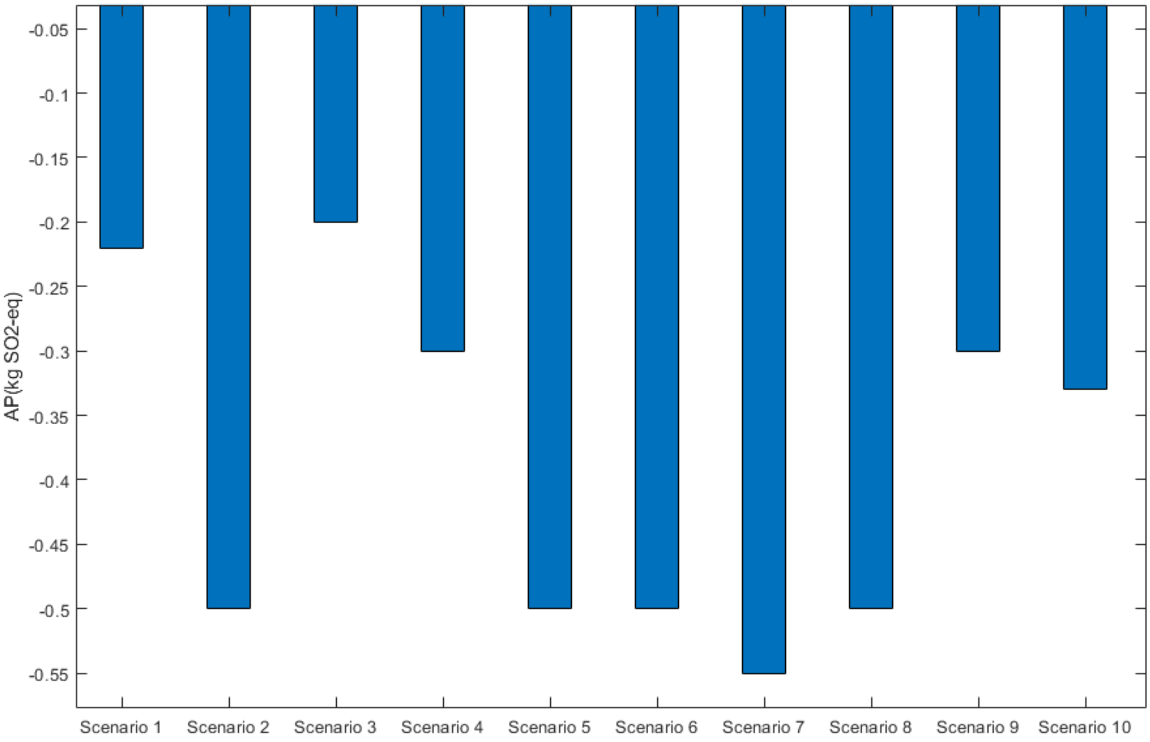


Figure 4.5 The AP results of the systems for all scenarios.

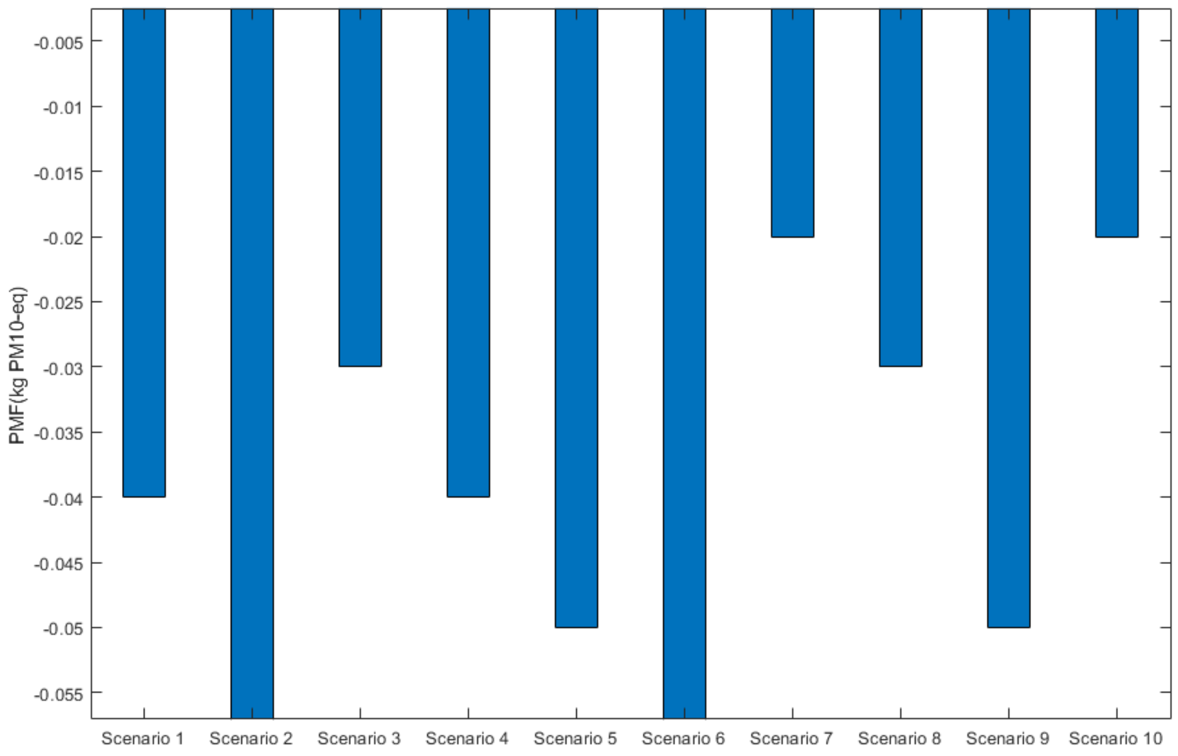


Figure 4.6 The PMF results of the systems for all scenarios.

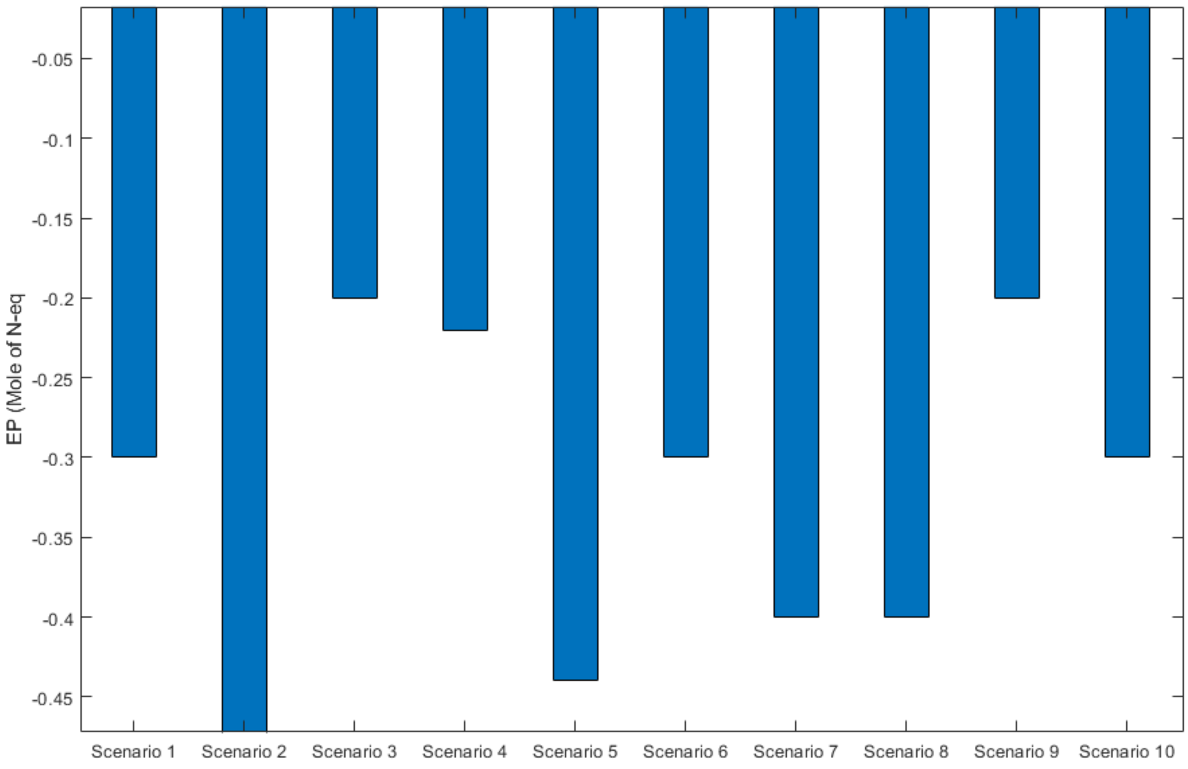


Figure 4.7 The EPs results of the systems for all scenarios.

The general outcomes for the influence classifications terrestrial AP and EP are familiar with all scenarios (Figures 4.5 and 4.7). Regarding EP, diverse values predominantly stem from alterations in the electricity generation sourced from natural gas. Different technologies employed in each scenario have led to outcome variations across the ten scenarios (scenarios 1-10). For example, Scenario 2 displaced 0.5 Mole of N-eq, whereas Scenario 5 displaced 0.415 Mole of N-eq. Scenarios 7 and 8, each of which replaced 0.4 Mole of N-eq, were similar. The impact category AP yielded displacements of 0.551, 0.5, and 0.312 Mole for scenarios 7, 5, and 10, respectively. Scenarios 2, 5, 6, and 8 are very similar, which displaced 0.5 Mole of H + -eq. Each situation received negative summations in the two impact classifications, thus illustrating an advantageous environmental influence. The PMF is shown in Figure 4.6. The shunned emissions obtained in Scenarios 1 and 6 resulted in 0.062 kg PM_{10}-eq, the most significant negative. The complete influence of Scenarios 5 and 9 on PMF was 0.051 kg PM_{10}-eq.

As illustrated, the system procedures contributed intensively to all the influence classifications considered. A logical approach to lowering the CO_2 emissions emerging from plants is to incorporate storage systems and carbon capture. Enhanced filtration systems may further aid in cleaning exhaust gases, thus leading to a lower emission impact.

4.3.1 Sensitivity Analysis

A sensitivity analysis was conducted to assist in comprehending the impact of uncertainty on LCA parameters and the influence of variable parameters on the outcomes of LCA. A sensitivity analysis was performed to showcase the primary procedure parameters and to identify prospective enhancements. The primary variables incorporated in the study were equivalency factors of biogenicity, energy utilization rate, and biogas leakage. The consequences of some vital parameters on environmental aftermath were transverse. The outcomes of the sensitivity analysis are shown below.

The effect of lowered heat utilization is illustrated by the impact classification GWP; for instance, a 20% reduction in heat utilization resulted in none, while a decrease to 40% in heat utilization divided the environmental advantage by 50%. An increase in GWP to 150 kg CO_2-eq resulted from an 8% rise in biogas leakage. The GWP was affected considerably by biogas leakage and heat utilization rates, as they lowered the advantage of the effect classification by a similar magnitude.

The GWP impacts were changed by shifting the biogenic CO_2 from 0 to 2. As a result, emissions due to the system rose significantly from 20 to 130 kg CO_2-eq. Upon incorporating biogenic CO_2 in the evaluation, the emissions also shifted.

4.4 Conclusion

This chapter sets out to develop and apply LCA methodology to assess waste treatment by using the most recent energy technologies that are green and environmental to support NZEBs. The developed model has been applied to a case study based in Glasgow. Depending on the status of waste production, the limits to which waste-to-energy technologies can contribute to support NZEB were also highlighted. The novelty of this chapter is identifying the environmental performance to identify the most appropriate technology-feedstock combinations for distributed bioenergy-supported NZEBs.

The developed model has proven applicability; any municipality can utilise this framework with the required data. The stakeholder's interest regarding their preferred end products determines the choice of effective waste-to-energy technologies. Moreover, legislative bodies and governments also significantly impact the choice of optimum waste-to-energy technologies. For instance, if legislative bodies or the government can subsidize the preferred waste-to-energy technology despite being a less favourable option, they want to foster any specific waste-to-energy technology to attain the policy targets or for any other reason. Such measures make achieving sustainability in any waste management system extremely hard.

The results showed that biochemical technology is more favourable to converting organic waste, while thermochemical waste-to-energy technologies are suitable for processing combustible fractions of organic and inorganic waste. Finally, a general framework was proposed for selecting the most suitable waste-to-energy technologies to support NZEBs and for a sustainable waste-management system.

Chapter 5 - Multi-Objective Optimization of Waste-to-Energy Technologies-Based Net-Zero Energy Buildings

As detailed in Chapters 1 and 2, this study focuses on the systematic design of processing routes for waste utilization, aiming to generate renewable energy for developing NZEBs. The approach considers technical, economic, and environmental aspects. This chapter will employ multi-objective optimization to enhance waste-to-energy technology's environmental impact and economic viability, maximising net profit while minimizing greenhouse gas emissions.

The MCA model will be applied in the next chapter to analyze optimal solutions among these alternatives. The results from the MCA method will illustrate which scenario is the most favourable among the different ones, contributing to the support of NZEBs and the waste-management system in Glasgow.

5.1 Introduction

The effectiveness of each technology hinges on various factors, such as feedstock type and mass composition. Given the absence of a universally dominant technology scheme applicable to all cases, it becomes imperative to explore different combinations of technologies. Given the intricacy of the problem, a systematic approach is vital to identify the "most appropriate" solution. A robust tool for optimizing complex systems like waste management is Mixed Integer Linear Programming.

The waste management model used in this study is developed to generate all Pareto-optimal solutions, primarily focusing on minimizing both cost and GHG emissions. The outcomes reveal compelling insights, particularly in the divergence of proposed solutions, notably in the context of waste-to-energy options.

The key assumptions are derived from the evaluation of ten scenarios, each carefully considered for the general suitability of the technologies in waste treatment. Previous chapters outlined the design of a distributed energy supply system. This work uses MOO to establish a sustainable energy supply system.

