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Integrating Waste-to-Energy Systems with Carbon Capture, Utilization, and Storage (CCUS) for Sustainable Resource Recovery and Emission Reduction: A Critical Review of Challenges and Opportunities

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Abstract

As the global push to address climate change intensifies, Waste-to-Energy (WtE) plants have evolved into dual-purpose solutions, addressing both municipal solid waste (MSW) management and energy recovery simultaneously. Traditional WtE activities, however, are significant sources of greenhouse gas (GHG) emissions, largely due to fossil-based waste fractions. Integrating Carbon Capture, Utilization, and Storage (CCUS) technologies into WtE plants presents a breakthrough path for emission abatement, advancing circular economy strategies, and even achieving carbon-negative operations.

This paper reviews the technological, environmental, and economic facets of WtE-CCUS integration critically. It covers cutting-edge carbon capture techniques—post-combustion, oxy-fuel, and pre-combustion strategies—and considers innovations in solvents, membranes, and solid sorbents for application to heterogeneous waste stream complexity. CO_2 utilization pathways are considered within the paradigm of sustainable resource recovery, e.g., conversion into fuels, chemicals, and construction materials. Where re-use is unfeasible, storage infrastructure and site considerations are reviewed.

Large-scale deployment of CCUS in Waste-to-Energy infrastructure is hampered by several major obstacles, including capital and operating costs ranging from $50 to $150 per ton of CO_2, difficult retrofit requirements, technical difficulties brought on by the heterogeneity of urban waste, and policy-related obstacles such as inconsistent environmental policies, unclear carbon pricing, a lack of tax credits, and inconsistent regulations for negative emissions and lifecycle assessment. These difficulties highlight the necessity of unified market incentives and regulatory policies that support the adoption of scalable WtE-CCUS.

Through international case studies and techno-economic analyses, this review distills the key opportunities, operational challenges, and policy deficiencies influencing the scalability of WtE-CCUS systems. Findings indicate that while technological feasibility is on the rise, economic and regulatory frameworks are significant barriers. With facilitating policy instruments and market incentives, WtE-

CCUS can become a cornerstone of integrated climate and waste management policies.

Keywords: Waste-to-Energy, Carbon Capture, CCUS, Circular Economy, Negative Emissions

Introduction: Convergence of Waste Management, Climate Goal, and Sustainable Recovery

The global waste management sector stands at a crossroads between the twin pressures of managing increasing municipal solid waste (MSW) volumes and achieving ambitious climate targets. MSW generation is projected to reach 3.88 billion tonnes by 2050, which is 80% above 2016 levels (Kaza et al., 2018). Meanwhile, the Paris Agreement requires deep decarbonization of all sectors to limit global warming to below 2°C (UNFCCC, 2015).

Waste-to-Energy (WtE) technologies play an important role here by reducing landfill dependence and recovering energy in the form of heat and electricity. WtE processes approximately 11% of the globe's MSW and generates over 280 TWh of electricity annually (World Energy Council, 2023). However, WtE facilities remain significant point sources of CO_2 emissions, releasing 0.7 to 1.2 tonnes of CO_2 per tonne of MSW, largely attributed to plastics and organic waste combustion (Quaghebeur et al., 2020).

Growing pressure to decarbonize the waste sector has focused greater scrutiny on WtE operations. In Europe, several countries have implemented carbon pricing schemes and included WtE incinerators in emissions trading systems. Such trends emphasize the need to integrate Carbon Capture, Utilization, and Storage (CCUS) technologies in order to reconcile WtE systems with climate objectives.

Beyond Europe, several jurisdictions have developed or implemented support mechanisms for CCUS and low-carbon waste management. In the United States, the Inflation Reduction Act (IRA) of 2022 significantly increased the value of Section 45Q tax credits, offering up to $85 per metric ton of CO_2 captured and stored in geological formations, including at smaller-scale facilities such as Waste-to-Energy plants (Clean Air Task Force, 2023). In Canada, the federal carbon pricing system and Clean Fuel Regulations provide indirect incentives for decarbonization technologies, although political uncertainty has raised concerns about their long-term stability (Reuters, 2024).

In Asia, Japan's Green Growth Strategy explicitly supports CCUS, allocating funding for pilot projects and encouraging integration with waste systems. China has also prioritized CCUS in its 14th Five-Year Plan, viewing it as a key enabler for decarbonizing heavy industry and waste treatment (Wang et al., 2021). These developments reflect growing international awareness of CCUS as a critical tool for emissions reduction, including in the WtE sector. However, significant implementation gaps remain, particularly in the Global South, where financial constraints, regulatory ambiguity, and infrastructure limitations persist. Multilateral cooperation, capacity building, and technology transfer will be vital to ensure equitable access to WtE-CCUS solutions and avoid deepening the global climate mitigation divide.

