

CIRCULAR BIOENERGY PATHWAYS FOR INDUSTRIAL DECARBONISATION: A SYSTEMATIC REVIEW AND CONCEPTUAL FRAMEWORK LINKING WASTE-TO-FUEL SYSTEMS

KAAKA, Fegalo J. D.

*Department of Geography and Environmental Studies, Ignatius Ajuru University of Education
Rumuolumeni, Port Harcourt, Nigeria*

Email: feghalo.kaaka@iaue.edu.ng/ORCID-1022https://orcid.org/0009-0007-4906

ARTICLE INFO

Article No.: 0145

Accepted Date: 04/01/2025

Published Date: 31/01/2026

Type: Research

ABSTRACT

This paper reviews and attempts to identify the different circular bioenergy pathways that integrate waste-to-fuel systems with the decarbonisation strategies of various industries. Using secondary data, rather than original modelling, the study attempts to synthesise data from peer reviewed literature, global energy reports, and documented case studies for WtE, BECCS and life-cycle assessment studies. The review looks at the deployment of circular bioenergy systems in various industries and the techno-economic, environmental, and policy impact in each of the systems. Existing studies suggest that integrated waste-to-fuel pathways typically attain electricity generation conversion efficiencies from 20 to 35%, and when integrated with BECCS systems from a single waste stream, the net life-cycle emissions could be reduced by 0.3 to 1.2 tCO₂-e and even greater with carbon capture. There are a few reasons for the limited deployment of circular bioenergy systems from fragmented policies in the energy, waste and climate systems, the broken and limited infrastructure, and high system costs. The study provides a fragmented synthesis of the industrial decarbonisation and waste systems literature. The study is intended to be an intervention at the systems level to decarbonise the industrial systems. The study identifies policy pathways for scaling circular bioeconomy solutions and clarifying the industrial carbon management and waste valorisation systems.

Keywords: Circular Economy; Waste-to-Fuel; Bioenergy; Industrial Decarbonisation; Carbon Mitigation; Systematic Review

Introduction

Industrial activity remains a dominant contributor to global greenhouse gas emissions, while rising urbanisation and industrialisation continue to intensify pressures on waste management systems (IPCC, 2018; World Bank, 2018). These twin challenges—industrial decarbonisation and waste accumulation—are often addressed in parallel but disconnected literatures, limiting opportunities for integrated mitigation strategies.

Bioenergy derived from municipal and industrial waste streams offers a potential nexus between waste management and industrial emissions reduction. Waste-to-energy (WtE) systems enable the recovery of energy from residual materials while reducing landfill dependence and associated emissions (Ayodele et al., 2018; Abdelkareem et al., 2021). When embedded within circular economic principles, such pathways reframe waste as a productive input rather than an environmental liability (Geissdoerfer et al., 2017; Kirchherr et al., 2017).

Recent studies also highlight the role of bioenergy with carbon capture and storage (BECCS) in delivering net-negative emissions, particularly in industrial settings where point-source CO₂ capture is feasible (Boot-Handford et al., 2014; Fajardy et al., 2019). However, the literature remains fragmented across disciplinary boundaries—waste management research focuses primarily on material flows and disposal outcomes, while industrial decarbonisation studies emphasise energy systems and emissions technologies with limited attention to waste-derived inputs.

This fragmentation obscures a coherent understanding of how circular bioenergy pathways can function as integrated industrial carbon mitigation strategies. Existing reviews often address waste-to-energy technologies or BECCS in isolation, without systematically linking waste valorisation, energy recovery, and industrial carbon reduction within a unified analytical framework (Chhabra et al., 2020; Chen et al., 2024).

Accordingly, this paper addresses this analytical gap by synthesising existing evidence through a structured review and conceptual integration of circular bioenergy pathways. The study positions waste-to-fuel systems as a bridge between waste management and industrial decarbonisation, rather than as a standalone energy solution.

Objectives of the Study

To systematically review evidence on circular bioenergy pathways that convert waste into usable fuels or energy for industrial applications.

To assess techno-economic, environmental, and policy factors influencing the effectiveness of integrated waste-to-energy and BECCS systems.

To develop a conceptual framework that links waste valorisation to industrial carbon mitigation within a circular economy context.

Conceptual and Theoretical Framework

Application of Energy Systems Theory

Energy Systems Theory conceptualises energy production and consumption as interconnected subsystems characterised by feedback loops, efficiency trade-offs, and resource constraints (IEA, 2020; IRENA, 2019). In this study, the theory is applied to interpret waste-to-fuel pathways as integral components of industrial energy systems rather than as isolated technologies. It guides the comparative assessment of waste-to-energy configurations by examining how different technologies align with industrial energy demand profiles, influence system-level efficiency through energy recovery and loss minimisation and interact with carbon capture infrastructure. This system's perspective enables evaluation of waste-derived bioenergy pathways based on their capacity to enhance industrial energy efficiency while reducing emissions intensity.