This study developed a generic multi-objective optimization framework combining techno-economic and environmental performance assessment. The integration of techno-economic with environmental performance was achieved through multi-objective optimization, which assesses the waste-to-energy technologies specifically contributing to NZEBs. Waste-to-energy is a dual-purpose tool for waste management and energy production, dependent on technology and efficiency improvement for upscaling and large-scale implementation. Considering that each scenario has advantages and disadvantages, the proposal is to employ MOO as a foundational tool.

5.2 Methodology

A superstructure was developed based on the identified technology and their interconnections; it comprises waste segregation and treatment technologies (Figure 1). The technical, economic, and environmental data in this work were listed in chapters 3 and 4. Chapter 3 utilizes CBA to provide data for the financial objective, while Chapter 4 presents the results from the LCA, supplying the data for the environmental objective. Optimization is applied to all scenarios from 1 to 10. The primary purpose is to minimize the GHG emissions for each scenario, quantified through LCA. The secondary objective is to reduce the total cost of each scenario, determined through CBA. This dual-objective approach addresses both environmental impact and economic considerations in evaluating and optimising each scenario.

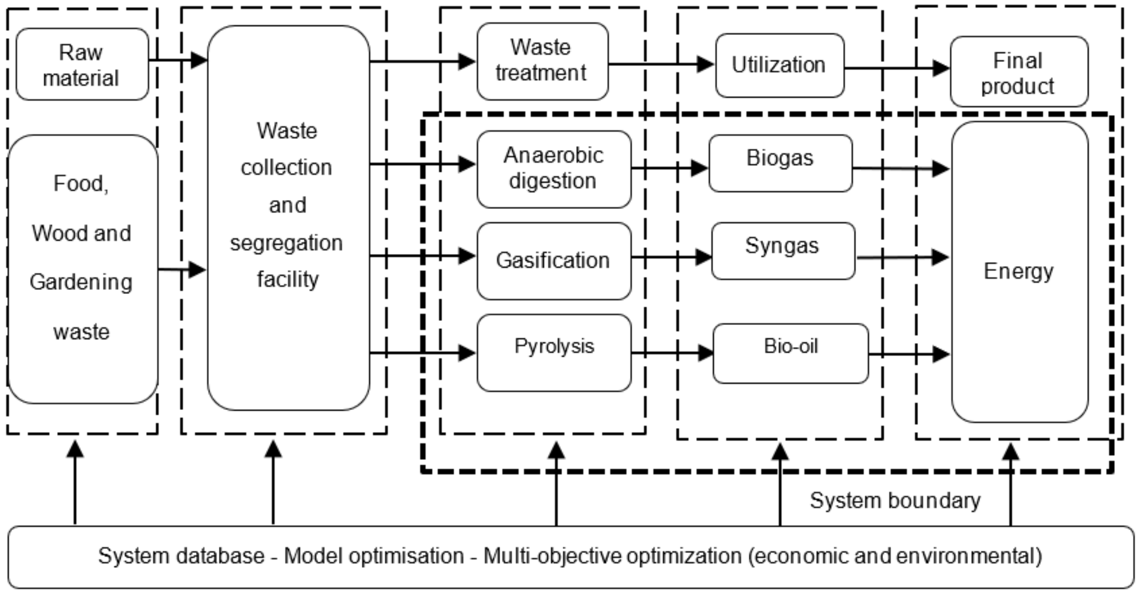
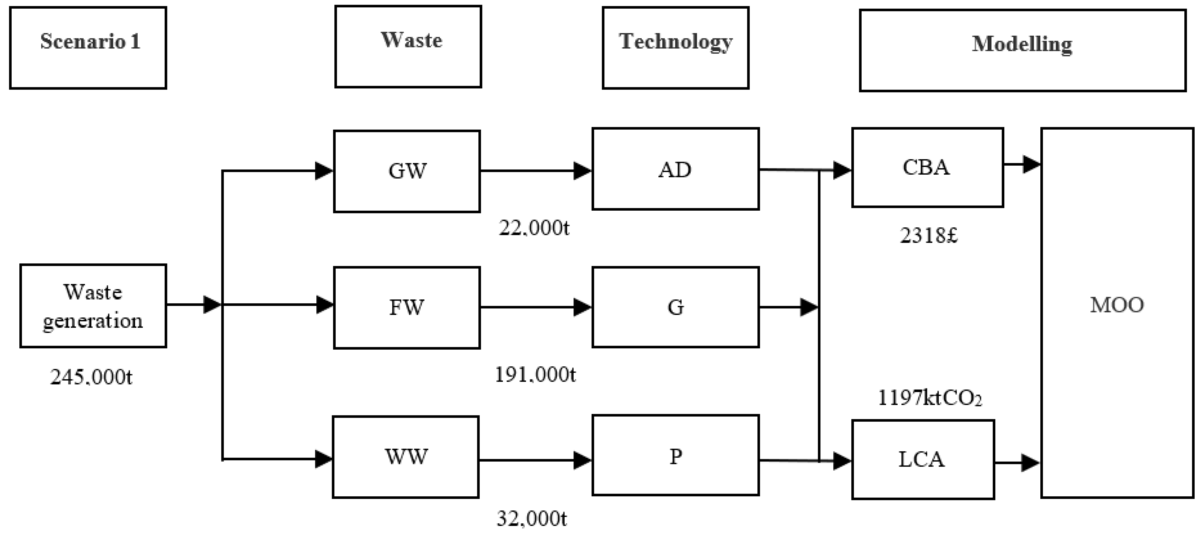
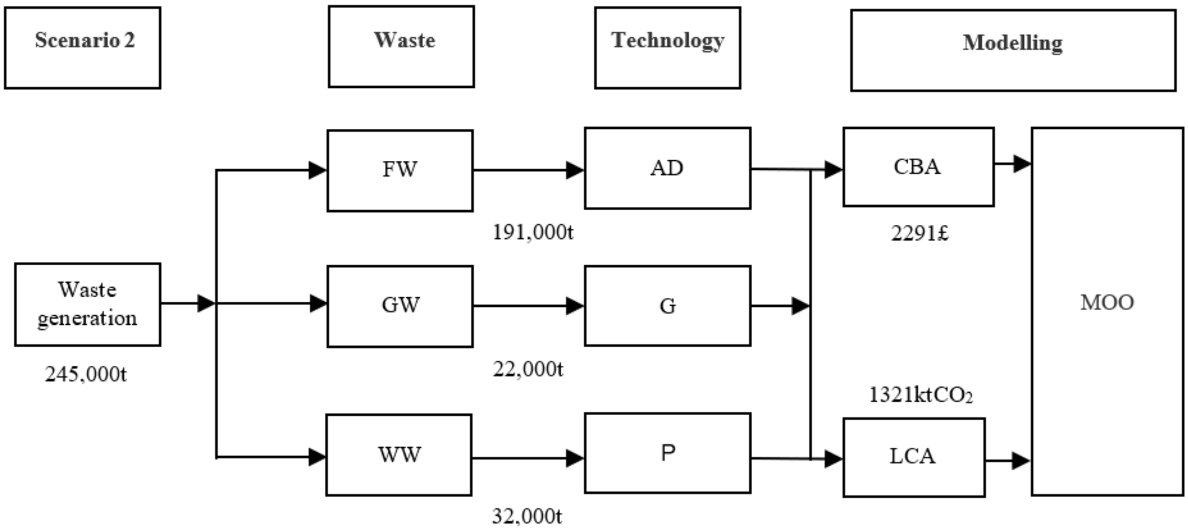


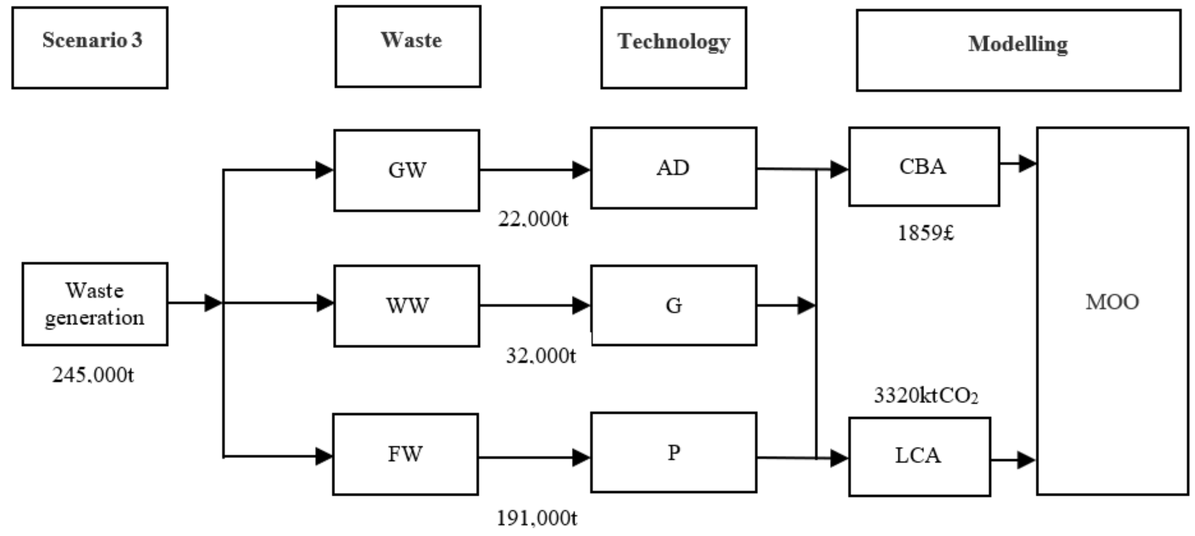
Figure 5.1 Waste superstructure and system boundary

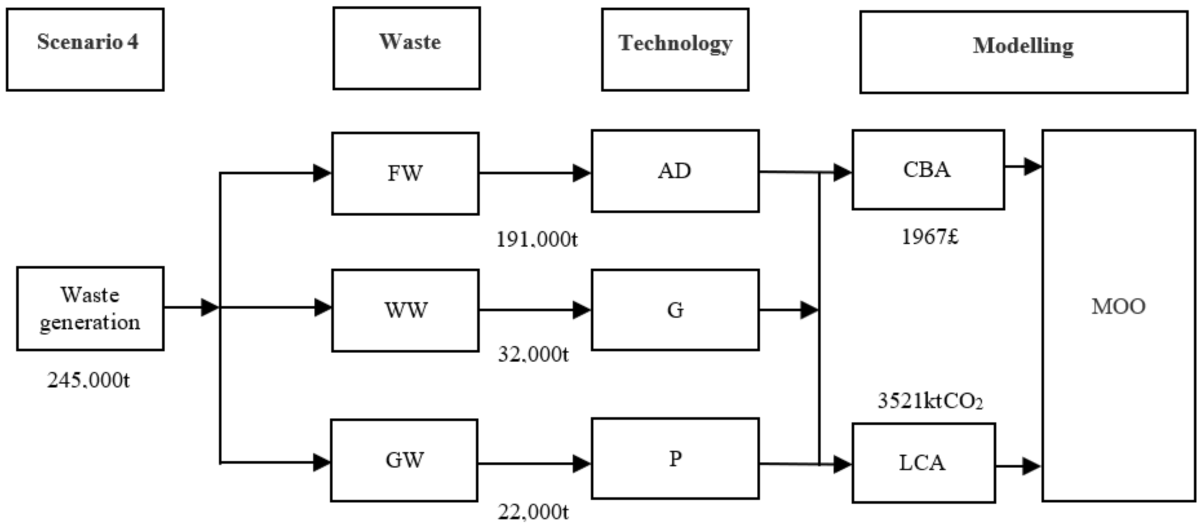
The model furnishes details for each solution, outlining the system specifications for every scenario, encompassing technology, capacity, and annual waste input. Figure 5.2 (scenario 1 -

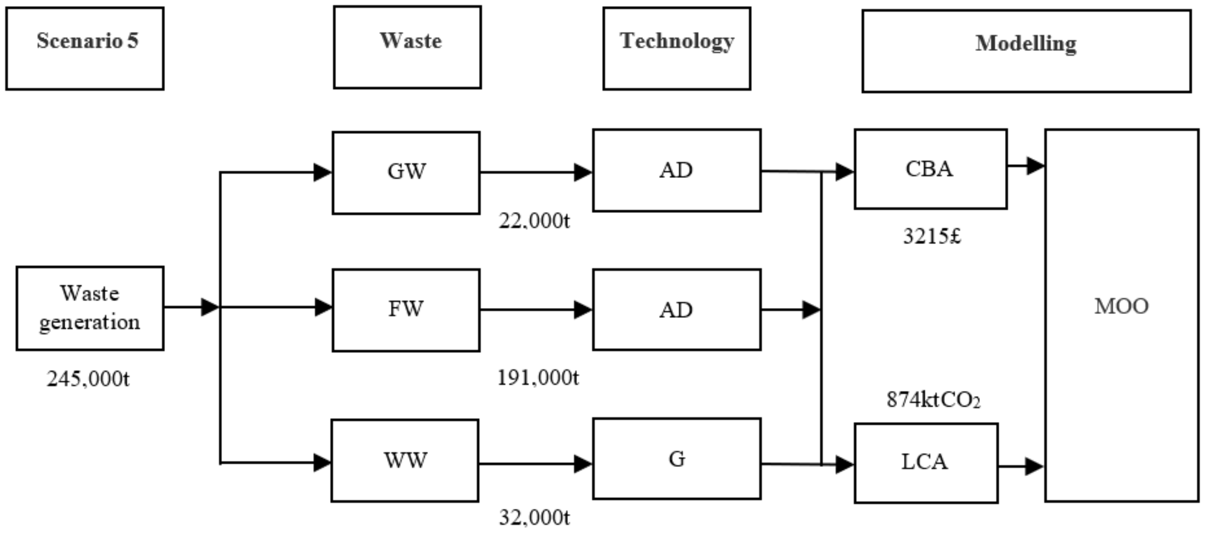
10) is a schematic representation illustrating the scenarios and the corresponding average yearly mass flows (collection, treatment technologies, and products) within the proposed waste management scheme. These figures highlight the configurations for the minimum cost, best compromise, and minimum GHG emissions solutions across all scenarios.