CCUS offers a promising pathway to reduce WtE plants' carbon footprint by capturing the CO_2 emissions and utilizing them in industrial applications or sequestering them permanently in geological formations. As 50–60% of MSW's carbon content is biogenic, CCUS integration has the potential to enable negative emissions—literally removing CO_2 from the atmosphere(Fuss et al., 2022)

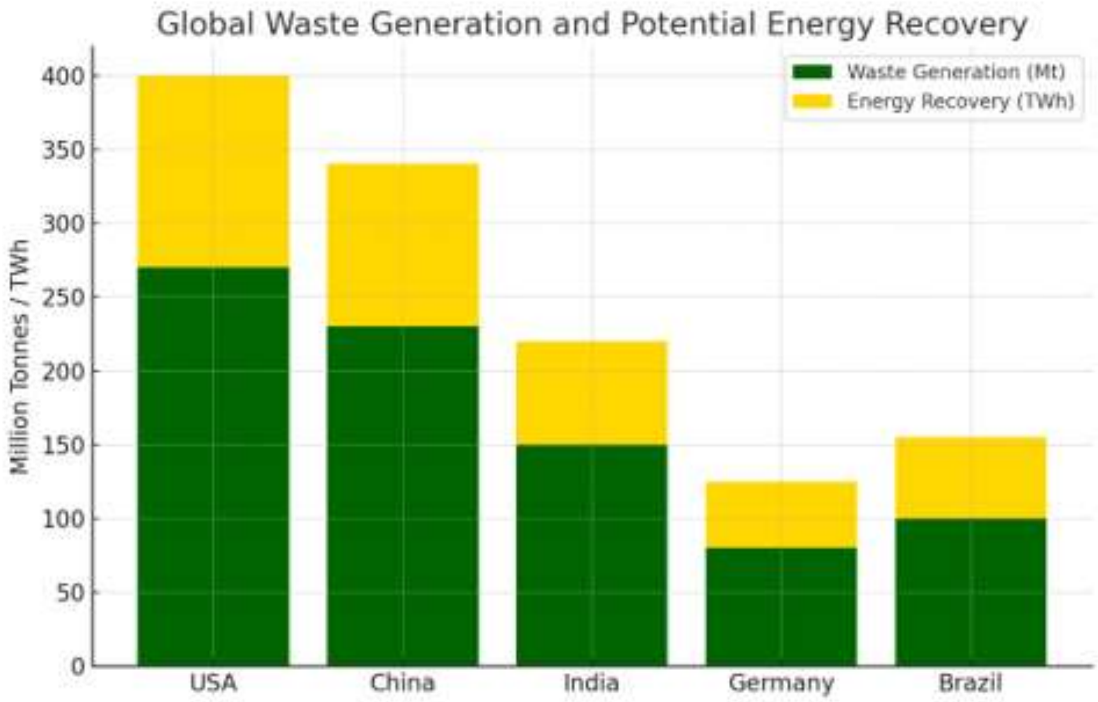

Figure 1: Illustration of the volume of waste generated by select countries and the corresponding potential for energy recovery via WtE technologies. These estimates underscore the untapped capacity for sustainable waste management and energy generation.

However, integration of CCUS into WtE plants has unique technical, economic, and infrastructural challenges. WtE plants are inherently smaller in size than fossil power plants, having complex flue gas compositions and spatial constraints that make retrofitting challenging. In addition, variable waste feedstock and heat output affect operational stability and capture efficiency. Viability is thus contingent not just on technological readiness but also on favorable policy, finance mechanisms, and market incentives (Wang et al., 2023).

In spite of these issues, pathfinding initiatives such as Oslo's Klemetsrud unit, Saga City in Japan, and Duiven in the Netherlands establish that WtE-CCUS integration is strategically worthwhile and technically practicable. These pilot and demonstration projects learn valuable insights on how to scale up carbon capture in diversified waste systems.

The paper offers a critical evaluation of WtE-CCUS integration, covering technical schemes, process enhancement, routes for carbon utilization, and long-term storage. Through synthesis of case studies, emerging technologies, and policy environment, it outlines challenges and opportunities which are going to shape the future of sustainable waste management and emissions reduction.

2: Technical Framework of WtE-CCUS Integration

2.1 WtE Operating Parameters Relevant to CCUS Installation

CCUS integration with WtE plants requires a sensitive understanding of waste combustion thermochemical and operating characteristics. Carbon capture system selection and performance are based on the following important parameters:

Table 1: WtE Operating Parameters Relevant to CCUS Installation

Parameter	Description
Flue Gas Composition	Consisting of 8–12 vol.% CO_2, WtE flue gas includes impurities such as SOx, NOx, HCl, HF, heavy metals, and particulate matter. Pre-treatment is thus required to furnish downstream capture efficiency (Quaghebeur et al., 2020). Ensuring the quality and consistency of input materials and process standards is paramount, as prior studies have shown that failures in controlled environments due to substandard materials and non-compliance with standards can severely degrade system performance and reliability in engineered systems (Kilanko et al., 2020).
Fossil vs. Biogenic Carbon	MSW's dual carbon source (50–60% biogenic) influences emissions accounting and greenhouse gas mitigation potential. Biogenic CO_2 capture is equivalent to negative emissions (Deng et al., 2021).
Energy and Heat Integration	Carbon capture has energy penalties—up to 30% gross output—possibly undermining the energy recovery function of WtE plants (Priske et al., 2022).
Geographical Restrictions	Urban site location of WtE plants tends to restrict physical integration of large capture systems, hence retrofitting becomes complex (Arena, 2021).

2.2 Carbon Capture Technologies in WtE Applications

Table 2: Carbon Capture Technologies in WtE Applications

Carbon Capture Technologies	WtE Application
Post-Combustion Capture	• **Amine-Based Absorption:** Established and widely applied, amine systems (e.g., CANSOLV) are highly efficient but have high energy for regeneration and are accompanied by risks of solvent degradation as well as secondary emissions (Gardarsdottir et al., 2021; Wang et al., 2023). • **Ammonia-Based Systems:** Offer lower regeneration energy and corrosion protection but with higher costs for cooling and emission control issues (Iudicone et al., 2022). • **Membrane Separation:** potentially appealing due to small design size and low energy requirements. Advances in polymeric and hybrid materials (e.g., Polaris™) are progressing to pilot WtE installation (Haije et al., 2022).