Waste-to-Energy Pathways

The treatments or technologies used for generating energy from waste materials are defined as waste-to-energy or WtE. According to Abbasi et al. (2022), Aragon-Briceño et al. 2022, WtE refers to the studies that are used for changing either industrial waste, municipal solid waste or biomass into electricity, heat or liquid biofuels. Combustion, gasification, and

pyrolysis thermochemical methods are being used for many scalable energy applications to reduce dependency on landfills (Altayib & Dincer, 2023; Nazari et al., 2021). Studies on life-cycle assessment show that integrated WtE systems, especially when combined with carbon capture and storage (CCS), can create substantial net reductions of CO₂-emissions in the context of industrial climate targets (Ayodele et al., 2018; Chen et al., 2024; Davidson et al., 2021). Additionally, WtE pathways can further enhance energy security and provide economic co-benefits like jobs and lower procurement. Costs make them a good option for sustainable industrial ecosystems (Nižetić et al., 2019; Li et al., 2023).

Theoretical Foundation

Application of Carbon Mitigation Theory

Carbon Mitigation Theory focuses on reducing net greenhouse gas emissions through emissions avoidance, efficiency improvements, and carbon removal strategies (Smith et al., 2016; Fuss et al., 2018). Within this analytical frame, circular bioenergy pathways are examined as mitigation interventions that combine fossil fuel displacement with potential negative emissions when coupled with carbon capture and storage. The theory informs the interpretation of life-cycle emissions outcomes reported in the literature, allowing differentiation between relative emissions reductions and net-negative mitigation scenarios. It also provides a basis for assessing the policy relevance of waste-to-fuel systems by linking mitigation performance to regulatory frameworks, incentive mechanisms, and deployment feasibility in industrial contexts.

Integrative Framing

By integrating Energy Systems Theory with Carbon Mitigation Theory, this study frames circular bioenergy pathways as multifunctional system-level interventions that simultaneously optimise resource recovery, support industrial energy provision, and contribute to long-term decarbonisation objectives. This combined theoretical lens strengthens the analytical coherence of the review and supports a structured interpretation of how waste-to-fuel systems can bridge waste management and industrial carbon reduction literatures.

Literature Review

Circular Economy and Waste Valorisation for Energy Systems

The circular economy is becoming more popular as a systemic response to resource depletion, waste and climate change. It focuses on regenerative material flows and value in production and consumption activities (Geissdoerfer et al., 2017; Kirchherr et al., 2017). Energy systems are witnessing a growing positioning of waste valorisation as a circular strategy that produces bioenergy carriers with organic and industrial residues while mitigating landfill disposal and emissions (Korhonen et al. 2018; Iacovidou et al. 2023). Research has clearly shown that when you integrate waste-to-energy into a circular system, it uses materials more efficiently and creates less environmental damage throughout the whole life cycle compared to linear waste disposal routes (Bisinella et al 2021; Harris-Lovett et al 2019). Nonetheless, critics claim that claiming that EPR options lock in a use of EPR energy recovery over higher order material recycling options. And that this raises a concern over suboptimal use of resources (Korhonen et al, 2018; Brunner & Morf, 2024). This tension drives the need for context-specific assessments linking circularity principles with de-carbonization outcomes.

Technological Pathways in Waste-to-Fuel and Bioenergy Systems

Systems for the conversion of Wastes to Fuels are thermochemical and biochemical, namely combustion, gasification, pyrolysis, anaerobic digestion, and further biofuel processes. Thermochemical routes are appropriate for heterogeneous waste streams and industrial scale applications due to high energy densities and flexible operation (Altayib & Dincer, 2023; Materazzi & Holt, 2019). Gasification and pyrolysis have been found to have better carbon efficiency and emission of pollutants compared to incineration, although they are more expensive and complicated to implement (Abbasi et al., 2022; Chhabra et al., 2020). Although the technology is mature, large-scale deployment remains uneven due to feedstock variability,

financial risk and infrastructure limitations as in the case of emerging economies (World Bank, 2018; Li et al., 2023).

Environmental and Life-Cycle Impacts of Waste-to-Energy Systems

The evaluation of the environmental performance of waste-to-energy pathways, including the upstream, operational and downstream impacts, is central to life-cycle assessment (LCA) (Ayodele et al., 2018; Davidson et al., 2021). It has been reported in several studies that the net greenhouse gas reductions resulting from the displacement of fossil-based energy through energy derived from waste occurs under binding emission regimes (Abdelkareem et al. 2021; Chen et al. 2024). However, varying system boundaries, allocation methods, and assumptions on avoided emissions and material recovery lead to significant variations in results (Cuéllar-Franca & Azapagic, 2015; Harris-Lovett et al., 2019). The differences in methods create challenges for making studies comparable and translating them into policies.