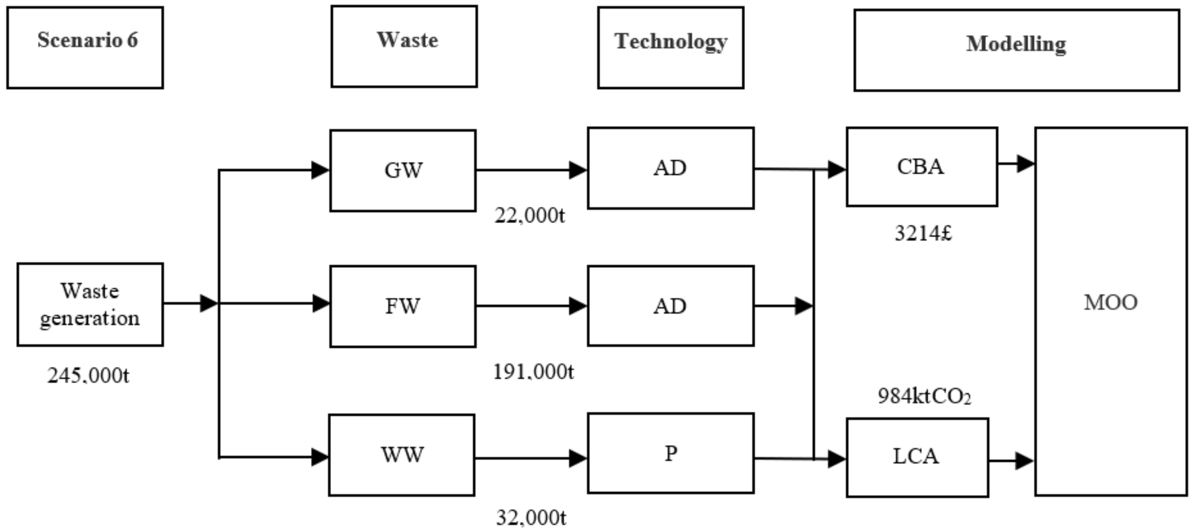




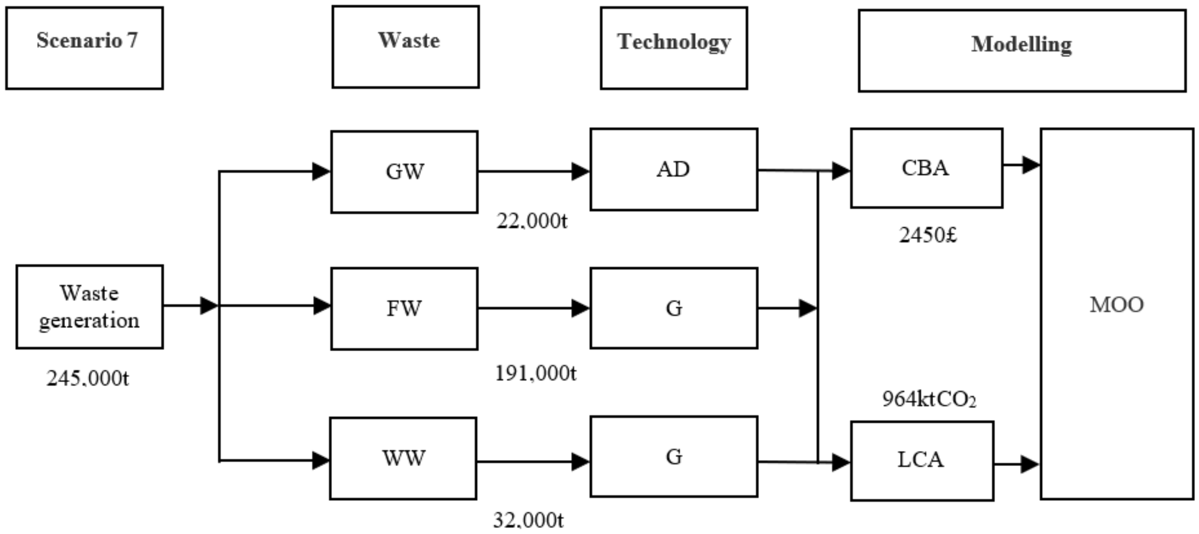

Scenario 3
Waste
Technology
Modelling
Waste generation
245,000t
GW
22,000t
WW
32,000t
FW
191,000t
AD
G
P
CBA
1859£
3320ktCO₂
LCA
MOO


Scenario 4
Waste
Technology
Modelling
Waste generation
245,000t
FW
191,000t
WW
32,000t
GW
22,000t
AD
G
P
CBA
1967£
3521ktCO₂
LCA
MOO

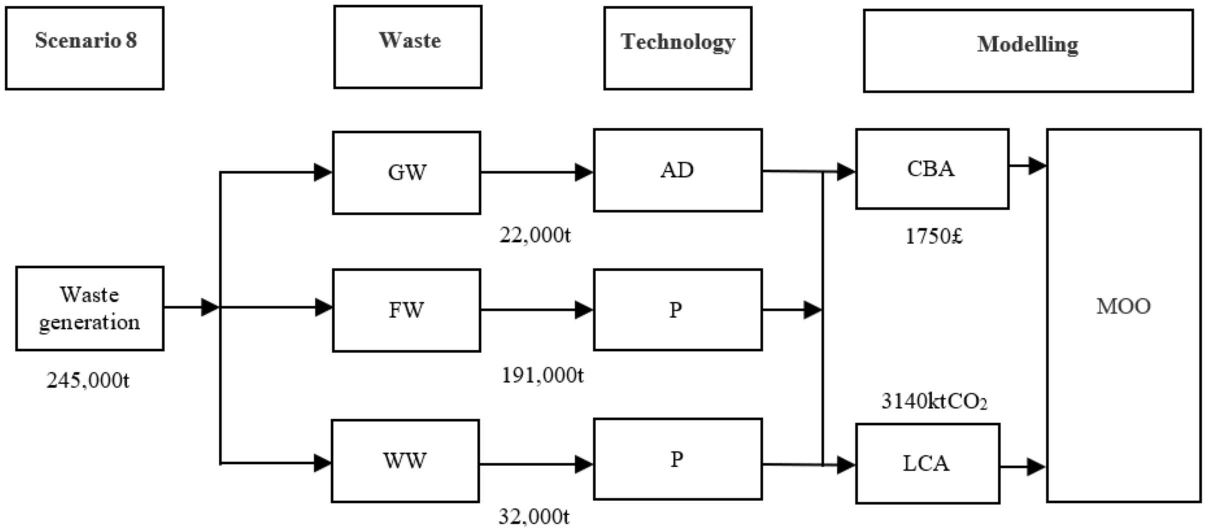

Scenario 5
Waste
Technology
Modelling
Waste generation
245,000t
GW
22,000t
FW
191,000t
WW
32,000t
AD
AD
G
CBA
3215£
874ktCO₂
LCA
MOO



Scenario 6
Waste
Technology
Modelling
Waste generation
245,000t
GW
FW
WW
AD
AD
P
22,000t
191,000t
32,000t
CBA
3214£
984ktCO2
LCA
MOO



Scenario 7
Waste
Technology
Modelling
Waste generation
245,000t
GW
FW
WW
AD
G
G
22,000t
191,000t
32,000t
CBA
2450£
964ktCO2
LCA
MOO



Scenario 8
Waste
Technology
Modelling
Waste generation
245,000t
GW
FW
WW
AD
P
P
22,000t
191,000t
32,000t
CBA
1750£
3140ktCO2
LCA
MOO

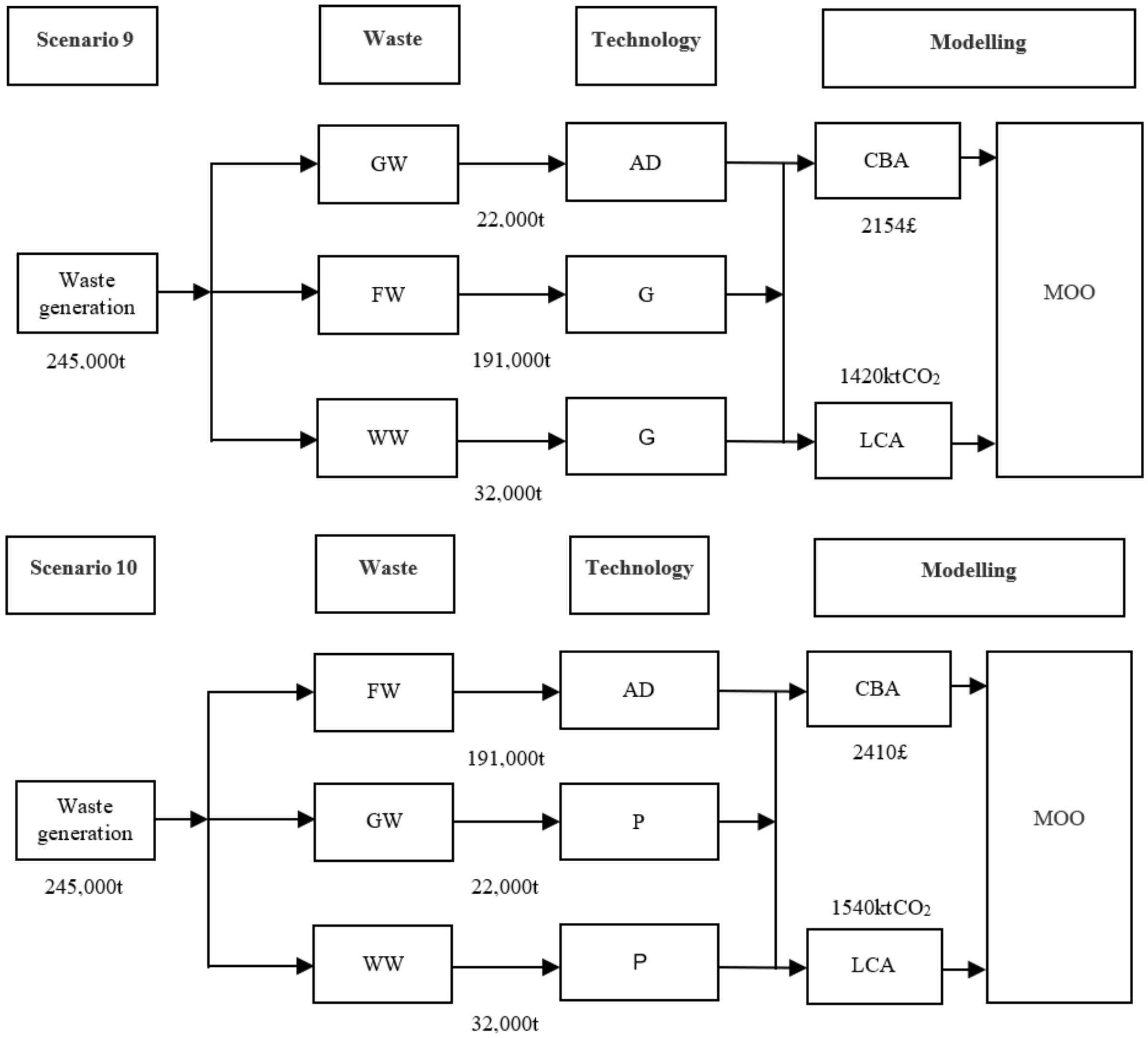


Figure 5. 2 A schematic representation of all scenarios.

5.2.1 The Optimization Method

Several factors must be considered when designing energy technologies to support NZEBs, such as technical systems and economic and environmental factors. The complexity of these aspects will be used to develop several optimization models consisting of:

1. Different objectives, including maximizing net profit or minimizing costs and emissions.
2. Various constraints, such as environmental constraints and economic constraints
3. Different modelling approaches, e.g., MILP.

MILP is a mathematical optimization technique employed to address optimization problems featuring both continuous and discrete decision variables. MILP algorithms are adept at handling mixed-variable challenges and can efficiently discover optimal solutions within a reasonable computational timeframe.

This work focuses on waste-to-energy technologies as renewable energy sources that can support the development of NZEBs of individual residential buildings while facilitating sustainable waste management. Using waste in energy generation minimizes the environmental impact of uncontrolled disposal, and the decomposition of organic wastes often encourages ecological sustainability. More details about the considered technologies, along with the associated capital investment and operational costs, can be found in Chapter 3.

This work proposes developing an integrated optimization model of the waste-to-energy technology route identification framework by maximizing the CBA and minimizing life-cycle analysis using an entirely new MILP modelling approach. The proposed model involves system design by comparing the selected technologies' economic viability, environmental impact, and technical performance. The framework is applied and developed to optimize multi-objective optimization using a MILP. The framework is designed to investigate how the environmental and economic aspects affect the solution. The multi-objective optimization model employed in this study is a Multi-Objective Mixed Integer Linear Programming model. The generation of Pareto optimal solutions is a vital outcome of this model, offering solutions that represent the optimal trade-offs between conflicting objectives. The steps in the multi-objective optimization process encompass formulating the objective function, specifying decision variables, and establishing bounds and constraints. This study employed MATLAB software to conduct multi-objective optimization.

5.2.2 Mathematical Formulation

This section presents the mathematical framework of the model for investing in utilizing waste to generate energy to support NZEBs. The two-objective model was developed to address the waste superstructure’s economic and environmental aspects simultaneously. The objective functions are given by Equation (11):

$$Z = w_1 . z_1 - w_2 . z_2 \tag{11}$$

$$Z_1 = Profit = Product\ Sales - O\&M Cost - Capital\ Cost \tag{12}$$

$$Z_2 = \ Total\ emissions \qquad (13)$$

The economic constraints focus on determining the system's cost (O&M cost and capital cost) given by Equations (14) and (15):

$$O\&M\ cost = \sum_j \sum_k \sum_i \left(OM_{k,j} \cdot y_{k,j} \cdot {F^{in}}_{i,k,j} \right) \qquad (14)$$

$$Capital\ cost = \sum_j \sum_k \ \left(cCost_{k,j} \cdot y_{k,j} \right) \qquad (15)$$

where $OM_{k,j}$ is the O&M cost of alternative (k,j). $cCost_{k,j}$ is the capital cost of alternative (k,j).