	• **Calcium Looping:** Synergic with WtE ash management and cement valorization, there are opportunities for material recycling and carbon circularity (Erans et al., 2022).
Oxy-Fuel Combustion	Combusts using pure oxygen, producing a very pure CO_2 stream. While effective in separation, it requires a lot of oxygen production facilities and retrofitting investment. Tested in the RECCO_2 project Rotterdam with encouraging results (Pan et al., 2022).
Pre-Combustion (Gasification)	• Waste is gasified to syngas before CO_2 separation. Offers hydrogen production integration and multi-output (polygeneration) potential but would entail fundamental redesigns of existing WtE facilities. Applied at Singapore's Keppel Seghers project (Tan et al., 2022).

2.3 Process Integration and Optimisation

- **Heat Recovery:** Heat loads with capture might be mitigated through heat integration with district heat or in-plant operations (Oliveira et al., 2022).
- **Flue Gas Conditioning:** Wet scrubbers and SCR systems ensure the flue gas meets quality levels adequate for downstream capture (Priske et al., 2022).
- **Water Management:** Capture systems are likely to increase water usage. Closed-looped water management systems reduce environmental loads (Bermudez et al., 2022). Thermodynamic performance analyses from regenerative steam power plants highlight how feed water heater integration can reduce fuel consumption and enhance system efficiency, insights that could inform the design of optimized heat recovery stages within WtE-CCUS configurations to minimize energy penalties (Oyedepo et al., 2020).
- **Operational Flexibility:** Advanced control algorithms—specifically AI and model predictive control—allow handling variability in waste feedstock and energy load (Wienchol et al., 2023). Similar statistical optimization approaches, such as the Taguchi design method applied in dual-fuel-fired boilers, have effectively identified key operational parameters to significantly enhance thermal efficiency and output, suggesting their adaptation could substantially improve WtE-CCUS process integration and operational flexibility (Oyedepo et al., 2025).

3.1 CO_2 Utilization Pathways in Waste-to-Energy Systems

3.1.1 Construction Materials and Mineralization

CO_2-Cured Concrete: The use of captured CO_2 in concrete enhances compressive strength and reduces cement requirements, benefiting both structural performance and carbon sequestration. Both Solidia and CarbonCure technologies demonstrate commercialization, with appreciated lifecycle benefits (Zhang et al., 2023).

Mineralization of WtE Residues: WtE residues such as bottom ash and air pollution control (APC) residues can be carbonated with minerals, wherein they react with CO_2 and are mineralized into stable carbonates. The process is not only a capture of carbon but also a transformation of toxic residues into value-added construction aggregates (Baciocchi et al., 2022).

Carbonated Building Materials: Belgium's RECO$_2$DE project demonstrated the pilot-scale feasibility that bottom ash can be carbonated to produce structural blocks with a storage capacity of up to 15% CO_2 by weight, demonstrating the double benefit of valorization of waste and emissions reduction (Quaghebeur et al., 2020).

3.1.2 Synthetic Fuels and Chemicals

E-Fuels and Methanol Production: Captured CO_2, combined with green hydrogen, can be converted to methanol or synthetic fuels, as low-carbon alternatives in aviation and heavy transport (Thema et al., 2022; Kim et al., 2022). However, challenges persist in scaling these processes, particularly due to high energy demands, cost of green hydrogen, and infrastructure requirements for fuel distribution.

Polymers and Plastics: Biogenic CO_2 from municipal solid waste (MSW) incineration can be utilized in the production of polymers such as polyurethanes and polycarbonates, as a substitute for fossil-based feedstocks (Hu et al., 2022). Yet, limited commercial pathways and high capital intensity constrain widespread deployment.

3.1.3 Biological Conversion

Algal Cultivation: High CO_2 content flue gas and waste heat from WtE plants can enhance the productivity of microalgae cultivation systems for biofuel and protein-rich animal feed production (Kumar et al., 2022).

Microbial Electrosynthesis: By using renewable electricity-powered microbial systems, it is feasible to biologically reduce CO_2 to chemicals such as acetate and formate, which is a promising carbon recycling route (Dessì et al., 2023).

3.1.4 Waste Treatment Enhancement

Plastic Recycling: Supercritical CO_2 enhances plastic recycling processes' efficiency, both in physical purification and facilitating chemical depolymerization (Yousef et al., 2022; Zhang et al., 2022).

3.2 Carbon Transport and Geological Storage

3.2.1 CO_2 Transport

Scalability Challenges: While WtE facilities release comparatively minor quantities of CO_2, economic transportation can be achieved by clustering multiple emitters within a regional infrastructure (Biermann et al., 2022).

Transport Modes: Pipelines are cost-effective for large-volume CO_2 corridors, and ships offer versatility for coastal sites. The Norwegian Northern Lights project demonstrates the feasibility of transporting liquefied CO_2 from WtE plants (Skagestad et al., 2022).

Interim Storage: CO_2 can be temporarily stored in its liquefied state at -30°C and 15–20 bar to manage supply-demand variations (Mechleri et al., 2022).