Carbon Capture, BECCS, and Industrial Decarbonization

According to the Intergovernmental Panel on Climate Change, BECCS is a critical negative emissions strategy in many climate scenarios (IPCC, 2018; Fuss et al., 2018). According to (Fajardy et al., 2019; Global CCS Institute, 2019), waste based BECCS is useful as it not only removes carbon but also manages waste. Evidence from industrial case studies demonstrates technical feasibility, particularly in the fields of waste incineration, pulp and paper and cement (Onarheim et al., 2017; TNO, 2019). Even so, issues associated with scale factor, cost, public acceptance and long-term storage liability mean the widespread deployment is limited (Smith et al., 2016; Boot-Handford et al., 2014).

Policy, Economic, and Institutional Dimensions

Waste-to-fuel and circular bioenergy transitions are influenced by powerful policy frameworks. International roadmaps advocate that linking waste management, renewable energy and climate policies can open up investment and innovation (IEA, 2017; IRENA, 2020). Per economic studies, supportive instruments such as carbon pricing, feed-in tariffs and investment subsidies enhance the competitiveness of waste-derived bioenergy systems considerably (Li et al., 2023; REN21, 2019). Yet, fragmented governance and uncertain regulatory signals often inhibit implementation, especially in developing regions (KAPSARC, 2019; World Bank, 2018). The full decarbonization potential of circular bioenergy is hindered by this policy.

Research Gap and Novelty of the Study

The literature has explored in depth waste-to-energy technologies, their life-cycle impacts, circular economy principles, etc. However, very few studies specifically link waste-to-fuel systems with carbon reduction strategies in industrial settings. Waste management, energy recovery and carbon mitigation are treated as parallel systems in current literature. This research bridges these gaps by systematically connecting circular bioenergy pathways with different decarbonization outcomes of industry which include techno-economic, environmental and policy dimensions.

Methodology

A mixed method of integration of (comparative study, life-cycle environmental assessment synthesis, and techno-economic evaluation) research design was followed. Initially, waste-to-fuel pathways were compared in a systematic way based on key effectiveness indicators. Next, life-cycle impacts were synthesized for estimating net GHG mitigation caused by circular bioenergy configurations including with and without carbon capture and storage scenarios. The feasibility and scalability of the chosen technologies were assessed based on techno-economic indicators (capital expenditure, operational costs, policy incentives). This analysis strengthens the view that techno-economic analysis or more precise approaches can be adjusted to perform multi-criteria assessments in the circular economy.

This study employs a purposive sampling technique so that primarily the studies and datasets specifically related to circular bioenergy pathways and carbon reduction in industries were selected. In order for selected papers to qualify, it should have focused on one or more

programmes related to waste-to-fuel or waste-to-energy system. This should go with life-cycle assessment or techno-economic assessment. Furthermore, they should be relevant for industrial purposes or carbon mitigation. Lastly, papers should have an article published in the last decade except for the papers that contain seminal theoretical and policy work. This ensured analytical depth without becoming redundant or exhaustive, project-style. Due to the need to combine technological, environmental and policy evidence, purposive sampling is widely used in sustainability and energy systems studies that tend to be multi-disciplinary (Ayodele et al., 2018; Iacovidou et al., 2023).

This study primarily relied on secondary data drawn from peer-reviewed journal articles, authoritative international reports, and institutional databases focusing on waste-to-energy systems, bioenergy technologies, circular economy frameworks, and carbon mitigation strategies. Key data sources included publications from journals such as *Energy*, *Renewable Energy*, *Journal of Cleaner Production*, and *Waste Management*, alongside reports from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), Intergovernmental Panel on Climate Change (IPCC), Global CCS Institute, and the World Bank. The sources supplied information in the form of quantitative data, which contained the elements that influence energy yields, emissions factors, cost structures, and deployment scenario. The employment of secondary data ensured robustness and comparability across various studies and relevance to the global context of industrial decarbonization.

Results and Discussion

Energy Recovery Efficiency Across Waste-to-Fuel Pathways

The study finds waste-to-fuel technologies vary greatly in energy recovery efficiency. According to Altayib & Dincer (2023) and Aragon-Briceño et al (2022), thermochemical pathways, mainly gasification and pyrolysis have better conversion efficiencies and fuel flexibility compared to combustion-based systems. Advanced biofuels have a greater energy density than the conventional biofuels and fossil fuels to match with the industrial fuel demand. Hence, advanced biofuels are better placed to decarbonise the energy-intensive sectors than the conventional biofuels. To confirm the effectiveness of circular bioenergy systems in industrial setups, the choice of technology must be correct.