The environmental constraints estimate the emissions of each scenario's waste processing operation. The environmental emissions were modelled as indicated in Equation (16):

$$EM_e = \sum_j \sum_k \sum_i \left(\xi_{e,i,k,j} \cdot y_{k,j} \cdot \hat{F}^{in}_{i,k,j} \right) \qquad (16)$$

The $\xi_{e,i,k,j}$ Denotes the emission factor modelling the environmental emissions of waste processing in alternative (k,j).

It introduced a binary variable. $y_{k,j}$ which selects scenario k. The superstructure configuration model is given by Equation (17) as follows:

$$\sum_k y_{k,j} \ \leq 1 \qquad (17)$$

The superstructure configuration constraint is given by Equation (17), and the flows of the process are modelled by Equations (18) and (19), respectively:

$$F_{i,j} = \sum_k \left(y_{k,j} \cdot \hat{F}_{i,k,j} \right) \qquad (18)$$

$$R_{i,j} = \sum_k \left(y_{k,j} \cdot \hat{R}_{i,k,j} \right) \qquad (19)$$

The $\hat{F}_{i,k,j}$ and $\hat{R}_{i,k,j}$ represents the process flows and the residue streams exiting the scenario alternative (k,j).

$$\hat{F}^{in}_{i,k,j} = \varepsilon_{i,k,j} \ . F_{i(i')} \ ,j - 1 \qquad (20)$$

The $\varepsilon_{i,k,j}$ is utilized in allocating component i of the scenario $y_{k,j}$. The following operation can be modelled using the waste conversion aided by yield data.

$$\widehat{F}_{i,k,j}^{out} = \widehat{F}_{i,k,j}^{in} + \sum_{i'} \left(\alpha_{i.i',k,j} \cdot \widehat{F}_{i,k,j}^{in}\right) - \left(\theta_{i,k,j} \cdot \widehat{F}_{i,k,j}^{in}\right) \tag{21}$$

The feed at the processing stage is modelled by Equation (22):

$$\widehat{F}_{i,1,1} = \varphi_i \tag{22}$$

The model linearity consists of the bilinear terms in Equations (14), (16), (18), and (19). The Glover linearization method was used for linearizing and introduced additional constraints and new continuous variables [374] [375]. An auxiliary variable $\hat{S}_{i,k,j}$ was presented to linearize and replace the bilinear term of Equation (14), as given below:

$$O\&M\ cost = \sum_{j}\sum_{k}\sum_{i}\left(OM_{k,j} \cdot \widehat{S}_{i,k,j}\right) \tag{23}$$

With the following additional constraints:

$$\widehat{F}_{i,k,j}^{in} - \widehat{F}_{i,k,j}^{in^U}\left(1 - y_{k,j}\right) \le \hat{S}_{i,k,j} \le \widehat{F}_{i,k,j}^{in} - \widehat{F}_{i,k,j}^{in^L}\left(1 - y_{k,j}\right) \tag{24}$$

$$y_{k,j} \cdot \widehat{F}_{i,k,j}^{in^L} \le \hat{S}_{i,k,j} \le y_{k,j} \cdot \widehat{F}_{i,k,j}^{in^U} \tag{25}$$

Similarly, Equations (6), (8), and (9) can be linearized. They are linearized as follows:

$$EM_e = \sum_{j}\sum_{k}\sum_{i}\left(\xi_{e,i,k,j} \cdot \widehat{T}_{i,k,j}\right) \tag{26}$$

$$\widehat{F}_{i,k,j}^{in} - \widehat{F}_{i,k,j}^{in^U}\left(1 - y_{k,j}\right) \le \widehat{T}_{i,k,j} \le \widehat{F}_{i,k,j}^{in} - \widehat{F}_{i,k,j}^{in^L}\left(1 - y_{k,j}\right) \tag{27}$$

$$y_{k,j} \cdot \widehat{F}_{i,k,j}^{in^L} \le \widehat{T}_{i,k,j} \le y_{k,j} \cdot \widehat{F}_{i,k,j}^{in^U} \tag{28}$$

$$F_{i,j} = \sum_{k} \widehat{P}_{i,k,j} \tag{29}$$

$$\widehat{F}_{i,k,j}^{in} - \widehat{F}_{i,k,j}^{U}\left(1 - y_{k,j}\right) \le \widehat{P}_{i,k,j} \le \widehat{F}_{i,k,j} - \widehat{F}_{i,k,j}^{L}\left(1 - y_{k,j}\right) \tag{30}$$

$$y_{k,j} \cdot \widehat{F}_{i,k,j}^{L} \le \widehat{P}_{i,k,j} \le y_{k,j} \cdot \widehat{F}_{i,k,j}^{U} \tag{31}$$

$$R_{i,j} = \sum_{k} \widehat{Q}_{i,k,j} \tag{31}$$

$$\widehat{R}_{i,k,j} - \widehat{R}_{i,k,j}^{U}\left(1 - y_{k,j}\right) \le \widehat{Q}_{i,k,j} \le \widehat{R}_{i,k,j} - \widehat{R}_{i,k,j}^{L}\left(1 - y_{k,j}\right) \tag{33}$$

$$y_{k,j} \cdot \hat{R}^{L}_{i,k,j} \leq \hat{Q}_{i,k,j} \leq y_{k,j} \cdot \hat{R}^{U}_{i,k,j} \tag{34}$$

The parameters were chosen considering their conflicting impact on GWP and cost, as illustrated in Table 5.1.

Table 5.1 Description and units of the parameters used.

No.	Parameter Evaluated	Value Range	Unit
1	Feedstock input	$33{,}00 \leq F \leq 43{,}000$	t/y
2	Syngas yield	$80 \leq S \leq 115$	m3/t
3	Efficiency	$40 \leq E \leq 70$	%
4	Capacity factor	$60 \leq C \leq 80$	%
5	Energy production	$222{,}000 \leq EP \leq 345{,}000$	MWh/y
6	Plant lifetime	$10 \leq F \leq 25$	y
7	Temperature	$55 \leq F \leq 700$	^{O}C

In this study, multi-objective optimization was executed utilizing the Genetic Algorithm. Two objective functions were formulated to represent the primary economic and environmental considerations. The first objective function aims to minimize the GWP of each scenario, computed via LCA. The second objective function focuses on minimizing the total system cost, computed via CBA.

Parameters were chosen based on their conflicting impacts on GWP and the cost. The parameters employed for multi-objective optimization include feedstock input, syngas yield, efficiency, capacity factor, energy production, plant lifetime, and temperature. Constraints utilized in the multi-objective optimization encompass temperature thresholds, cost limits, capacity factor restrictions, waste input rates, and syngas production rates.

5.2.3 An Optimization Strategy

A multi-objective optimization that considers all objective functions is required to choose the best possible function. In this case, it merely considers the two objective functions of GWP and investment costs. It employs an optimality margin of 1% and an ε-constraint approach with nine equidistant intervals between average annual expenses and the consequences of global warming while reducing the investment cost for the computation of the three-dimensional Pareto front. It then selects the most effective bi-objective and single criteria based on the outcomes of the overall front by leaving out two of the three objective functions so that one can obtain the most significant criterion.

If employed as a single-objectify objective function in this work, the costs result in the shortest distance (δ = 0.68). The investment and operating costs are added to determine the annual cost. The value of an investment and its effect on climate change rely on the choice of whether to invest or operate. Accordingly, overall annual costs result in favourable trade-offs for the costs of investment and the effects of global warming. Inevitable trade-offs would disappear if investment costs or the effects of global warming were treated as single-objective functions (δ = 1.00).

The ideal bi-objective criterion is chosen using an objective reduction approach. There are three possible pairings of objectives for bi-objective optimization: total annual spending and operation costs, total annual expenses, and the effects of global warming and investment costs. The shortest distance becomes possible with an investment cost plus global warming influence of δ = 0.23. This distance is much smaller than the other distances of 0.46 total year expenses and climate change impact or 1.00 average investment costs and annual cost. Therefore, bi-objective optimization suffers from a significant loss of information when a NPV is used as the objective function. The compromise between operational and investment costs and impacts is challenging to identify because the annual costs and the net current value have become consolidated objective functions. When total annual costs and the operation's impact on global warming are used as optimization methods, the operation affects both; however, investment expenses only impact total yearly costs. Other objectives are preferred for examining bi-objective synthesis' intrinsic trade-offs. Investment costs and the effects of global warming are regarded as ideal bi-objective goal functions.

In multi-objective optimization problems, there is not a single optimal solution that simultaneously optimizes all the criteria but a set of equally good alternatives with different trade-offs, also known as Pareto-optimal solutions. The optimization of the multi-objective model yields a comprehensive set of Pareto optimal solutions for the waste management problem. These solutions collectively form the Pareto frontier, outlining the trade-offs between conflicting objectives. The Pareto frontier offers valuable insights to the decision-maker.

Constraints were systematically applied to decision variables to regulate input parameters and avoid unrealistic relationships. Multiple decision criteria were incorporated to facilitate decision-making, considering a range of factors. The optimal alternative is then selected as a compromise from the available solutions. The ultimate decision rests on the decision-maker's preferences, whether a policy maker, climate advisor, or company investor.

A criteria decision-making method is employed to pinpoint the best solution on the Pareto front for each scenario's optimization results. Various data points from the optimization results are identified as potential ideal solutions and ranked to determine the most valuable solution.

5.3 Results and Discussion

The optimization results are investigated and discussed for each scenario in this section. For each scenario, Pareto fronts have been represented. Optimal solutions showcasing the waste management system's feasibility from economic and environmental perspectives have been identified.

The set of Pareto optimal solutions facilitates a detailed comparison between individual objective functions and operating conditions. These solutions collectively form the Pareto curve, illustrating the trade-off relationship between environmental impact and economic feasibility. Each point along the Pareto front represents a viable solution, and the selection depends on the optimization target defined by the decision-maker. This study deliberately chooses the optimisation point to reflect the minimum total cost and GWP.

As depicted in Figure 5.3, the Pareto fronts for all scenarios differ due to the cost terms in the first objective function. Notably, the cost of Scenario 2 consistently surpasses that of Scenario 4. However, this discrepancy is not uniform across the entire Pareto fronts. The gap diminishes when transitioning from the least costly solution to the least GHG emissions solution. Ultimately, the two scenarios converge, providing the same solution as the least GHG emissions solution.

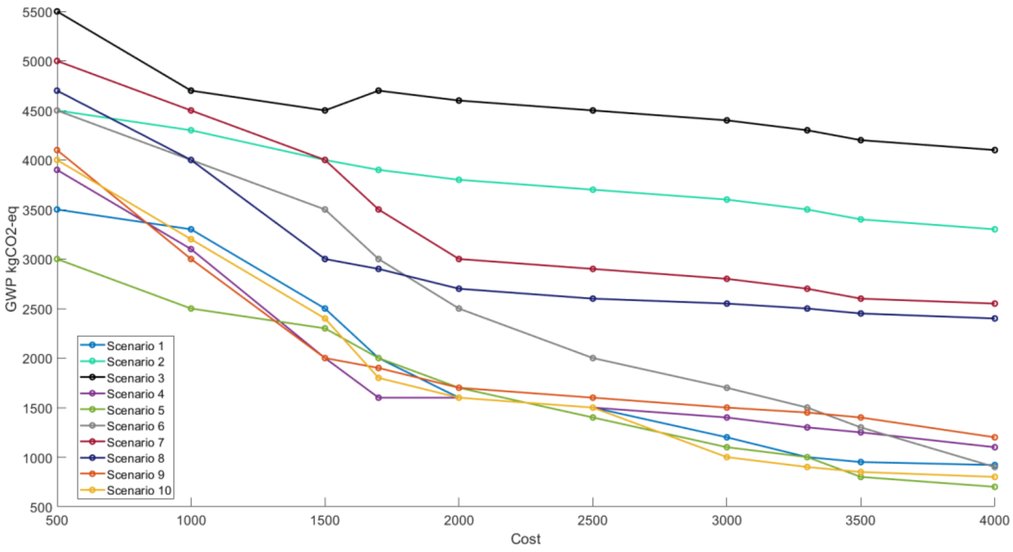


Figure 5.3 Pareto fronts of optimization for all scenarios.

The steep slopes observed in the Pareto curve highlight promising areas for the decision-maker, indicating favourable trade-offs between the two objective functions (where a modest sacrifice in one criterion yields substantial improvement in the other). Notably, in Scenario 5, transitioning from the minimum cost solution to the Pareto optimal solution results in a 56% reduction in GHG emissions with only a 20% increase in economic cost. Similarly, in Scenario 9, emissions decrease by 64% with only a 5% increase in the total cost. These significant slopes indicate that substantial reductions in GHG emissions can be achieved with minimal additional cost.

The pronounced slopes in Scenario 5 demonstrate the potential for substantially reducing GHG emissions without incurring a significant additional cost. Across all scenarios, the Pareto optimal solutions have been identified as the best compromise solutions, representing the most effective trade-offs between economic cost and GHG emissions.

5.4 Conclusion

This chapter sets out to develop and apply an optimization approach to assess waste treatment using the most recent waste-to-energy technologies considering economic, technical, and environmental criteria to support NZEBs.

The developed model has proved applicable; any municipality can utilise this framework with the required data. Economic and environmental factors were used to determine the comprehensive performance of waste-to-energy systems for sustainable waste management. This chapter developed a generic MOO framework for developing waste pathways for sustainable management based on the waste superstructure. The study's results offer insights into deciding on sustainable waste handling and management.

In the next chapter, MCA will serve as the basis for the decision. MCA is specifically chosen due to its ability to address the trade-off between environmental quality and economic objectives. By utilizing this approach, the study aims to determine the most favourable scenario for supporting NZEBs and the waste-management system in Glasgow.

The results derived from the MCA method will provide a clear illustration of the scenario that best aligns with the desired objectives. Through a comprehensive evaluation of different scenarios, the MCA analysis will enable informed decision-making regarding the optimal scheme. It will consider both environmental and economic considerations, striking a balance between these aspects.