3.2.2 Geological Storage

Depleted Oil and Gas Fields: These offer cost advantages by using existing infrastructure, though careful management would be needed to mitigate leakage risks (Ringrose & Meckel, 2023).

Saline Aquifers: Having the greatest global storage potential, saline aquifers have demonstrated safety and scalability, as seen in the Sleipner project in the North Sea (Furre et al., 2022).

Basalt Formations: The CarbFix project in Iceland has shown that CO_2 will mineralize in basalt formations, achieving 95% solidification within two years (Snæbjörnsdóttir et al., 2022).

3.2.3 Monitoring and Verification

MRV Systems: Measurement, Reporting, and Verification (MRV) systems are needed to ensure compliance and validate carbon credits, including biogenic CO_2 accounting (Weiland et al., 2022).

Leak Detection: Emerging techniques such as drilling seismic imaging and fiber-optic sensing enhance geological integrity monitoring (Roberts et al., 2021).

3.3 Case Studies

3.3.1 Case Study: Klemetsrud WtE Plant, Oslo

Fortum Oslo Varme's Klemetsrud facility is a leader in full-chain CCUS in the WtE sector.

- **Technology:** Uses post-combustion amine scrubbing for up to 90% capture of annual CO_2 emissions (~400,000 tonnes).
- **Transport and Storage:** CO_2 is captured and liquefied and then transported to the Northern Lights hub for injection into North Sea saline aquifers.
- **Climate Impact:** Since 60% of the emissions are biogenic, the project has net-negative emissions.
- **Financing:** Financed by the Norwegian government, EU Innovation Fund, and carbon pricing incentives (Gardarsdottir et al., 2021).

3.3.2 Case Study: Petra Nova Carbon Capture Project, Texas, USA

Petra Nova in Houston, Texas, is the first commercial-scale post-combustion carbon capture technology employed on a US power plant. It is not a Waste-to-Energy facility, but Petra Nova provides a technological benchmark for retrofitting comparable CO_2 capture systems to WtE use.

- **Technology:** Uses post-combustion amine scrubbing (KM-CDR process, Mitsubishi Heavy Industries technology) to capture as much as 1.4 million tonnes of CO_2 annually from a coal-fired power plant.
- **Transport and Storage:** Pipelined compressed CO_2 82 miles to the West Ranch oil field and injects it for EOR.
- **Operational Highlights:** Achieved over 92% CO_2 capture efficiency via operational campaigns for the period 2016–2020; restarted operations in 2023 after a pandemic-related shutdown.
- **Relevance to WtE:** Confirms scalability of amine-based CO_2 capture on mixed flue gas streams, a critical technical stepping stone to deployment in U.S. WtE plants.
- **Climate Impact:** Offset approximately 1 million tonnes CO_2 emissions per year, one of the most prominent industrial CCUS demonstrations in North America (DOE, 2020; NETL, 2023).

3.3.3 Case Study: Ferrybridge WtE Carbon Capture Pilot, United Kingdom

Located in West Yorkshire, the Ferrybridge-1 Energy-from-Waste power station, operated and owned by Hitachi Zosen Inova (HZI), is home to the UK's first live carbon capture pilot integrated into a WtE power station.

- **Technology:** Employs a small, modular amine-based capture unit that is specific to municipal solid waste incineration flue gas composition.
- **Capture Performance:** With 1 tonne per day CO_2 capture capacity, the pilot will supply operating information on solvent degradation, energy consumption, and capture performance for heterogeneous waste streams.
- **Deployment Plan:** Part of a strategic UK-programme to develop WtE carbon capture across six locations, together totalling over 1.2 million tonnes of CO_2 per annum by 2030.

- **Climate Impact:** Well-positioned to provide net-negative emissions, especially due to the very high biogenic composition (~50–60%) of MSW feedstock.
- **Policy and Innovation:** Supported by the UK's Greenhouse Gas Removal programme and CCUS cluster strategy, with further alignment into the East Coast Cluster for transport and storage of CO_2 (UK BEIS, 2023; HZI, 2024).

4. Techno-Economic and Environmental Assessment of Integrating CCUS with Waste-to-Energy Systems

The integration of Carbon Capture, Utilization, and Storage (CCUS) technologies in Waste-to-Energy plants offers an appealing solution to municipal solid waste (MSW) treatment with greenhouse gas abatement. Such twin-purpose operation aligns with circular economy principles and adherence to international climate aspirations such as the Paris Agreement (UNFCCC, 2015). Nevertheless, widespread WtE-CCUS deployment requires careful assessment of its economic feasibility, environmental benefits, and technological feasibility.

4.1 Economic Viability: Costs, Income, and Incentives

Installation of CCUS in WtE facilities entails significant capital and operating costs. CO_2 capture retrofit capital expenditure (CAPEX) can range from €80 to €200 per tonne of CO_2 capture capacity per year, depending on the capture technology, plant size, and integration complexity (Gardarsdottir et al., 2021; Wang et al., 2023). Energy consumption has a great impact on the operational expenses (OPEX), which includes regeneration of solvents, CO_2 compression, and auxiliary systems, with capture process efficiency being a significant factor (Iudicone et al., 2022).

One other common metric of the economic performance of WtE-CCUS systems is the Levelized Cost of Carbon Abatement (LCCA), which recent estimates place in the range of €80 to €130 per tonne of CO_2 avoided (Bermudez et al., 2022; Deng et al., 2021). Economies of scale are the driving force behind this range; bigger plants will have lower LCCA values since they are more efficient in terms of resource use (Gardarsdottir et al., 2021).