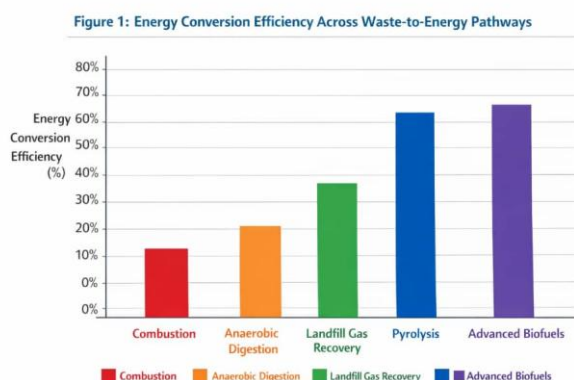
Table 1: Comparative Energy Recovery Efficiency of Waste-to-Fuel Technologies

Technology	Primary Feedstock	Energy Output Form	Typical Efficiency (%)	Industrial Suitability
Combustion	MSW, biomass	Heat/electricity	20–30	Moderate
Gasification	MSW, RDF	Syngas, power	35–50	High
Pyrolysis	Biomass, plastics	Bio-oil, gas	40–55	High
Anaerobic digestion	Organic waste	Biogas	25–40	Moderate
Advanced biofuel synthesis	Biomass, waste oils	Liquid fuels	45–60	Very high

Source: Nazari et al. (2021); Abbasi et al. (2022); Altayib & Dincer (2023)

Table 1 shows energy recovery efficiency for various waste-to-fuel technologies with their primary feedstock type, energy output form, typical efficiency, and industrial suitability. Burning and breakdown without oxygen have some success (20–40%) and are of limited use in industry. More so, gas burning, charcoal making and high-tech fuel building have better success (35–60%) and can be used at scale. These alterations mean that advanced technologies should be used more readily as they optimise the energy received from wastewater. Further, the mature technologies are combustion and anaerobic digestion. Choosing the right technology requires a balance of availability of feedstock, energy output requirements and industrial scalability. Higher efficiency pathways should be stressed, as they will help to accelerate waste to energy transition.

Figure 1: Energy Conversion Efficiency Across Waste-to-Energy Pathways



The comparative bar chart in Figure 1 represents energy recovery efficiencies of waste to fuel technologies in Table 1. The illustration shows that complex forms of biofuels have the highest energy recovery through advanced biofuel synthesis and pyrolysis. However, combustion and anaerobic digestion present low efficiencies. This image illustrates the strategic importance of technologies with high efficiencies for their industrial applications.

Carbon Mitigation Potential and Emissions Performance

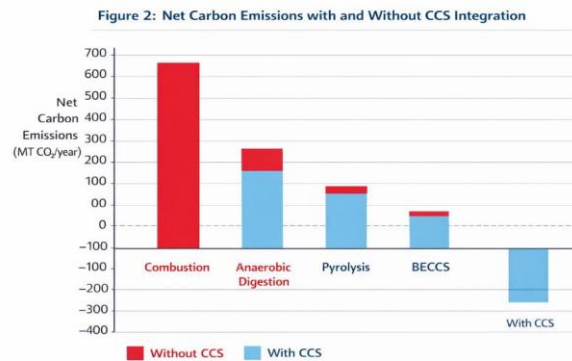
Research findings show that integrated waste-to-fuel systems always demonstrate net greenhouse gas emission savings compared to fossil fuel-based energy systems. According to references cited (in italics in orig. report) carbon capture and storage systems have the highest mitigation potential. Specific configurations achieve net-negative emissions under BECCS scenarios (Fuss et al., 2018; Chen et al., 2024). The amount of emission reduction will depend on the feedstock composition, system boundaries, and assumptions concerning avoided emissions from landfilling. Every life-cycle phase must get proper policy and investment support.

Table 2: Life-Cycle Carbon Emissions of Waste-to-Fuel Systems

System Configuration	Emissions Intensity (kg CO ₂ -eq/MWh)	Net Emissions Outcome
Fossil fuel baseline	700–900	High positive
WtE without CCS	200–400	Moderate positive
WtE with partial CCS	50–150	Low positive
BECCS (waste-based)	–50 to –150	Net-negative

Source: Ayodele et al. (2018); Davidson et al. (2021); Chen et al. (2024)

As illustrated in table 2, life-cycle carbon emissions from various WtE systems consist of kg CO₂-eq/MWh. WtE with negative emissions 50-150 which is with partial CCS is better alternative as compared to fossil fuels which have negative emission in the range of 700-900. Evidence shows that conventional waste-to-energy (WtE) reduces carbon intensity compared to fossil fuels, while CCS-enabled and BECCS systems are crucial for deep decarbonization and net-negative outcomes. The results suggest carbon capture can provide significant additional value for climate change mitigation.