Chapter 6 - Decision Making of Waste-to-Energy Technologies-Based Net-Zero Energy Buildings: Multi-criteria Analysis.

The performance of waste-to-energy production is highly dependent on the types of feedstock and technologies. Thus, in this chapter, an MCA method was applied to identify the appropriate combination of technology and feedstock with the consideration of economic, environmental, and technical criteria.

6.1 Introduction

The identification framework for the waste-to-energy technology that incorporates the CBA and LCA approaches into an MCA model used the analytical hierarchy process method (AHP); it has been proved that AHP is the most extensively applied decision-making method for assessing technology options in waste management and energy technology projects [292]. The AHP method analyses complex problems and determines the preferred rankings of the decision options utilizing the weighting process. The most preferred resulting option is the one that has the highest weight. AHP combines the expenses, revenues, opportunities, and risks frameworks in a more insightful decision-making method; it has proven to help assess and compare energy technologies.

The results will help determine the feasibility of waste-to-energy projects by providing energy that explicitly contributes to NZEBs that are looking to increase the use of renewable energy and decarbonization.

6.2 Methodology

The solutions from the optimization model are used as input parameters to the MCA model. To identify the optimal solution on the Pareto front in each scenario's optimization results, the AHP is employed as the criteria decision-making method. MCA aids decision-making by considering various criteria, and the optimal alternative is selected as a compromise among available solutions. The best compromise is determined by comparing it to the ideal solution. A set of data points from the optimization results is chosen as potential perfect solutions, and they are ranked to assign a value, indicating the best solution in the context of the analysis.

The criteria used present both numerical and linguistic impact values. It starts by identifying the values of considered criteria, which are then ‘translated’ into grades based on a given grade scale (1 good performance and 10 poor performance). The score of each scenarios route is calculated by adding the products of the grade of criteria and their weights.

The units used are different. For example, the net profit was appraised using £ units, while ‘tonnes CO_2 eq.’ units were used to assess the GHG emissions. Thus, the weight factors should be carefully selected/allocated to account for the unit difference. In this study, the whole possible range of w1 and w2 factors has been explored and evaluated; that is, w1 varying from 0 to 1, and on the contrary, w2 going from 1 to 0.

6.3 Results and Discussion

The best solutions for all scenarios are presented in Table 6.1. From the results, scenario 5 is the ideal choice for waste treatment. Energy generation from waste using AD and gasification technologies is a sustainable solution for managing waste. Gasification and AD are selected primarily for their efficiency in converting waste into energy and high production value. Smith et al. highlighted in their analysis that waste production through gasification presents promising economic benefits. The choice of these technologies underscores their capacity to effectively harness energy from waste materials, making them key players in the quest for sustainable energy solutions [376].

Table 6.1 The optimum solution for all scenarios

Scenarios	Minimum cost solutions	Minimum GWP emissions	Best compromise solutions
Scenario 1	2318	1199	7
Scenario 2	2291	1321	5
Scenario 3	1859	3320	6
Scenario 4	1967	4542	4
Scenario 5	3215	961	1
Scenario 6	3214	963	2
Scenario 7	2450	968	3
Scenario 8	1750	3140	10
Scenario 9	2154	1420	8

Scenario 10	2410	1540	9

In this work, the scores of each scenario in terms of environmental and economic. This comprehensive approach allows for a more informed decision-making process, ensuring that the most suitable and beneficial scenario is identified for implementation. The ranking of the scenarios is shown in Table 6.1. The results indicated that scenario 5 is more appropriate than other systems. The findings of this study are compatible with the studies by [373] and [294]. They identified that using gasification to produce syngas from waste and its use in energy creation is an economically and environmentally viable option for managing waste sustainably. The results are also compatible with the study by Yap and Nixon [294], which evaluated the opportunities, benefits, risks, and costs of waste-to-energy technologies in the UK. The considered technologies are gasification, mass-burn incineration, landfill gas recovery, AD, and refuse-derived fuel incineration. The criteria considered are technical, environmental, and economic. It was found that gasification technology is preferred for the treatment of waste. Additionally, it has high government funding opportunities and a lower environmental risk compared to other technologies.

The model acts as a foundational tool for directing the design and planning of NZEBs, aligning with low-carbon development objectives. Findings from the model reveal that opting for a solution with a lower significance level enhances system reliability but comes with increased system costs. Conversely, pursuing cost reduction intensifies the risk of violating constraints.

6.3.1 Sensitivity Analysis

The primary purpose of the sensitivity analysis is to examine and assess the effect of selected model parameters on the obtained results and the suitable combination of technology. These parameters are grouped into economic, technical, and environmental and are illustrated in Table 6.2. To conduct the sensitivity analysis, the value assigned to each parameter varies independently, while other parameters are kept constant.

Table 6.2 The parameters used and quality in the sensitivity analysis.

No	Parameters	Technology	Rank
1	Economic	Pyrolysis	2
		Gasification	1
		AD	3

2	Technical	Pyrolysis	3
		Gasification	2
		AD	1
3	Environmental	Pyrolysis	3
		Gasification	1
		AD	2

Table 6.2 indicates that all stated parameters influence technology accordingly. The table shows that environmental and economic parameters rank gasification first, while they prioritize pyrolysis second. Meanwhile, the technical parameter ranks AD as second and pyrolysis as third.

The analysis indicates that the stated parameters (economic, technical, and environmental) are directly linked with technological improvement and the appropriate combination of technology. Improving these parameters can increase benefits while managing and controlling waste sustainably and systematically. Thus, sensitivity analysis is significant in providing optimal solutions in terms of waste management.

In an additional sensitivity analysis, as presented in Figure 6.1, the net profit is most sensitive to the selling price of commodities. A 50% increase in the selling price of energy leads to a remarkable 130% rise in net profit. Furthermore, this change in the selling price of power influences the optimal design, notably when its value decreases by 20% or more, indicating its significant impact.

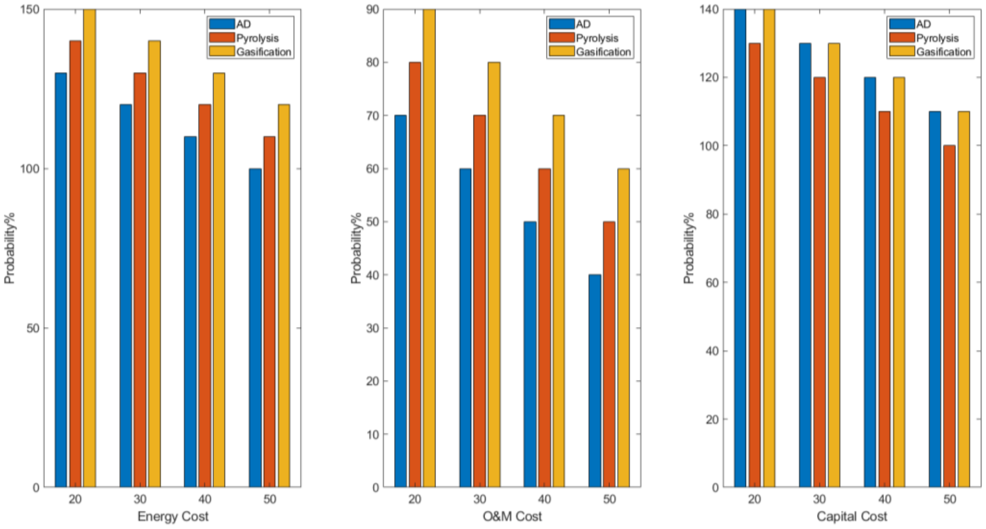


Figure 6.1The sensitivity analysis of the parameters.

The second most sensitive factor affecting net profit is the yield of technology. A 50% increase in technology yield results in a substantial 120% increase in net profit. Similar to the selling price of energy, changes in technology yield also influence the optimal design, particularly when its value decreases by 20% or more.

Moreover, O&M and capital costs exhibit high sensitivity concerning net profit and optimal design. A 40% decrease in O&M and capital costs of technology leads to a noteworthy 60% increase in net profit. These findings underscore the critical importance of commodities' selling energy, technology yield, O&M costs, and capital costs in influencing the system's economic viability and optimal design. Table 6.3 summaries the parameters used and their effect.

Table 6.3 The parameters used and their effect in the additional sensitivity analysis.

Parameters	Effect on profit	Effect on technology		
		Pyrolysis	Gasification	AD
The capital cost of technology	Yes	3	1	2
O&M cost of technology	Yes	3	1	2
The selling of energy	Yes	3	2	1

6.4 Conclusion

The analysis findings indicate that the economic, technical, and environmental parameters associated with all the technologies are susceptible to optimal solutions. The significant impact of the commodities' selling energy, technology yield, O&M costs, and capital costs on net profit and optimal design can be attributed mainly to the impressive yield of individual technologies and the high production value of the resulting commodities. These favourable characteristics contribute substantially to the economic performance and efficiency of the system, underlining the importance of these factors in the overall analysis.

Chapter 7 An In-Depth Critique of Achieving Net-Zero Futures: Decarbonization Strategies on International, National, and Local Levels

This chapter addresses the existing waste regulations and renewable energy in Scotland and offers insight into the Scottish Government's efforts to enhance both sectors. Additionally, it delves into waste-related legislation and its current applications in Scotland. The study examines waste-to-energy technologies' economic and environmental advantages in supporting NZEBs in Glasgow. However, local policies could significantly influence the implementation of engineering methods. Given that Glasgow serves as a foundational example for applying the waste-to-energy model to support NZEBs, the pertinent policies in the area are also reviewed.

7.1 Analyzing Governmental Policies and Regulations Worldwide

A practical and reasonable policy system must have a strong base for waste-to-energy development. Environmental friendliness and the renewable nature of waste-to-energy have attracted interest from governments worldwide. A set of regulations and policies have been developed to achieve mid and long-term waste-to-energy goals [377].

In 2012, waste-to-energy standards for harmless waste disposal were put forward in China; a plan to construct harmless household waste treatment facilities was implemented by making the 12th Five-Year Plan on national facility construction of harmless disposal of urban waste [378]. Waste incineration technology has attracted 4.24 billion worth of investment in five years [379]. Denmark is one of the pioneers in banning combustible and organic waste from landfills [380]. As the Environmental Protection Act requires, each municipality must ensure the proper waste disposal within its geographical area. To achieve these objectives, the government deploys robust regulatory and economic instruments. For instance, landfill taxes have been introduced and are still rising [381]. Municipalities develop long and short-term plans for waste management and provision of systems to treat waste, e.g., waste-to-energy technologies [382]. Waste development legislation is centralized at the national level in Portugal. Regulatory and economic incentives for clean technologies motivate energy recovery from waste. National recycling networks are dedicated to different types of waste material. The systems are created by recyclers and producers' representatives and are managed by a non-profit entity. Under the Regulation of Waste Management in Portugal, power plants are assigned to cement producers [383].

The UK's policy and legislation on waste management have been greatly influenced by the Waste Framework Directive set by the European Union (EU). Industrial symbiosis development has been shaped through a mixture of voluntary, regulatory, and economic instruments introduced by the UK government. The national symbiosis program was developed to help redirect waste from landfills and establish partners that can utilize the waste to realize economic and environmental gain [384]. For example, managing unique and urban waste is the duty of respective businesses. A private recycling market controls Waste recovery and transfer [385]. In Switzerland, waste incineration was firmly entrenched as a method for reliable recycling and energy recovery [386]. In general, to accelerate the development of the waste-to-energy industry, the government was required to form strong policies and provide financial backing for waste-to-energy projects. The MSW Rules, 2000" emerged for the first time in India to recover the effectiveness of the municipal waste management system and make it more sustainable. India's primary waste management strategy aims to reduce waste disposal and recycle and reuse waste. Sustainable waste treatment involves using diverse optional technologies and techniques such as AD, pyrolysis, gasification, and incineration, among the most common alternatives [387].

7.2 Scotland's Path to Zero Waste: An Analysis of Renewable Energy Policies and Targets

In 2010, Scotland initiated its inaugural Zero Waste Plan [388] to enhance material separation in waste streams to facilitate renewable energy generation from food waste. The plan proposed adopting AD to produce renewable energy, suggesting that waste-derived energy could power 170,000 households. The plan outlined several future targets, including:

- They are imposing bans on landfilling materials.
- Advancing Environmental and Clean Technologies.

To reduce waste volume, the Scottish Environmental Protection Agency introduced new legislation in 2021 prohibiting the disposal of Biodegradable Municipal Waste in landfills [389]. The ban's objectives were to:

- Decrease landfill waste.
- Extract organic materials from waste streams.
- Reduce greenhouse gas emissions resulting from landfilling biodegradable waste.

The legislation defines biodegradable municipal waste as commercial or household waste capable of anaerobic or aerobic decomposition, such as garden waste, food, cardboard, and paper [389].

The Scottish Energy Strategy: Shaping Scotland's Energy Future report from 2017 outlined a plan to boost renewable energy generation and decrease dependence on fossil fuels [390]. With a projected 60% increase in gas demand by 2050, the report set forth several targets:

- Establish a Bioenergy action plan.
- By 2030, raise renewable energy plants to 50%.

The Bioenergy action plan aimed to advance and integrate bioenergy development into the transition to net-zero emissions [390]. This objective was reiterated in Scotland's Climate Change plan, with an updated version released in response to the COVID-19 pandemic and heightened climate change concerns.

The revised report introduced new ambitious targets post-COVID-19 and made several commitments to bioenergy [391]:

- Achieve a 75% reduction in emissions from 1990 levels by 2030, ultimately reaching net-zero by 2045.
- Eliminate Biodegradable Municipal Waste landfilling by 2025.
- In 2022, initiate the Green Gas support initiative aimed at boosting the injection of biomethane into the gas grid, taking over from the Renewable Heat Incentive program.
- Implement funding schemes to assist farmers in adopting anaerobic digesters, thereby curbing emissions from manure and slurry management.
- Release a bioenergy progress report in 2021, followed by a comprehensive action plan by 2023.