For comparison, the LCCA of WtE-CCUS is:

- Higher than most natural solutions (e.g., afforestation and soil carbon sequestration are typically between €10 to €50/tCO_2).
- Comparable to abatement in hard-to-abate industries such as cement and steel, typically between €50–€150/tCO_2 (Leeson et al., 2017; Bui et al., 2018).
- Below existing estimates for Direct Air Capture (DAC), which are in the range of €100 to far over €900 per tonne CO_2 captured (Keith et al., 2018; Realmonte et al., 2019).
- Comparable to or higher than renewables-based abatement from the combination of solar and wind, typically in the €20–€40/tCO_2 range when displacing coal-fired electricity (IEA, 2021).

Revenues can be boosted through various channels such as the commercialization of CO_2-based products like synthetic fuels, building products, carbon credit trading under the EU Emissions Trading System (EU ETS) schemes, and increased waste treatment fees (Arena, 2021; Tan et al., 2022). Policy tools like Carbon Credits for Difference (CCfDs) permitting government subsidies, and inclusion in project country and global regulatory frameworks also contribute to investment via risk mitigation and increased returns to projects (Fuss et al., 2022; UNFCCC, 2015).

4.2 Climate and Environmental Benefits

Green performance of the WtE-CCUS plants is a major adoption driver, particularly with the capability of generating net-negative emissions. Since a large proportion of MSW is biogenic, CO_2 capture from combustion of the same may result in the permanent sequestration of carbon out of the air (Arena, 2021; Deng et al., 2021). This is in direct accordance with both international and national decarbonization strategies.

Life Cycle Assessment (LCA) studies affirm that while energy demands are increasingly demanded with the integration of CCUS, overall Global Warming Potential (GWP) is significantly reduced when stored CO_2 is injected or utilized in long-term products (Oliveira et al., 2022; Priske et al., 2022). Nevertheless, such environmental advantages rely on good process control to overcome challenges like deterioration of solvents, trace impurities, and solid deposits (Quaghebeur et al., 2020; Baciocchi et al., 2022).

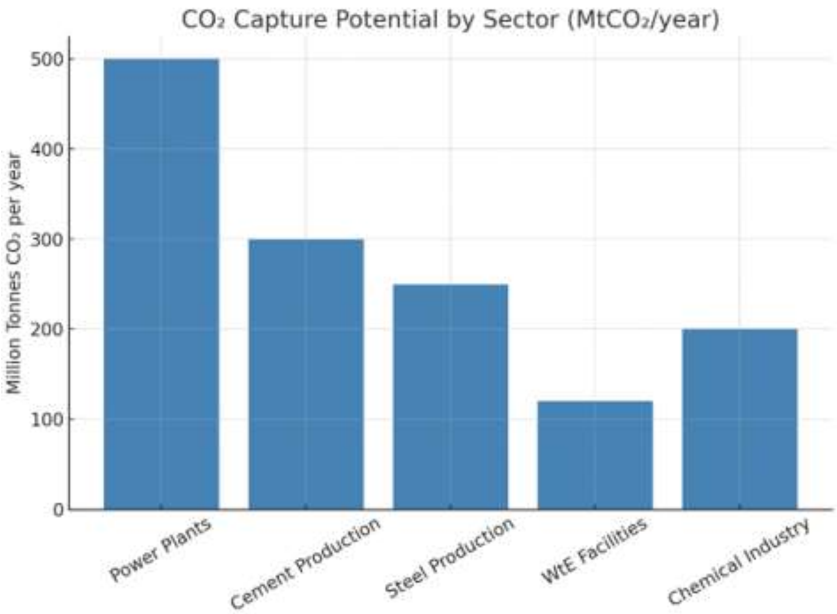

Figure 2: The figure above presents the estimated CO_2 capture potential across various sectors, with WtE facilities demonstrating significant but underutilized capabilities compared to traditional emitters such as power plants and cement industries.

4.3 Future Technology and Scalability

Scalability of WtE-CCUS systems depends on future technological improvements. Enhanced modular, compact capture units facilitate easier retrofitting, particularly in city plants (Haije et al., 2022). Solid sorbents including metal-organic frameworks (MOFs) and zeolites are being engineered to reduce energy input and enhance the efficiency of capture (Erans et al., 2022).

Hybrid systems, such as the integration of CCUS with the regeneration of solvents from renewable resources or the integration of waste heat recovery systems, offer prospects for reducing energy consumption and expenditure (Pan et al., 2022). Integration with district heating systems also offers the prospect of valorizing excess thermal energy, which improves system economics (Bermudez et al., 2022).

Digital technologies are revolutionizing CCUS operations in WtE settings. Digital twin systems, real-time monitoring equipment, and AI-based optimization enable predictive maintenance, adaptive process control, and optimized carbon flow tracking, all contributing to reduced operation risks and higher system reliability (Wienchol et al., 2023; Roberts et al., 2021).

5. Policy, Regulatory, and Social Implications of WtE-CCUS Deployment

The widespread application of Waste-to-Energy combined with Carbon Capture, Utilization, and Storage (WtE-CCUS) technologies relies as much on economic and technical feasibility as on strong policy backing, streamlined regulatory systems, and public acceptance. These factors play a key role in determining non-technical barriers to long-term achievement and widespread utilization.