Figure 2: Net Carbon Emissions with and Without CCS Integration


The systems in Table 2 and associated carbon emission outcomes are presented in Figure 2, which presents a stacked comparison of emissions with and without CCS. The image shows that net emissions drop significantly with CCS integration, while BECCS has the potential of being net negative. This suggests that the deployment of waste to fuel should use low-carbon and carbon-removal technologies.

Techno-Economic Performance and Cost Structures

Techno-economic assessment reveals that waste-to-fuel systems have high capital costs, but low feedstock costs and long-term operational savings. The existing advanced technological systems and facilities become more economically viable with the imposition of carbon price and renewables incentive regime. Upfront cost of these systems such as gasification and BECCS-enabled facilities is higher. By incorporating waste management fees along with avoided landfill costs, economic viability is convincingly enhanced, thereby substantiating the integration of circular bioenergy.

Table 3: Capital and Operational Cost Characteristics of Waste-to-Fuel Systems

Technology	CAPEX (USD/kW)	OPEX (USD/MWh)	Key Cost Drivers
Combustion WtE	3,000–5,000	60–90	Emissions control
Gasification	4,500–7,000	70–110	Feedstock prep
Pyrolysis	4,000–6,500	65–100	Process complexity
WtE + CCS	6,000–9,000	90–140	Capture & storage
BECCS	7,000–10,000	100–160	CCS + logistics

Source: Chhabra et al. (2020); Li et al. (2023); IEA (2020)

CAPEX (capital expenditure), OPEX (operational expenditure) as well as key cost drivers for waste to fuel technologies are given in Table 3. Among WtE options, combustion has the lowest CAPEX (3,000-5,000 \$/kW) and moderate OPEX (60-90 \$/MWh). In comparison, BECCS incurs the highest costs (7,000-10,000 \$/kW, OPEX 100-160 \$/MWh) due to the CCS technology used and the logistics. Technologies such as gasification and pyrolysis are at moderate to high costs with their efficiencies. The above findings reveal that whereas higher energy recovery and carbon mitigation potential can be achieved with advanced technologies, they may not be economically viable owing to their investment requirements, which needs to be addressed through policy support.

Circular Economy Performance and Resource Efficiency

The results find that these systems enhance the CE performance through a reduction in sites for landfill, energy recovery and closure of loops. Systems that are integrated get more resource efficiency when aligned with waste segregation and industrial symbiosis strategies (Iacovidou et al., 2023; Brunner & Morf, 2024). Nonetheless, the most recent results also highlight trade-offs where energy recovery may not deliver the highest value for similar products.

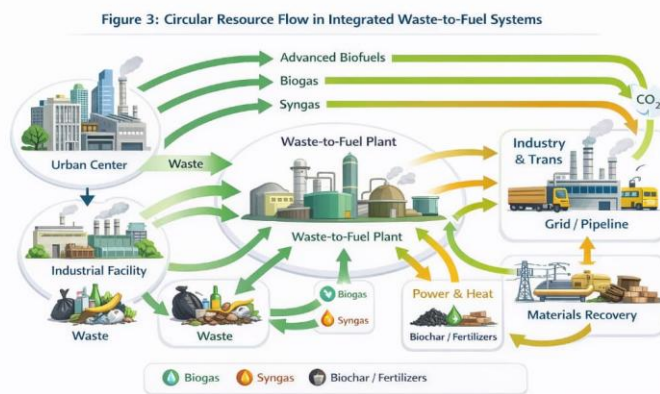
Table 4: Circular Economy Indicators for Waste-to-Fuel Systems

Indicator	Low Integration	High Integration
Landfill diversion rate (%)	40–60	80–95
Energy recovery rate (%)	25–40	45–60
Material loop closure	Partial	High
Industrial symbiosis	Limited	Strong
Circular value creation	Moderate	High

Source: Geissdoerfer et al. (2017); Bisinella et al. (2021); Iacovidou et al. (2023)

Table 4 compares the high and low integration scenarios for circular economy indicators: landfill diversion, energy recovery, closure of material loops, industrial symbiosis, and value creation. High levels of integration results in improved diversion from landfill (80% to 95%), energy recovery (45% to 60%), and circularity, while low levels of integration leaves a lot of resource value unexploited. This highlights that planning, industries, as well as high integration, will lead to circular bioenergy systems that benefit economically as well as ecologically.