Incorporating bioenergy as a sustainable energy resource and a means to mitigate emissions is gaining prominence in Scottish policy. The adoption of biogas and biomethane has surged in Scotland, with no active installations in 2014 and 160 biogas and 20 biomethane installations documented in 2020 [392].

Although most of Scotland's energy is derived from fossil fuels, there's a gradual shift towards reducing fossil fuel dependence and embracing diversified energy sources. In 2015, 93% of Scotland's primary energy was from fossil fuels [393]. Oil and gas extraction remains crucial to Scotland's economy and energy supply, but environmental concerns have prompted a transition towards sustainable energy [394]. Scotland's energy mix comprises a complex blend, with 73.9% from petroleum products and natural gas and 24.0% from renewables.

Scotland stands out among nations' renewable energy progress, mainly due to its geographical advantages. Renewable energy contributed 27% of Scotland's total energy in 2020. The country has set ambitious targets for renewables, aiming to more than double power generation by 2030 and achieve 100% renewable electricity. By 2045, Scotland aims to complete its Zero-Net plan [395]. However, the dominance of intermittent and unstable sources like wind and hydropower poses challenges to meeting these goals.

Implementing renewable energy projects can yield favourable economic outcomes, extending beyond environmental concerns to economic and geopolitical realms. Renewable sources can spur economic growth, job creation, and energy security [396]. The renewable sector also fosters innovation, investment, and sustainable economic development [397]. Embracing renewables paves the way for net zero emissions [398].

7.3 Navigating Glasgow's Net-Zero Journey: An In-depth Analysis of Fulfillment Routes

The UK government has pledged to eliminate greenhouse gas emissions by 2050 completely. Scotland aims to achieve net-zero goal and Climate Change Plan by 2045 [399]. Among these cities, Glasgow, the largest city in Scotland, is determined to reach the net-zero goal by 2030, setting a remarkable example in the journey toward a sustainable future [400]. These goals require a thorough and harmonized plan to decrease greenhouse gas emissions throughout every sector of the economy. The extensive uptake of renewable energy resources becomes a crucial strategy in attaining net-zero targets within Glasgow, given the pressing requirement to tackle the consequences of climate change. Shifting towards renewable energy sources allows countries to substantially reduce their carbon emissions and alleviate the adverse effects of climate change [401]. Moreover, adopting renewable energy presents chances for diminishing reliance on imported fossil fuels, diversifying energy sources, and enhancing energy security [402].

Glasgow, historically known for industry, is facing the challenge of transitioning to a low-carbon economy. The city's commitment to achieving net-zero carbon emissions is evident as it hosts the COP26 climate summit [400, 403]. Policies like the Glasgow Green City Plan and Clyde Mission showcase its dedication to renewable energy, serving as a model for other cities. Ongoing projects aim to cut carbon emissions, target net zero by 2030, and embrace a circular economy [403]. The city is implementing measures such as LED lighting, energy management systems, and solar panels, with a five-year program targeting a significant reduction in carbon footprint. Glasgow aims to decrease carbon emissions by 50% from current levels by optimizing buildings and retrofitting. The city is also developing energy efficiency plans to reduce building sector emissions further [400]. To create a more environmentally sustainable urban environment, it's crucial to actively integrate renewable energy systems, starting with buildings, and adopt comprehensive strategies to reduce carbon emissions effectively.

The unit of measurement known as CO_2 equivalent (CO_2e) standardizes the climate effects of diverse greenhouse gases. It facilitates a more precise assessment of the overall impact of greenhouse gases on climate change from different sources to the GWP, serving as a reference point. This tool is instrumental in comprehending and reducing emissions. Over the past two decades, Scotland's greenhouse gas emissions have declined by 50%, from 87.16 $MtCO_2e$ in 1990 to 42.88 $MtCO_2e$ in 2021. The energy sector accounted for 13.25% of emissions in 2020 [404].

In Glasgow, the primary energy supply primarily hinges on conventional fossil fuels such as natural gas, oil, and coal, mainly catering to building lighting and heating needs [405]. Carbon emissions from electricity generation have been declining due to the increased use of sustainable energy sources, dropping from 0.28307 kg per kWh in 2019 to 0.2556 kg per kWh in 2020. This decrease in emissions is observed in most sectors in Glasgow, except for the public sector. The commercial industry registered a notable decline of 40 kt in CO_2 emissions in 2019, the most substantial reduction across industries. Carbon emissions from the industrial and domestic sectors also experienced reductions of 36 $ktCO_2$ and 22 $ktCO_2$, respectively. Glasgow's total carbon emissions in 2019 amounted to 2414 kt of CO_2, reflecting a 5% decline from 2018 and a notable 41% decrease from 2006 [406]. Noteworthy strides have been made in reducing carbon emissions in Glasgow. Glasgow is on track to attain net zero emissions by 2045, primarily driven by the significant expansion of sustainable energy capacity. As the utilization of sustainable energy has surged, the consumption of fossil fuels has correspondingly diminished.

Glasgow's renewable energy production is relatively modest, generating 64 GWh. Given the city's urban nature, natural resources for sustainable energy are limited. However, the substantial urban population contributes to a significant renewable energy source through household waste and waste products. In 2021, biomass and energy derived from waste products accounted for 46 GWh, constituting approximately 71% of the city's renewable energy.

Creating large-scale sustainable energy power stations within cities is challenging due to the significant demand for natural resources. As a result, urban areas tailor their approaches based on local conditions, commencing with projects at the community and infrastructure levels. Several initiatives have already been undertaken in various parts of Glasgow. In September 2022, the city council initiated the 'Greenpoint for Investment' program to establish the necessary infrastructure for future low-carbon cities. Projects include renovating household insulation, expanding the Glasgow Recycling and Renewable Energy Centre, and creating green spaces.

Businesses and employers have committed to the net-zero carbon objective in Glasgow by signing the Sustainable Glasgow Green Economy Hub Charter [407]. Glasgow has invested £2.1 million to construct a CHP system and establish a community-based district heating network for affordable heat supply [408]. The city has implemented a Low Emission Zone as mandated by the Transport (Scotland) Act (2019) to tackle greenhouse gas emissions [409]. Glasgow City Council, developed in partnership with Scottish Power Energy Networks, Sustainable Glasgow, and the University of Strathclyde, received endorsement in 2015 [405]. This plan introduced a strategic energy framework for the city, enabling small- and large-scale projects to establish a robust local energy system and promote community energy growth, aligning with low-carbon emission goals. Multiple sustainable energy policies in Glasgow have emerged from this masterplan.

The University of Glasgow is actively committed to climate-related objectives. It has set a clear timeline to cease fossil fuel usage by 2024 and has taken significant steps towards sustainability. Glasgow signed the Sustainable Development Goals Accord in 2017, showcasing its dedication to global sustainability objectives. Moreover, the city's declaration of a climate emergency in May 2019 highlights its proactive response to the urgent climate crisis [410]. The university's Centre for Sustainable Solutions utilizes research resources to address net-zero emissions challenges and provide practical solutions [411]. Through the Living Lab Accelerating Novel

Transformation (GALLANT) program in partnership with the city council, innovative sustainable solutions are tested within Glasgow.

The Glasgow City Council unveiled the Climate Plan and Glasgow Green Deal in 2021, focusing on climate change mitigation strategies tailored to the city's specific environmental challenges as it strives for a net-zero future [412], [413]. This prompted the Natural Environment Research Council to commission the GALLANT initiative, which collaborates with the University of Glasgow to address critical urban environmental challenges like community power generation, biodiversity preservation, and efficient transportation solutions.

In addition to addressing these crucial environmental challenges, strategies to reduce the city's energy consumption were also considered. Acknowledging the rise in electricity demand due to electrification, there's also a recognition of the need to reduce overall energy consumption through enhancements in energy efficiency. While multiple sectors offer opportunities for energy efficiency improvements, transportation and heating are among the primary sectors identified.

Glasgow City Council is actively implementing various initiatives to reduce the carbon footprint from waste generated within the city. Their Resource and Recycling strategy, from 2020 to 2030, charts a course for Glasgow to become a zero-waste city. This entails substantially reducing the carbon impact of waste management practices and boosting overall sustainability. The Waste Strategy for Glasgow seeks to change how waste is viewed, turning it from a problem into a valuable resource. It also involves integrating technology to maximize the potential of waste while concurrently advancing sustainability goals (Glasgow City Council, 2020). Glasgow has plans to organize its waste management system. As part of this initiative, residents utilizing the brown bin service can apply for a garden waste permit starting October 1, 2023 (Glasgow City Council, 2023).

Glasgow City Council has received £6.845 million from the Scottish Government's Energy Efficient Scotland Area Based Schemes program to enhance home energy efficiency. The program aims to improve energy efficiency, aligning with Scotland's goal of making existing buildings almost carbon-neutral by 2045. The funding focuses on owner-occupiers and private landlords in economically disadvantaged areas of Glasgow to install energy-efficient measures, prioritizing achieving an EPC rating of C or better by 2030. This initiative supports various city and national strategies related to sustainability and climate change (Glasgow City Council, 2023).

7.4 Strategies, Policies, and Targets for Decarbonizing the Building Sector (NZEBs)

Numerous countries have established clear targets for promoting the development of NZEBs. For example, in Europe, the Directive on Energy Performance of Buildings establishes that all new buildings in Europe must comply with the specified standards of NZEB. The United States has set a zero-energy target for 50% of its commercial constructions by 2040 and all buildings by 2050 [414]. The EU is one of the forerunners in promoting decarbonization and renewable energy, as reflected by its target of 20% GHG emission reduction, a 20% increase in renewable energy use, and a 20% upsurge in energy effectiveness [415].

Renewable energy growth in Scotland has been remarkable recently, with the country possessing abundant resources for renewable generation, ranking among the leading European regions in this regard. The Glasgow Energy Strategy sets ambitious goals, targeting 60% of total energy consumption from renewables. Glasgow's approach encompasses incorporating renewable energy sources for electricity and heat while striving to increase energy efficiency by 30% across multiple sectors. This comprehensive strategy demonstrates the city's commitment to sustainable energy production and responsible resource consumption [390]. The Climate Change plan aims for a 75% emissions reduction by 2030 (compared to 1990) and net-zero emissions by 2045. A key objective is to transition 50% of buildings to low or zero-carbon heating by 2030. This requires innovation, cost reduction, technology adoption, and a transformative energy system change [390]. Scotland has already surpassed its 2015 target of 50% renewable electricity, potentially exceeding 140% of electricity consumption through renewables by 2030. The 2030 renewable energy target includes significantly expanding renewable electricity capacity to about 18 GW from 10 GW in 2017, bolstered by improved connectivity with the EU. The plan highlights the shift to ultra-low-emission vehicles for non-electric transport. It aims to fulfil 20% of non-electric heat demand with renewable heat sources like heat pumps and biomass. It is also considering expanding district heating using renewable fuels. The aim is a diverse and sustainable energy mix where renewables play a significant role by 2030 [391]. Integrating sustainable energy is expected to substantially reduce carbon emissions by 2032, as outlined in the Climate Change Plan.

Scotland's goals have spurred the adoption of renewable energy across various scopes, including industry, homes, and communities. This growth encompasses both central installations and smaller ones at building levels. Despite the recognition of community-driven distributed energy systems like Community Renewable Energy projects, their contribution to onshore renewable energy remains at 4% [416]. Even though Scotland surpassed its 2015 target of 500 MW for renewable energy capacity ahead of schedule, authentic community ownership only amounted to 70 MW. Analysis suggests that a sizeable renewable project could cost approximately 10.7 billion pounds, roughly 8% lower than a 75% renewable energy system, showcasing the feasibility and cost-effectiveness of high renewable integration [417].

Scotland has achieved substantial advancements in renewable energy expansion. In 2014, renewables contributed to nearly half (49.8%) of total electricity consumption. By 2020, renewables took the lead as the primary electricity contributors in the UK, making up 43% of the entire generation. This progress is attributed mainly to solar, bioenergy, and wind sources. In 2020, Scotland sourced 95% of its gross electricity consumption from renewables, approaching the 100% target (Scottish Government, 2021). On May 15, 2023, the UK achieved one trillion kWh of electricity from renewables, sufficient for UK households for about 12 years [418]. Despite the journey spanning five decades, the next trillion kWh is projected to be reached. Scotland's achievements highlight its potential and success in renewable energy, mirrored by similar advancements in the heating sector. Renewables met 6.4% of non-electrical heat demand in 2020, surpassing the halfway point of the 11% target for 2020. The 4.5 percentage point increase from the 2010 figure of 1.9% and a minor 0.2 percentage point dip from 2019 signals a shifting trend. [419]. Integrating renewable energy systems into buildings faces technical, economic, and regulatory barriers. A notable technical challenge is sizing integrated systems to harmonize production sources and storage devices with demand. Precise sizing is pivotal for energy-efficient structures involving flexible metamodel architectures and software for Hybrid Renewable Energy Systems [419]. Additionally, achieving NZEBs requires addressing energy demand reduction and internal energy generation [420], [418]. A flexible metamodel architecture and software implementation are essential to enable the design of Hybrid Renewable Energy Systems (HRES) from the ground up. Additionally, the goal of achieving NZEBs involves tackling two key aspects: firstly, reducing energy demand and, secondly, generating energy within the building itself. This multifaceted approach recognizes the importance of holistic solutions for sustainable energy systems and energy-efficient buildings.

Economic barriers, including high investment risks and limited economic justification, act as deterrents to integrating renewable energy systems within buildings. The initial costs associated with constructing such buildings tend to exceed those of conventional ones [421]. Dissuading potential investment. Furthermore, insufficient awareness and education about the advantages of incorporating renewables contribute to this economic challenge. Nevertheless, it's essential to recognize that buildings with integrated renewable energy systems provide long-term benefits that outweigh their upfront expenses [422]. Simultaneously, the Lack of guidelines and incentives deters owners [421], but efforts for NZEB policies and certifications are ongoing. [423].

The implementation of renewable energy systems can be hindered by architectural constraints [424]. Incorporating systems into existing buildings is challenging due to limited space, and establishing distributed energy systems needs consistent communication networks for managing renewables and storage effectively. This underscores the importance of addressing physical and technological challenges in advancing renewable energy adoption [425]. Standardizing these networks is crucial to ensure the streamlined functionality and seamless integration of distributed energy resource systems.