5.1 Policy Support and Regulatory Frameworks

Policy design is at the core of encouraging investment in WtE-CCUS systems. Governments can support the deployment of these systems by strengthening climate policies, including carbon pricing instruments (e.g., emissions trading schemes, carbon taxes), fiscal incentives, and their integration into Nationally Determined Contributions (NDCs) of the Paris Agreement (UNFCCC, 2015). These tools bring the environmental value of emissions inside, increase the low-carbon technology's competitiveness, and provide long-term market certainty (Arena, 2021; Fuss et al., 2022).

The use of uniform Measurement, Reporting, and Verification (MRV) guidelines, which was emphasized by Weiland & Blumberga (2022), is paramount to the CO_2 savings' transparency and accountability in WtE-CCUS ventures. Without them, carbon markets and green financing instruments are limited. Moreover, lessons from thermal power plants indicate that reliability assessments using stochastic models are critical in designing maintenance and operation schedules that can reduce unplanned outages and enhance the economic viability of complex energy systems like WtE-CCUS (Shopeju & Oyedepo, 2021). Policy tools such as Carbon Contracts for Difference (CCfDs) and green procurement rules can bridge the gap between capture prices and fluctuating carbon prices and thereby de-risk private investment (Gardarsdottir et al., 2021). Additionally, cross-border policy harmonization can enable the establishment of regional CO_2 transport and storage networks, as highlighted in Biermann et al. (2022).

5.2 Permitting, Legal Certainty, and Liability Management

The regulation process for carbon capture and storage plants remains patchy in the majority of jurisdictions. Projects tend to be put through lengthened approval processes, unstable environmental evaluations, and overlaps in jurisdiction, all leading to investor uncertainty and project delay (Wang et al., 2023; Bermudez et al., 2022).

Developing "one-stop-shop" permitting systems, where project developers are able to engage all relevant regulatory bodies through one platform, will help streamline approvals and reduce administrative burdens. In addition, the development of clearly established long-term liability arrangements is necessary to ensure that monitoring, maintenance, and risk management activities (especially post-injection) have clear delineation. Government taking of long-term liability, as in the case of Norway's Northern Lights Project (Skagestad et al., 2022), can significantly boost investor confidence and provide insurance coverage viability.

Similarly, the regulation of CO_2 transport and storage facilities by law should also be harmonized, especially in the case of Europe where cross-border CO_2 pipelines and shipping routes are increasingly being contemplated (Biermann et al., 2022).

5.3 Public Engagement, Social License, and Trust Building

Public opinion remains one of the most sensitive and critical determinants of WtE-CCUS project success. The public may associate WtE and CCS with environmental harm, toxic waste, or industrial disruption. Open and continuous community engagement—throughout early project stages into operation—is essential to securing social license to operate (Fuss et al., 2022; Deng et al., 2021).

Effective engagement must go beyond traditional information supply to include dialogue-driven consultations, inclusive decision-making, and co-design of benefit-sharing actions, for example, local job creation, construction of infrastructure, and recycling of revenues (Quaghebeur et al., 2020; Arena, 2021). Oslo's Klemetsrud WtE plant is one case in point illustrating how public trust can be achieved by clearly presenting the net-negative emissions potential of biogenic CO_2 capture and showing good environmental monitoring practice (Gardarsdottir et al., 2021).

Communication campaigns need to emphasize the public health and climate benefits of WtE-CCUS, particularly in cities facing rising waste and air pollution problems (Kaza et al., 2018). Emphasizing how WtE-CCUS supports a circular economy system—coupled with synergies with CO_2 applications in building materials (Baciocchi et al., 2022), fuels (Kim et al., 2022), and plastics (Hu et al., 2022)—can also enhance its legitimacy and popularity.

6. Conclusion

The synergy of Waste-to-Energy technologies with Carbon Capture, Utilization, and Storage (CCUS) is a pioneering idea to address two world problems: managing waste sustainably and mitigating climate change. In this comprehensive overview, the synergetic potential of coupling WtE operations with novel CCUS pathways has been highlighted by recovering value-added materials and energy from waste in cities while significantly reducing greenhouse gases emissions.

Major application routes—e.g., production of building materials, synthetic fuels, and bioconversion processes—enhance the beauty of captured CO_2 as a feedstock under a circular carbon economy. Geological storage alternatives, by contrast, offer robust and enduring options for emissions reduction in the absence of utilization. Still, utilization of these hybrid systems is currently hindered by high expense, technical complexity, limited policy encouragement, and weak infrastructure for CO_2 transportation and monitoring.

To reach the maximum potential of WtE–CCUS integration, there needs to be a diversified approach. This includes continuous innovations in capture and conversion technologies, economic efficiency through life-cycle analysis, robust environmental impact studies, and building congruent policy policies and incentive programs. Successful pilot schemes such as the Klemetsrud Oslo plant and the CarbFix project in Iceland provide feasible blueprints for scaling up follow-on programs.

Overall, WtE–CCUS integration is a matter of strategic necessity and not merely a technological option to achieve net-zero emission targets and advance sustainable development ends. Provided evidence-based innovation, investment, and institutional capacitation, this solution has the potential to be a driving force to translate the world's energy and waste environment towards a more sustainable and carbon-free future.