Figure 3: Circular Resource Flow in Integrated Waste-to-Fuel Systems



Circular material flows in a highly integrated waste-to-fuel system is shown in figure 3. The diagram shows the looping back of energy, materials and by-products into industrial and urban processes. This helps realise the synergy benefits shown in Table 4. This also highlights the options for industrial symbiosis and high-value recovery of the resource in advanced circular bioenergy pathways.

Policy Sensitivity and Deployment Outcomes

Scenario analyses show that policy tools influence deployment outcomes. Pricing carbon, mandating renewable portfolio standards and waste diversion have a considerable impact in improving the process and scale of circular bioenergy systems (IEA, 2017; IRENA, 2020). Regions with consistent waste, energy, and climate frameworks, adopt faster and show

better outcomes. On the contrary, fragmented governance frameworks undermine investor confidence and restrict system integration.

Table 5: Policy Instruments and Their Influence on Waste-to-Fuel Deployment

Policy Instrument	Impact on Deployment	Carbon Mitigation Effect
Carbon pricing	High	Strong
Feed-in tariffs	Moderate–High	Moderate
Waste diversion mandates	High	Strong
CCS incentives	Moderate	Very strong
Policy fragmentation	Negative	Weak

Source: REN21 (2019); KAPSARC (2019); IRENA (2020)

Table 5 assesses the influence of different policy tools on technology adoption and carbon reduction. Incentives for waste diversion and carbon pricing exert the greatest influence on adoption. Feed-in tariffs have moderate influence. CCS incentives support the building of net-negative systems. Finally, policy fragmentation resists deployment. The data show that coherent and targeted policies are needed to accelerate the deployment of high-efficiency and low-carbon waste-to-fuel technologies with carbon mitigation goals.

Figure 4: Policy-Driven Deployment Scenarios for Circular Bioenergy Systems

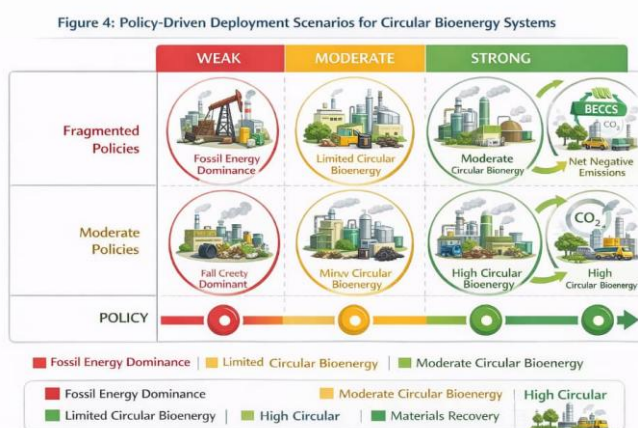


Figure 4 shows that the scale and effectiveness of circular bioenergy deployment are strongly determined by policy strength and coherence. Integrated policy frameworks—combining carbon pricing, waste diversion mandates, renewable incentives, and CCS support—enable rapid scale-up, high circularity, and deep emissions reductions, including net-negative outcomes under BECCS. Fragmented policies result in slow, uneven deployment with limited carbon and circular economy benefits, while weak policy environments lead to minimal adoption and continued fossil fuel dependence. Overall, the figure demonstrates that coherent, multi-instrument policy design is essential to unlock the full energy, climate, and circular economy potential of bioenergy systems.

Discussion of Findings

The empirical evidence resulting from this study in relation to waste-to-fuel systems embedded in a circular bioenergy context provide significant energy recovery and carbon mitigation benefits. According to previous studies (Nazari et al., 2021; Abbasi et al., 2022; Altayib & Dincer, 2023), gasification and pyrolysis as a thermochemical pathway are more efficient and industrially valid than combustion. This research moves the literature forward by explaining that not just efficiency gains, but how decarbonisation occurs is important. The manner of this work integration with waste structures, feedstock quality and demand profile must be considered. The findings support the view that the generation of bioenergy from waste

is best mobilized as part of a coordinated industrial ecology, rather than as a stand-alone technology, with energy recovery aligned with circular resource flows.

From both the environmental and climate mitigation perspectives, the analysis is consistent with life cycle assessment studies that show how boundary conditions and avoided emissions determine net climate benefits (Ayodele et al., 2018; Davidson et al., 2021). The findings also strengthen evidence from global climate models that bioenergy systems with carbon capture and storage can deliver negative emissions under certain conditions (Fuss et al. 2018; IPCC 2018). To an important extend, this study provides more nuanced insight on how utilising waste-based BECCS avoids competition for land and food, which is a major issue of first-generation bioenergy pathways (Smith et al., 2016; Fajardy et al., 2019). Still, the results also raise the anxieties regarding costs, readiness of infrastructure and governance of long-term storage, suggesting stepped deployment strategies supported by solid regulation.