Consequently, incorporating renewable energy systems into buildings faces various hurdles and limitations spanning technical, economic, and regulatory dimensions. Several challenges must be overcome to achieve widespread integration of renewable energy technologies within buildings and progress toward an energy-efficient built environment. These challenges include determining appropriate system sizes, dealing with high initial costs, addressing limited awareness, filling regulatory gaps, working around architectural limitations, and establishing consistent communication networks. Successfully addressing these obstacles is crucial for realizing the vision of a future where renewable energy is seamlessly integrated into building structures, promoting sustainability and energy efficiency. Therefore, conducting thorough techno-economic analyses becomes essential for gauging the viability of new projects incorporating renewable energy systems [426].

Rajavelu (2021) studied the feasibility of hybrid renewable energy systems in buildings, aiming to optimize distribution benefits and find the best Hybrid Renewable Energy System setup. They considered costs, selecting the optimal choice of the G-PV-wind system [427]. This setup achieved an impressive 28% to 30% reduction in CO_2 emissions while satisfying the building's electricity demands.

Another study focused on implementing a grid-connected PV system for a building in Malaysia. This initiative aimed to reduce the building's dependence on the primary electricity grid by generating and storing renewable energy locally [428]. Performance was evaluated across various load growth and renewable resource scenarios, highlighting the potential of battery storage in enhancing renewable energy penetration despite a slight increase in net present cost.

Conducting a feasibility analysis for microgrid design in Pakistan, Awan et al. (2022) assessed multiple configurations for a building's energy supply [429]. The chosen hybrid microgrid design incorporated solar PVs, battery storage, and a diesel generator, ensuring an uninterrupted energy supply with a 99% renewable fraction over 25 years from a selection of 979 feasible designs.

Furthermore, a study conducted by Bayoumi in 2020 explored the feasibility of combining energy generation with solar thermal cooling in a building [430]. This research evaluated the economic viability of integrating these technologies and delved into energy management strategies to enhance overall efficiency. The study's results highlighted significant reductions in non-renewable energy usage and considerable coverage fractions achieved through the synergistic implementation of electrical energy generation and solar thermal cooling methods.

In summary, the studies discussed underscore the essential significance of techno-economic feasibility analyses when evaluating the practicality and benefits of incorporating renewable energy systems into buildings. These investigations provide valuable perspectives on economic considerations, improvements in energy efficiency, and potential economic gains associated with integrating renewable energy sources into building structures.

7.5 Waste-to-Energy Technologies for Decarbonizing the Building Sector.

The research demonstrates that waste-to-energy technologies exhibit moderately reduced GWP values, capitalizing on their evident advantages as dual-purpose systems that produce energy while disposing of waste.

In urban areas densely populated with buildings, providing energy supply solutions addresses the demand for infrastructure. The study proposes systems that can notably transform this city into a hub for zero-emission structures and on-site energy production (on-site energy supply options within NZEBs.

Among various waste-to-energy technologies, gasification and AD emerged as the most favourable choices [373]. When integrating systems, the preference sequence was identified as AD combined with gasification and AD paired with incineration, particularly in cases where AD was integrated with thermochemical processes [431]. Consequently, the assessment concludes that gasification and AD stand out as notably dependable waste-to-energy technologies in terms of environmental performance in megacities.

Diversifying energy sources yields benefits such as bolstering supply chain resilience, enhancing energy system flexibility, and addressing energy gaps, like meeting the energy needs of remote areas for building purposes. Ultimately, this should instil confidence in waste-to-energy technologies to support environmental objectives and advance decarbonization endeavours (toward net-zero energy-building targets).

Effectively implementing such sustainable waste-to-energy projects necessitates a comprehensive national energy policy, which should account for the following aspects:

- The government should extend support to institutions willing to undertake sustainable waste-to-energy initiatives.
- Local authorities should play a pivotal role in promoting the advantages of sustainable waste-to-energy generation plants.
- Government efforts should encourage local development and electricity generation through waste-to-energy technologies. This approach offers multiple benefits, including relatively lower electricity generation costs from sustainable sources, local investments, and employment opportunities. These positive outcomes will likely inspire other regions and communities to adopt similar sustainable waste-to-energy facilities.

7.6 Discussions on Waste Management and Energy Production for NZEBs

In Glasgow, the substantial energy consumption in buildings poses significant environmental protection and energy conservation challenges. The primary opportunities to decarbonize the city lie in reducing total energy consumption in buildings and increasing energy generation from renewable resources. NZEBs represent a promising solution for decarbonizing the building sector. Concurrently, sustainable waste management presents a significant challenge for Glasgow due to rapid economic growth and population expansion. Waste-to-energy technologies have been recognized to convert waste into valuable energy and minimize the problems related to it. Waste-to-energy technologies can play a crucial role in supporting the development of NZEBs while contributing to sustainable waste management.

The renewable energy supply options are essential considerations in the design of NZEBs. Renewable energy sources from outside the building site boundary could play a key role in facilitating the development of NZEBs. This is possible with the onsite availability of specific renewable sources, such as waste, as considered in this work. Energy recovery from waste (i.e. waste-to-energy) is a promising alternative and an efficient, viable solution for waste management, alleviating GHG emissions and decreasing the demand on the land needed for landfill disposal. The performance of waste-to-energy production is highly dependent on the types of feedstock and technologies. Waste-to-energy technologies have the potential to tackle the triple crisis (waste pile-up, climate change, and increased energy demand).

Gasification, pyrolysis, and AD are relatively advanced methods that can potentially achieve higher environmental benefits [432]. For example, it was found that gasification could achieve a carbon-saving potential of 107.9 kg CO_2 per tonne of waste, which was 30% more than that of incineration [278]. It was shown that 40,000 tonnes of CO_2 could be saved by treating one million tonnes of food waste through AD [433]. Pyrolysis could contribute to a 61% reduction of carbon emissions per unit of gross domestic product in 2030 compared to 2005 and decrease air pollutant emissions. The cumulative GHG reduction could reach up to 8620 Mt CO_2-eq by 2050, contributing 13–31% of the global GHG emission reduction goal [434].

Domestic and international energy policies strongly emphasize the use of renewable energy sources for the generation of energy. Recycling waste to obtain energy sources has already been seen as a valuable source of green energy [435]. Waste-to-energy systems offer a solution to mitigate the detrimental environmental impacts caused by improper waste collection practices and the reliance on carbon fuels for electricity production. These systems can effectively minimize these adverse effects by utilising waste as an energy source. Waste-to-energy systems convert readily available renewable energy resources into usable power. Recycling waste can enhance global energy security due to the worldwide dominance of fossil fuels like coal in the energy industry.

Different bioenergy technologies can be classified into thermochemical and biochemical processes, respectively. Typical thermochemical processes include combustion, gasification, and pyrolysis, while biochemical processes include fermentation and digestion [436].

AD is one of the most effective methods for managing organic waste. Utilizing this method also allows a high percentage of resources to be recovered. Microbes are used to carry out the biological mechanism of the anaerobic process when there is insufficient oxygen – the anaerobic process produces biogas and compost. CH_4, which makes up between 55% and 70% of biogas, and CO_2 are by-products of the process. Based on its nutrient composition, compost can be utilized as fertilizer [188]. Both pyrolysis and gasification can be seen as effective thermal waste treatment technologies. It was found that bioenergy technologies could be used to reduce the carbon footprints of waste management [437]. It was discovered that the bioenergy treatment of solid waste using anaerobic and gasification technologies could save over 300kg of CO_2 per tonne found in Glasgow. Also, these technologies could produce and supply up to 30% of energy demands [151].

Bioenergy has been used to supply energy to households via different means. For example, some buildings in Belgium have been powered by biomass boilers, solar thermal panels, PV panels, and gas boilers, which improved the efficiency by 78% compared with the ones supported by conventional energy supply. Similarly, in Ireland, buildings that relied on biomass heating based on natural gas and PV electricity production exhibit a 50% improvement in energy efficiency [313]. Waste management (waste-to-energy) and NZEBs actively contribute to pursuing a Net Zero future.

7.7 Conclusion

Scotland is actively working toward a sustainable, low-carbon energy system with ambitious targets set by its government. These goals encompass increasing renewable energy usage for heating, transportation, and electricity, aiming for 50% by 2030, and complete reliance on renewables for electricity by the same year. The long-term vision includes renewable energy contributing to half of the final energy supply by 2050. The country also plans for 80% of residential energy and 100% of automotive energy to be supplied by electricity by 2050.

Scotland strives to generate more than twice its annual electricity demand by 2030 and over three times by 2045. Scotland aims to reduce total emissions by 75% from 2019 levels by 2030 and by 90% by 2040. In alignment with emissions, Scotland strives to reduce its total emissions by 75% from 2019 levels by 2030 and 90% from 2019 levels by 2040. Ultimately, the goal is to transition to a net-zero energy system by 2045.

While meeting these renewable energy targets would significantly elevate Scotland's electricity demand and peak capacity needs, the country's energy requirements are substantial. Aligned with the Scottish targets, Glasgow City Council has established sustainable development objectives and plans to attain net-zero carbon emissions by 2030. Their strategy involves emission reductions in transport, buildings, energy consumption, waste management, investments in renewable energy sources, and the promotion of sustainable living. Collaboration with local businesses and communities is essential for achieving these carbon reduction objectives.

The energy provision must be sustainable and accessible to all, given the multidisciplinary nature of the sustainable net-zero challenge. We must facilitate advancements toward the timely implementation of sustainable energy solutions at multiple scales, from local to global.

Waste-to-energy systems offer several advantages over conventional fossil fuels and other renewable energy sources. These benefits include sustainability, reduced carbon emissions, diversification of the energy mix, and the potential to drive economic growth and job creation. However, they also face drawbacks like instability due to weather-dependent sources, high initial costs, and the need for careful grid integration planning.

Technological progress enables the transformation of non-recyclable waste-to-energy forms, including heat, electricity, biogas, and biofuel. Conventional waste treatment methods encompass composting and landfilling, whereas AD, pyrolysis, and gasification offer elevated potential for enhancing the value of waste through conversion into valuable chemicals and fuels. Nonetheless, these methods encounter specific implementation challenges, with the technological maturity of each approach playing a pivotal role. Waste-to-energy technologies are more extensively applied in developed nations. This underscores the genuine potential of waste-to-energy to address global waste and energy concerns simultaneously.

These techniques aim to achieve three main objectives:
Reduction in the overall landfill disposal volume, irrespective of its origin. Minimize the biodegradable portion in waste to prevent secondary environmental contamination, including CH_4 emissions resulting from potential biodegradable remnants after treatment. Valorization of the energy content within non-recyclable solid waste, converting it into electricity and heat.

The comprehensive analysis conducted for this study supports waste management policies in Scotland and the UK, promoting pathways for low-carbon technologies like waste-to-energy. As revealed in the analysis, the anticipated growth of waste-to-energy serves as reasonable justification for further research into technologies like waste-to-energy, aiming to maximize resource utilization, particularly when such conversion can yield clean, low-carbon energy for the future.

Economic and environmental factors affect the design of waste-to-energy systems and are linked to various parameters, such as feedstock and technology selection, policies, and regulations. The present studies have revealed that waste-to-energy could contribute efficiently to the sustainable energy supply and mitigation of climate change.

Despite the numerous advantages of NZEBs, several obstacles hinder their progress. A significant challenge arises from the scarcity of tools to guide decision-making across various aspects of NZEB development, including policy, technical, and financial dimensions. Furthermore, there exists limited comprehension of the technological pathways and configurations of NZEBs supported by bioenergy. The lack of pertinent models for optimizing and designing bioenergy-supported NZEBs is also evident. Waste-to-energy technologies offer potential support for NZEB development while concurrently facilitating sustainable waste management. Given Glasgow's rapid economic growth and population expansion, achieving sustainable waste management poses a considerable challenge.

Chapter 8 – Discussions, Limitations, Conclusions and Further Work

This chapter provides a comparative analysis of previous results with the current research findings. In addition, it presents the results of this thesis and the economic viability and environmental impacts of different waste-to-energy technology scenarios to identify the most appropriate method and technical configurations for distributed bioenergy-supported NZEBs. The comparative analysis and the main findings of this thesis effort are presented in Section 8.1. Following this, a limitation, conclusion, and an overview of suggestions for future studies are also provided in Sections 8.2, 8.3, and 8.4, respectively.

8.1 Comparing Work with Research Findings: A Comparative Analysis

In this section, a thorough examination of various research findings has been conducted, selecting only the most robust and well-observed data for comparison. The investigation focused on bioenergy systems, aiming to optimize their performance through innovative configurations.

Through meticulous analysis and experimentation, the proposed work demonstrates that implementing a novel bioenergy configuration led to significantly improved results compared to conventional approaches. The synergy of cutting-edge techniques and insights from the best-researched sources allows us to harness the full potential of bioenergy, achieving remarkable advancements in efficiency and output.

Table 8.1 compares research findings with values reported in the literature, clearly understanding how this novel configuration outperforms existing alternatives. This work contributes to the body of knowledge in bioenergy and offers practical and sustainable solutions to the city's energy challenges and waste management.

Table 8.1 Summary of comparing research findings with values reported in the literature.

Reference	Technology used	Energy generation	Environmental findings	Economic findings
This work	Gasification, pyrolysis, and AD	390 MWh	150-350 kg CO_2-eq/t	£12,01million
[200]	AD	281 MWh	92.27 kg $CO_{2\text{-eq}}$	£10.3 million
[438]	Pyrolysis	-	250.4 kg CO_2-eq/t	\$11.53 million

[439]	Gasification Pyrolysis	-	-	$50 million
[138]	Gasification	643-901 kWh/t	114 g CO_2/kWh	65 to 112 $/t
[440]	AD	100-150 kWh/t	0.2 kg CO_2/kWh	€0.09/kWh
[211]	Gasification AD	204 MWh	320 kg of CO_2	-

Waste-to-energy technologies play a crucial role in mitigating climate change by reducing GHG emissions from landfills and substituting conventional energy production from fossil fuels [441]. A substantial increase in global waste treatment in waste-to-energy plants has been observed, reaching approximately 18% of the total generated waste in 2020, marking a 14% increase from 2012 [442]. These systems offer significant environmental and economic advantages by converting waste into usable energy through thermochemical or biochemical processes [443].