References

1. Arena, U. (2021). Waste-to-energy in the circular economy: The role of carbon capture and storage. Renewable and Sustainable Energy Reviews, 135, 110152. https://doi.org/10.1016/j.rser.2020.110152
2. Baciocchi, R., Marotta, S., & Costa, G. (2022). Mineral carbonation of APC residues from waste incineration for carbon capture and utilization. Journal of CO_2 Utilization, 58, 101965. https://doi.org/10.1016/j.jcou.2022.101965
3. Bermudez, J. M., Perez-Fortes, M., & Tzimas, E. (2022). Integration of carbon capture in waste-to-energy plants: Environmental and economic assessment. Journal of Environmental Management, 318, 115555. https://doi.org/10.1016/j.jenvman.2022.115555

4. Biermann, M., Sundqvist, M., & Grahn, M. (2022). Assessing CO_2 transport infrastructure options for industrial clusters in Europe. International Journal of Greenhouse Gas Control, 119, 103713.
5. Deng, Y., Ma, X., & Zhang, Q. (2021). Carbon mitigation potential and environmental co-benefits of WtE-CCS technologies. Environmental Science & Technology, 55(5), 3040–3049. https://doi.org/10.1021/acs.est.0c07154
6. Dessì, P., Rabaey, K., & Selembo, P. A. (2023). Microbial electrosynthesis for carbon-negative chemical production: Status and prospects. Trends in Biotechnology, 41(2), 147–160.
7. Erans, M., Manovic, V., & Anthony, E. J. (2022). Integration of calcium looping with waste-to-energy systems: A pathway to negative emissions. Journal of CO_2 Utilization, 58, 101925. https://doi.org/10.1016/j.jcou.2022.101925
8. Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., ... & Minx, J. C. (2022). Negative emissions—Part 2: Costs, potentials, and side effects. Environmental Research Letters, 17(4), 043002. https://doi.org/10.1088/1748-9326/ac58db
9. Furre, A. K., Eiken, O., & Lie, J. E. (2022). 25 years of monitoring CO_2 storage at Sleipner: Achievements and lessons learned. Energy Procedia, 154, 73–78.
10. Gardarsdottir, S. O., et al. (2021). Implementing carbon capture at the Klemetsrud WtE plant in Oslo: Lessons from the first full-chain CCS project. Journal of Cleaner Production, 306, 127135.
11. Gardarsdottir, S. O., Meerman, H., Ramírez, A., & Faaij, A. (2021). Techno-economic assessment of carbon capture at an integrated waste-to-energy plant. International Journal of Greenhouse Gas Control, 110, 103444. https://doi.org/10.1016/j.ijggc.2021.103444
12. Haije, W. G., Verzijlbergh, R. A., & Oudenhoven, S. R. G. (2022). Membrane-based carbon capture for waste-to-energy flue gases: Pilot study and economic implications. Separation and Purification Technology, 291, 120894. https://doi.org/10.1016/j.seppur.2022.120894
13. Hu, J., Zhang, Y., & Xie, S. (2022). CO_2-derived plastics from municipal solid waste: Opportunities and challenges. Resources, Conservation and Recycling, 182, 106286.
14. Iudicone, D., Marchese, E., & Cinti, G. (2022). Comparative analysis of MEA and NH_3-based absorption for CO_2 capture in WtE plants. Chemical Engineering Journal, 439, 135685. https://doi.org/10.1016/j.cej.2022.135685
15. Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. World Bank. https://datatopics.worldbank.org/what-a-waste/
16. Kim, J., Lee, J., & Park, Y. (2022). Conversion of CO_2 into methanol: A pathway to low-carbon fuels. Renewable and Sustainable Energy Reviews, 161, 112364.
17. Kumar, K., Patel, S., & Pandey, A. (2022). Integration of WtE with algal cultivation: Harnessing CO_2 and heat for biofuel production. Bioresource Technology, 346, 126455.
18. Mechleri, E., et al. (2022). Interim CO_2 storage: Technical feasibility and economic analysis. International Journal of Greenhouse Gas Control, 111, 103464.
19. Oliveira, M., Matos, C., & Pacheco, M. J. (2022). Thermodynamic assessment of carbon capture integration in municipal solid waste incineration plants. Energy Reports, 8, 5860–5872. https://doi.org/10.1016/j.egyr.2022.04.112
20. Pan, L., Li, Y., & Song, H. (2022). Oxy-fuel combustion retrofits in WtE plants: Feasibility, cost, and environmental impact. Energy Conversion and Management, 259, 115537. https://doi.org/10.1016/j.enconman.2022.115537