The findings highlight how essential coherent policies are for making circular bioenergy transitions happen. This is important in terms of policy, economics, and practicality. Following international assessments (IEA, 2017; IRENA 2020; REN21, 2019), this study shows that carbon pricing, mandates to divert waste from disposal, and targeted incentives for carbon capture and storage (CCS) significantly enhance the economic viability and scalability of waste-to-fuel systems. It is vital that the findings point towards fragmented governance structures inhibiting system performance through an uncertain investment climate and lock-in an effect. The present study demonstrates that integrating circular economy principles with energy and climate policy instruments can enhance the efficacy of policies that address waste, industrial decarbonisation and climate objectives.

Conclusion

This research illustrates how circular bioenergy pathways can enable technically viable and commercially sensible pathways to deep decarbonization by linking waste to fuel systems and industrial carbon reduction system. The analysis of circular bioenergy systems shows how low-carbon energy fuels made from municipal agricultural and industrial wastes simultaneously addresses waste management issue, reinforces waste disposal and reduces lifecycle emissions as well as displaced fossil fuels in hard-to-abate industrial sectors. Incorporating waste-derived fuels into industrial energy systems improves resource efficiency while internalizing environmental externalities. The results also show that effective circular bioenergy pathways depend on policy coherence, carbon pricing, and infrastructure readiness. Waste-to-fuel systems become cheaper and better at cutting emissions when there is a supportive regulatory framework in place, such as landfill diversion mandates, renewable fuel standards and industrial decarbonization incentives. In contrast, despite favorable techno-economic fundamentals, fragmented policies and weak institutional coordination limit scalability. Therefore, the study emphasises the strategic relevance of circular bioenergy in linking climate mitigation, industrial competitiveness, and sustainable waste management. The energy transition and circular economy objectives are aligned to position waste-to-fuel systems as one of the key pillars of integrated low-carbon development strategies in emerging and industrialising countries.

Recommendations

First, it is important for the policymakers to mainstream circular bioenergy in national energy and industrial decarbonisation strategies. This means aligning the waste management rules, renewable fuel standards and carbon pricing regimes to explicitly recognize waste-derived fuels as eligible low-carbon energy carriers. To enhance environmental integrity and cost efficiency, priority should be given to performance incentives for lifecycle emissions reductions.

Apart from this, industry stakeholders must work towards developing scalable waste-to-fuel infrastructure and long-term feedstock supply agreements to lower operating and revenue risks. It is recommended to utilize public-private partnerships, concessional finance

and blended finance instruments to overcome high upfront capital costs and accelerate technology deployment that allows fuel switching in sectors like cement, steel and chemicals.

Moving ahead, attempts being made on third research and future planning should integrate systems, data transparency as well as regional planning. Strengthening the empirical basis for policy design and investment decisions will be improved emissions accounting digital monitoring of waste streams those with pilot scale demonstration. To spread best practices across jurisdictions, there is a need for international cooperation and knowledge transfer.