Foster et al. conducted a comprehensive exploration of different waste-to-energy methods in the UK, determining that advanced technologies yield greater effectiveness. Their findings favored biofuel production from waste as the optimal choice [444]. Similarly, Abdallah et al. conducted a comparable study, identifying AD with non-food waste recycling as the most efficient approach. They also asserted that waste-to-energy systems have the potential to contribute 17% of the overall power consumption [445].

Chhabra et al. investigated the pyrolysis of mixed waste and found it economically viable while significantly reducing GHG emissions compared to open landfilling, with reductions reaching up to 250 CO2-eq/t waste [438]. McKendry analyzed the costs of various waste-to-energy facilities in the UK, including incinerators, biogas plants, advanced pyrolysis, and gasification. Initial capital investments for all facilities exceeded operational costs, with advanced pyrolysis and gasification having the highest costs due to their demanding processing conditions [439], [446].

Comparing incineration to AD for food waste, the latter showed lower costs, but Bilitewski et al. disagreed, finding higher operational costs for AD plants in Germany. However, these plants had smaller capacities [447]. Sadef et al. proposed an integrated waste management system for Lahore, Pakistan, with waste-to-energy technologies expected to reduce landfill waste volume.

They found that processing the entire organic waste stream with AD technology has the potential to generate approximately 8747.3 TJ or 2.43 TWh of energy [448].

Generating bioenergy from waste through the technologies mentioned in this work is a promising solution for tackling sustainable waste accumulation and renewable energy production [143]. A study by the Sustainable Development Commission Scotland found that 3.9% of Scotland's total heat demand could be provided through energy from waste [144].

Biological agents are used in biochemical processes to convert organic waste into liquid or gaseous fuels, with AD being a typical biochemical technology. Gasification is the most commonly adopted thermochemical technology [160], [161]. Thermochemical processes like pyrolysis and gasification are versatile for reducing both organic and inorganic waste, warranting their enhancement for improved waste reduction.

Using waste as the primary source of renewable technology for NZEBs would enhance the system's sustainability at the community level [152], [153]. Waste-to-energy systems typically integrate into broader waste management strategies, incorporating material recovery facilities, sanitary landfills, and one or more waste-to-energy plants. The choice of integrated strategy should align with specific local waste characteristics, environmental considerations, and economic conditions [435]. Establishing an integrated waste management strategy with a single type of waste-to-energy system may not simultaneously optimize environmental and financial benefits due to variations in waste materials' energy yield, particularly influencing thermochemical conversion systems' economics.

8.2 Limitation

The waste treatment systems face limitations in meeting energy coverage needs and ensuring the reliability of energy supply. Thus, it becomes imperative to integrate energy generation from diverse renewable sources, such as wind, solar energy, and heat pumps, to balance demand and ensure stability in supporting NZEBs.

Specific considerations were absent in the model, such as probabilistic concepts to address uncertainty and factors like future population changes and waste production per capita. These variables could significantly alter the available feedstock, system costs, and required size.

Future research should incorporate these aspects and assess potential reservations and their impact.

The study possesses limitations that warrant consideration when interpreting the results. Firstly, it focused on three types of waste, limiting the generalizability of the results to other waste types. Secondly, it omitted crucial factors like social and political considerations, which could influence the practical feasibility of waste-to-energy technologies.

8.3 Conclusions

Decarbonizing the building sector is paramount in the fight against climate change. NZEBs present a promising solution, aiming to reduce energy consumption and elevate the use of renewable energy. The journey to achieve net-zero energy status involves enhancements in energy efficiency, widespread adoption of renewable energy, and a careful balance of technical, financial, and environmental considerations.

This project delves into the pivotal role of waste-to-energy in advancing NZEBs and addressing the decarbonization challenge. It scrutinizes cost-benefit analyses and LCA of waste-to-energy, shaping the trajectory for future priorities. The evaluation of waste-to-energy processes encompasses economic performance, environmental impacts, and the legislative and policy landscape, contributing to a holistic understanding of decarbonization strategies for achieving net-zero futures.

A universal decision-making tool for optimal NZEB design and operation is imperative. The noteworthy emission reductions underscore the indispensable role of renewable energy in meeting global climate commitments, serving as a beacon for others. Sensitivity analysis sheds light on the significance of accurate data and potential areas for enhancement. This comprehensive techno-economic feasibility study provides invaluable insights for sustainable and carbon-neutral futures. By elucidating the intricate balance of technology, cost, and emissions, it serves as a roadmap toward ambitious renewable energy goals, resilience, and broader sustainability efforts, inspiring communities worldwide, not just in Glasgow.

The drive to enhance the utilization of bioenergy emerges as a key player in Scotland's transition to Net-Zero energy. Waste-to-energy appears vital to reducing reliance on fossil fuels, offering advantages such as independence from specific weather conditions and adaptability to diverse geographical locations. Moreover, this approach repurposes feedstocks that would otherwise be landfilled or discarded, fostering a circular economy, diminishing overall waste, and augmenting the energy supply.

Waste-to-energy systems hold the potential to provide energy security to remote or isolated locations, aligning with Scotland's landscape. These localized initiatives are pivotal in creating an innovative, decentralized energy market. The UK stands to benefit from ongoing innovations in waste-to-energy, presenting an opportune moment to showcase leadership at the UN Climate Change Conference (COP26) in Glasgow.

The acquired results serve as a guiding framework for researchers and municipal planners, directing attention to economically viable technological alternatives for sustainable waste management in Glasgow. A comprehensive roadmap is imperative for transitioning from current practices toward a promising and sustainable model.

Integrating multi-objective optimization into waste management systems through mathematical programming provides decision-makers with valuable insights that extend beyond the limitations of merely identifying the least-cost solution. This approach introduces a crucial environmental perspective by incorporating GHG emissions as an objective function, ensuring a more comprehensive evaluation that balances economic considerations with environmental impact. The calculations were compared with traditional approaches based on the most recent parameter values. Applied in Glasgow, the principal urban region in Scotland, this model sets the stage for future research exploring different scenarios and considering multiple objective functions, strengthening the analysis results.

The outcomes of multi-objective optimization shed light on optimal solutions for designed waste-to-energy technologies. The study emphasizes the significant impact of decision parameters on total project cost and GHG emissions, highlighting the importance of demonstrating the achievability of waste-to-energy technology optimization, even in the face of elevated total costs, capital investments, and operational challenges in waste management systems.

This work filled the gaps in knowledge by concentrating on the paradigm of distributed bioenergy generation supporting the development of NZEBs. Aligned with the UK's energy policy promoting renewable energy use, energy savings, enhanced energy efficiency, and decentralized energy generation for building consumption, the outcomes offer crucial insights for policymakers in advancing NZEBs. The acceleration of biofuel deployment is pivotal for decarbonizing the global building sector, and this project served as a feasibility study for the future trajectory of NZEBs, providing valuable data for the design of pilot-scale NZEBs. Notably, integrating CBA and LCA into the MCA model enhanced the value of this work, offering a comprehensive guide for the design of bioenergy-based NZEB development. This work adds value to existing works.

8.4 Suggestions for Future Work

This study is a foundational exploration into the environmental and economic dimensions of waste-to-energy waste management and energy production in Glasgow. While serving as a pivotal starting point, there exist avenues for future research and expansion, primarily falling into two main categories: economic studies and environmental work, with a specific emphasis on technological innovation and methodological approaches.

Economic Studies:

System Boundaries and Integration: Expand the waste-to-energy system by incorporating more significant system boundaries, including waste-to-energy facilities and potential integrated systems. Considering energy demand from these facilities can impact the system's overall cost and greenhouse gas emissions. Exploring variations in renewable energy technologies around Glasgow could yield valuable insights.

Market Analysis: Conduct a CBA of other products derived from waste-to-energy systems, such as biochar. Accompany this with a market analysis to identify demand or interest in these products, potentially leading to further processes for converting them into valuable commodities. This approach aims to reduce overall costs and minimize waste sent for disposal.

Environmental Studies:

LCA Expansion: Expand the LCA to include additional impact factors like water use and land use to gain a more comprehensive understanding of the environmental impact of a waste-to-energy facility.

Upscaling Considerations: Explore the upscaling of waste-to-energy facilities to assess larger volumes of waste, potentially extending the analysis to cover a larger city. Conduct a geographical analysis to identify optimal sites for waste-to-energy facilities, considering environmental factors like land use and water use.

Technological Advancements and Innovations:

Future Predictions: Given the rapid advancements and innovations in waste-to-energy technologies, conduct predictions on the possible direction of these technologies to enhance the study's longevity.

Economic Predictions: Work on economic predictions for future costs, including the changing value of waste as a feedstock, waste production per capita, and population size. Explore the implications of these changes on waste-to-energy implementation and assess their importance.

Social Implications:

Community Impact Study: Conduct a social study on the implications of waste-to-energy on the local population. Explore the benefits of a decentralized waste management system that produces energy locally for zero-carbon transport. Assess community sentiments and the impact of residing near a waste-to-energy facility, considering emissions related to transport, materials, the workforce, and operational processes.

These proposed extensions and innovations will contribute to a more comprehensive and forward-looking understanding of waste-to-energy systems, aligning with economic and environmental sustainability goals.

Chapter 9 – Achievements and References

9.1 Student's Researcher Development Log

This log encapsulates the preparatory work, activities, and familiarization with relevant aspects of my Ph.D. program throughout my academic journey. Regular bi-monthly meetings with my supervisor have been a cornerstone of this process, emphasizing the holistic nature of research encompassing not only laboratory or fieldwork but also broader engagement, skill development, and interdisciplinary networking.

In maximizing my PhD experience, I actively participated in multi-skills training activities, diverse courses, and an internship, capitalizing on the training opportunities provided. Concurrently, my role as a Teaching Assistant at the University of Glasgow from 2019 to 2023, in capacities such as Tutor, Demonstrator, and Marker, allowed me to contribute to and enhance various engineering courses. These experiences are invaluable assets that I anticipate will significantly benefit my academic pursuits and future career.

Engaging in training activities has proven to be a fantastic avenue for broadening my PhD experience. Beyond enhancing skills beyond my research project's scope, these activities have afforded me corporate exposure and opportunities for collaborative teamwork, mitigating the potential isolation often associated with PhD research. Additionally, I actively contributed to the peer-review process for manuscripts submitted to Elsevier, particularly for the 'Circular Bioeconomy: Integrated Sustainable Technologies for the Production of Biofuels and Chemicals.' Furthermore, I have a record of authoring and co-authoring publications.

These achievements signify a period of dedicated research and underscore the importance of broader engagement, skill development, and interdisciplinary collaboration. Multi-skills training activities have proven to be a catalyst for generating fresh ideas, renewing relationships, and energizing me for the exciting research challenges ahead. The publications are detailed below:

No.	Title	Details	Status
1	Li, Y., Ahmed, A., Watson, I., & You, S. (2020). Waste-to-biofuel and carbon footprints. In Waste Biorefinery (pp. 579-597). Elsevier.	Book chapter	Published
2	https://www.aiche.org/sites/default/files/files/docs/conferences/swmc_2020_pb.pdf	Conference presentation	Published
3	Ahmed, A., Sutrisno, S. W., & You, S. (2020). A two-stage multi-criteria analysis method for planning renewable energy use and carbon saving. Energy, 199, 117475.	Research paper	Published
4	Fang, Y., Li, Y., Ahmed, A., & You, S. (2021). Development, economics and global warming potential of lignocellulose biorefinery. Biomass, Biofuels, Biochemicals, 1-13.	Book chapter	Published
5	Ahmed, Asam, et al. (2022). Assessment of the renewable energy generation towards net-zero energy buildings: A review. Energy and Buildings 256 :111755.	Review paper	Published
6	Ahmed, A., Li, W., Varjani, S., & You, S. (2022). Waste-to-energy technologies for sustainability: Life-cycle assessment and economic analysis. In Biomass, Biofuels, Biochemicals (pp. 599-612). Elsevier.	Book chapter	Published
7	Waste-to-energy technologies to support net-zero energy buildings: a multicriteria decision analysis	Research paper	Under preparation
8	Techno-economic feasibility of waste-to-energy technologies-based net-zero energy buildings	Research paper	Under review
9	Waste-to-energy technologies to support net-zero energy buildings in Glasgow: life cycle assessment perspective	Research paper	Under review
10	Waste-to-energy: the optimal solution to tackle the quadruple crisis (waste pile- up, climate change, energy demand increase, and environmental sustainability crises)	Conference presentation and poster	Published

	https://www.supergen-bioenergy.net/news/future-game-changers-at-the-british-renewable-energy-awards-2023/		

My project has been shortlisted for the 'Future Game Changers' Award at the 18th British Renewable Energy Awards 2023, hosted by the Association for Renewable Energy and Clean Technology (REA) at the Grosvenor Hotel in London on June 23. The award recognizes postgraduate students with innovative ideas contributing to achieving net zero in renewable energy and technology.

Additionally, I participated in the 2021 Chemistry for Climate Action Challenge. My proposal has reached the semi-finals of the Elsevier Foundation Chemistry for Climate Action Challenge, a prestigious competition that attracted entries from postgraduate students across the UK.

Selected as one of the five finalists, this honour acknowledges my project's contribution to addressing challenges in renewable energy and sustainable and environmentally friendly solutions.

As a finalist, I participated in various activities, including presenting my project to esteemed judges and engaging in discussions with like-minded individuals. The event provided valuable networking opportunities, connecting me with industry leaders, researchers, and innovators actively shaping the future of renewable energy and sustainable solutions. Attending was to learn from exceptional researchers and industry leaders, gain insights, and foster potential collaborations in advancing renewable energy technologies and environmentally friendly solutions.

A PhD requires academic ability, resourcefulness, commitment, and resilience. I have completed my studies despite facing numerous challenges during these trying times.

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