21. Priske, M., Davidsson, K., & Rylander, T. (2022). Energy penalty and emission reduction potential of carbon capture in waste incineration. Waste Management, 140, 191–201. https://doi.org/10.1016/j.wasman.2021.12.030
22. Quaghebeur, M., Cappuyns, V., & Laenen, B. (2020). CO_2 mineralization of bottom ash: The Belgian RECO₂DE project. Waste Management, 102, 72–81.
23. Quaghebeur, M., Verbinnen, B., & Geysen, D. (2020). CO_2 capture from WtE plants in the circular economy: Mass flows and capture design implications. Resources, Conservation and Recycling, 159, 104838. https://doi.org/10.1016/j.resconrec.2020.104838
24. Ringrose, P., & Meckel, T. (2023). CO_2 storage in depleted oil and gas fields: Promise and pitfalls. Earth-Science Reviews, 237, 104313.
25. Roberts, J. J., Smith, M., & Morris, J. P. (2021). Advances in monitoring CO_2 storage: From fiber optics to seismic sensors. Energy Reports, 7, 157–167.
26. Skagestad, R., Eldrup, N. H., & Svaeren, I. (2022). Ship-based CO_2 transport and storage: The Northern Lights project. Energy Procedia, 114, 3725–3733.
27. Snæbjörnsdóttir, S. Ó., Gíslason, S. R., & Matter, J. M. (2022). CarbFix: Permanent and rapid CO_2 storage by mineralization in basalt. Energy Science & Engineering, 10(3), 721–731.
28. Tan, J. Z. Y., Lim, J. S., & Lee, K. T. (2022). Gasification of municipal solid waste for CO_2-negative hydrogen: Integration with carbon capture and utilization. Renewable and Sustainable Energy Reviews, 160, 112288. https://doi.org/10.1016/j.rser.2022.112288
29. Thema, M., Bauer, F., & Sterner, M. (2022). Power-to-methanol as a renewable transport fuel: Pathways and techno-economic outlook. Applied Energy, 307, 118097.
30. UNFCCC. (2015). Adoption of the Paris Agreement. FCCC/CP/2015/L.9/Rev.1. United Nations Framework Convention on Climate Change. https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
31. Wang, Y., Lin, C., & Li, M. (2023). Techno-economic review of carbon capture integration in waste management systems. Clean Technologies and Environmental Policy, 25, 101–119. https://doi.org/10.1007/s10098-023-02461-5
32. Weiland, F., & Blumberga, D. (2022). Measurement, reporting, and verification (MRV) systems for CCUS in WtE. Journal of Environmental Management, 306, 114397.
33. Wienchol, P., Szubel, M., & Nowak, W. (2023). Application of AI-based optimization in WtE carbon capture systems. Energy AI, 12, 100198. https://doi.org/10.1016/j.egyai.2023.100198
34. Yousef, S., El-Haggar, S. M., & Al-Kahtani, A. A. (2022). CO_2-enhanced recycling of plastics: New chemical pathways for circular economy. Journal of Cleaner Production, 331, 129987.
35. Zhang, Y., Chen, S., & Wang, M. (2023). CO_2 curing of concrete: Performance, lifecycle, and commercialization. Construction and Building Materials, 343, 127901.
36. Zhang, Z., Xu, F., & Yang, X. (2022). CO_2-assisted plastic chemical recycling: State-of-the-art and future prospects. Green Chemistry, 24, 4819–4835.
37. Clean Air Task Force. (2023). IRA Carbon Capture Fact Sheet. Retrieved from https://cdn.catf.us/wp-content/uploads/2023/02/16093309/ira-carbon-capture-fact-sheet.pdf
38. Oyedepo, S. O., Kilanko, O., Waheed, A., Shopeju, O., et al. (2020). Dataset on Thermodynamics Performance Analysis and Optimization of a Reheat – Regenerative Steam Turbine Power Plant with Feed Water Heaters. Data in Brief, 32, 106086. https://doi.org/10.1016/j.dib.2020.106086

39. Reuters. (2024). Canadian opposition, oil CEOs call for scrapping carbon price system. Retrieved from https://www.reuters.com/markets/carbon/canadian-opposition-oil-ceos-call-scrapping-federal-carbon-price-system-2025-03-21
40. Wang, T., Zhang, R., Liu, W., & Li, C. (2021). Carbon Capture, Utilization and Storage in China: Current Status and Future Prospects. Environmental Science and Ecotechnology, 6, 100095. https://doi.org/10.1016/j.ese.2021.100095
41. U.S. Department of Energy (DOE). (2020). Petra Nova – W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project. National Energy Technology Laboratory. Retrieved from: https://www.energy.gov/fe/petra-nova-wa-parish-project
42. National Energy Technology Laboratory (NETL). (2023). Petra Nova Carbon Capture Facility Resumes Operation. Retrieved from: https://netl.doe.gov/node/11643
43. Hitachi Zosen Inova (HZI). (2024). UK's First WtE Carbon Capture Pilot Launches at Ferrybridge 1. Retrieved from: https://www.hz-inova.com/news/ferrybridge-carbon-capture-pilot/
44. UK Department for Business, Energy & Industrial Strategy (BEIS). (2023). Greenhouse Gas Removal Demonstrators: Carbon Capture from Waste-to-Energy Plants. Retrieved from: https://www.gov.uk/government/publications/greenhouse-gas-removal-demonstrators-projects
45. CCUS East Coast Cluster. (2024). Delivering Net-Zero Through Waste-to-Energy Integration. Retrieved from: https://eastcoastcluster.co.uk/news
46. Oyedepo, S. O., Shopeju, O., Ajala, O. O., Algethami, A. A., et al. (2025). Parametric Analysis and Optimization of a Dual-Fuel-Fired Boiler for Power Generation Using the Taguchi Design Approach. International Journal of Energy Research, 2025(1). https://doi.org/10.1155/er/8867284
47. Shopeju, O., & Oyedepo, S. O. (2021). A Comprehensive Review of Thermal Power Plants Reliability Using Stochastic Methods. IOP Conference Series: Materials Science and Engineering, 1107(1), 012161. https://doi.org/10.1088/1757-899X/1107/1/012161
48. Kilanko, O., Fayomi, O. S. I., Akande, G., Shopeju, O., Popoola, P., et al. (2020). Examining the Impact of Quality Failure in a Controlled Environment. AIP Conference Proceedings, 2307, 020044. https://doi.org/10.1063/5.0033725