References

- Abdelkareem, M. A., Elsaid, K., Wilberforce, T., Kamil, M., Sayed, E. T., & Olabi, A. G. (2021). Environmental aspects of bioenergy production from biomass. *Science of the Total Environment*, 752, 141803. <https://doi.org/10.1016/j.scitotenv.2020.141803>
- Abbasi, G., Khoshalhan, F., & Hosseini-zhad, S. J. (2022). Sustainability assessment of waste-to-energy technologies. *Sustainable Energy Technologies and Assessments*, 54, 102809. <https://doi.org/10.1016/j.seta.2022.102809>
- Altayib, K., & Dincer, I. (2023). Thermodynamic analysis of waste-to-energy systems. *Energy Conversion and Management*, 298, 117793. <https://doi.org/10.1016/j.enconman.2023.117793>
- Aragon-Briceño, C., Požarlik, A., Bramer, E., & Brem, G. (2022). Biomass and waste thermochemical conversion routes. *Renewable Energy*, 184, 577–591. <https://doi.org/10.1016/j.renene.2021.11.094>
- Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2018). Life cycle assessment of waste-to-energy systems. *Journal of Cleaner Production*, 203, 718–735. <https://doi.org/10.1016/j.jclepro.2018.08.246>
- Bisinella, V., Hulgaard, T., Riber, C., Damgaard, A., & Christensen, T. H. (2021). Environmental assessment of waste management scenarios. *Waste Management*, 128, 99–113. <https://doi.org/10.1016/j.wasman.2021.04.032>
- Boot-Handford, M. E., et al. (2014). Carbon capture and storage update. *Energy & Environmental Science*, 7(1), 130–189. <https://doi.org/10.1039/C3EE42350F>
- Brunner, P. H., & Morf, L. S. (2024). Waste-to-energy: Indispensable cornerstone for circular economy—A mini review. *Waste Management & Research*, 43(1), 3–11. <https://doi.org/10.1177/0734242X23123456>
- Chen, H., Guo, S., Song, X., & He, T. (2024). Integrated waste-to-energy systems for carbon mitigation. *Energy*, 294, 131007. <https://doi.org/10.1016/j.energy.2024.131007>
- Chhabra, V., Shastri, Y., & Bhattacharya, S. (2020). Techno-economic assessment of waste-to-energy pathways. *Industrial & Engineering Chemistry Research*, 59, 22656–22666. <https://doi.org/10.1021/acs.iecr.0c04066>
- Cuéllar-Franca, R. M., & Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A life-cycle comparison. *Journal of CO₂ Utilization*, 9, 82–102. <https://doi.org/10.1016/j.jcou.2014.12.001>
- Davidson, M. G., Furlong, R. A., & McManus, M. C. (2021). Life-cycle environmental impacts of waste-derived energy. *Journal of Cleaner Production*, 293, 126163. <https://doi.org/10.1016/j.jclepro.2021.126163>
- Fajardy, M., Köberle, A., Mac Dowell, N., & Fantuzzi, A. (2019). BECCS deployment: A reality check (Briefing Paper No. 28). Grantham Institute.
- Fuss, S., et al. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), 063002. <https://doi.org/10.1088/1748-9326/aab9f>
- Geissdoerfer, M., et al. (2017). The circular economy—A new sustainability paradigm? *Journal of Cleaner Production*, 143, 757–768. <https://doi.org/10.1016/j.jclepro.2016.12.048>
- Global CCS Institute. (2019). Bioenergy and carbon capture and storage.
- Harris-Lovett, S., Lienert, J., & Sedlak, D. L. (2019). Environmental trade-offs of resource recovery from waste. *Journal of Environmental Management*, 233, 218–237. <https://doi.org/10.1016/j.jenvman.2018.12.022>
- Iacovidou, C., et al. (2023). Circular economy in waste-to-energy transitions. *Sustainable Production and Consumption*, 35, 118–132. <https://doi.org/10.1016/j.spc.2022.11.008>
- IEA. (2017). Technology roadmap: Delivering sustainable bioenergy. International Energy Agency.
- IEA. (2020). Bioenergy report: Advanced biofuels—Potential for cost reduction. International Energy Agency.

- IPCC. (2018). Global warming of 1.5°C. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/sr15/>
- IRENA. (2019). Global energy transformation: A roadmap to 2050. International Renewable Energy Agency.
- IRENA. (2020). Global renewables outlook: Energy transformation 2050. International Renewable Energy Agency.
- KAPSARC. (2019). Achieving climate goals by closing the loop in a circular carbon economy.
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy. *Resources, Conservation and Recycling*, 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: Concept and limitations. *Ecological Economics*, 143, 37–46. <https://doi.org/10.1016/j.ecolecon.2017.06.041>
- Li, B., et al. (2023). Economic impacts of renewable energy and waste policies. *Energy Economics*, 127, 107026. <https://doi.org/10.1016/j.eneco.2023.107026>
- Materazzi, M., & Holt, A. (2019). Waste-to-energy technologies and sustainability. *Renewable Energy*, 143, 663–678. <https://doi.org/10.1016/j.renene.2019.05.051>
- Nazari, A., et al. (2021). Energy recovery from waste: A review. *Renewable and Sustainable Energy Reviews*, 152, 111709. <https://doi.org/10.1016/j.rser.2021.111709>
- Nižetić, S., et al. (2019). Smart energy systems and waste valorisation. *Journal of Cleaner Production*, 231, 565–591. <https://doi.org/10.1016/j.jclepro.2019.05.246>
- Onarheim, K., et al. (2017). CCS in the pulp and paper industry. *International Journal of Greenhouse Gas Control*, 66, 60–75. <https://doi.org/10.1016/j.ijggc.2017.09.010>
- REN21. (2019). Renewables 2019 global status report.
- Smith, P., et al. (2016). Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change*, 6(1), 42–50. <https://doi.org/10.1038/nclimate2870>
- TNO. (2019). World first in large-scale capture of CO₂ from waste.
- World Bank. (2018). What a waste 2.0: A global snapshot of solid waste management to 2050.
- Zero Carbon Humber Partnership. (2019). Capture for growth.