Journal of Green Economy and Low-Carbon Development
https://www.acadlore.com/journals/JGELCD

Decarbonizing Power Through Waste: A Global Perspective on Electricity Generation from Municipal and Industrial Refuse

Haider Mohammed Makkyia[1], Muna S. Kassim[2*], Kifah A. Alimarah[3]

[1] Civil Engineering Department, College of Engineering, University of Baghdad, 10001 Baghdad, Iraq
[2] National Investment Commission, Mechanical Engineering Department, Mustansiriyah University, 10001 Baghdad, Iraq
[3] Water and Renewable Energy, Research and Technology Centre of Environment, Scientific Research Commission, Ministry of Higher Education and Scientific Research, 10001 Baghdad, Iraq

[*] Correspondence: Muna S. Kassim (munakassim@uomustansiriyah.edu.iq)

Received: 07-15-2025 **Revised:** 09-16-2025 **Accepted:** 09-25-2025

Citation: H. M. Makkyia, M. S. Kassim, and K. F. Alimarah, "Decarbonizing power through waste: A global perspective on electricity generation from municipal and industrial refuse," *J. Green Econ. Low-Carbon Dev.*, vol. 4, no. 3, pp. 140–159, 2025. https://doi.org/10.56578/jgelcd040302.

© 2025 by the author(s). Licensee Acadlore Publishing Services Limited, Hong Kong. This article can be downloaded for free, and reused and quoted with a citation of the original published version, under the CC BY 4.0 license.

Abstract: Urbanization has caused a great burden in waste management, along with the introduction of Waste-to-Energy (WtE) technology and the development of related waste treatment and renewable energy production. This paper perceived global WtE technology in respect of decarbonization of the power industry by comparing incineration, anaerobic digestion, gasification, and pyrolysis. It highlighted the necessity to shift the conventional landfill practices to the use of WtE plants, which would reduce the landfill amounts and generate biogas, syngas, and digestate as by-products with a high level of nutrients. This article evaluated the energy value of waste materials and provided an account of the adoption of WtE energy infrastructure both in Europe and Asia-Pacific. It dealt with the problems of developing economies like population growth, lack of sufficient regulations, a high cost of capital markets and other technological issues. The carbon capture and life cycle analysis to sustain WtE, as well as its implications on the environment and employment were discussed. The paper concluded with recommendations on policies, research, and development by emphasizing the imperatives of well-established cooperation among stakeholders, technological adjustments as well as investments in innovations.

Keywords: Waste-to-Energy; Municipal solid waste; Decarbonization; Energy recovery; Sustainable waste management; Smart grid integration

1 Introduction

Waste-to-Energy (WtE) technology is a novel technology to tackle the growing global waste and environmental problems associated with urban sprawl and population increase. The technology ranges from the simplest form of incineration to complex anaerobic digestion and gasification, in order to harness the waste resources and turn them into sources of energy. WtE technology could decrease waste disposal by 90% via burning waste, providing bio-gases as a result of anaerobic digestion of waste, and utilizing digestate as a fertilizer in agriculture.

Other issues dealt with by WtE technology include societal attitudes towards the quality of air and health hazards related to implementing new technologies. With the increased popularity of renewable energy sources, WtE could not be a universal way to resolve all the issues of waste management. Rather, it ought to be incorporated in other policies such as recycling and composting to control the amount of waste.

Another motivation behind WtE applications is energy security, because the oil prices are affected by decreasing fossil fuel reserves and geopolitical brawls. The waste streams could be utilized by countries to produce energy and become independent in respect of energy and waste management. Some good examples of WtE applications can be seen in Sweden, recycling 99% of its garbage; in Germany, possessing more than 70 high-efficiency WtE plants with advanced emission control systems; and in China, the largest country in Asia, owning more than 300 plants and a WtE capacity of over 10 gigawatts by 2022.

To sum up, WtE technology is one of the promising technologies in the sphere of sustainable waste management and energy generation. The significance of WtE is exemplified in the development of newer and less emitting technologies and processes [1–4].

2 WtE Technology for Power Generation

2.1 Overview of WtE Technology

WtE technology is an emerging practice of waste treatment and energy production, in which waste materials are used to produce electricity, heat or fuel. The technology is essential because the amount of waste produced is increasing, so greener sources of energy are required because of the emission of greenhouse gases by fossil fuels. The old processes of WtE processing are incineration, anaerobic digestion, gasification, and pyrolysis. Incineration is another process during which municipal solid waste (MSW) is burned to generate heat energy in order to reduce wastage and landfill. Anaerobic digestion generates biogas, mostly methane that may be utilized in the processing of organic wastes and agricultural waste products. Thermochemical processes including oil gasification and pyrolysis are processes that transform organic or fossil-based materials to synthetic gas or bio-oil through controlled heating in low-oxygen atmosphere. Syngas is also generated in gasification and it can be used in electricity plants, whereas useful hydrocarbons are provided in pyrolysis.

Recycling and reusing valuable materials can be achieved by means of WtE technology; however, the adoption rates are uneven because of the disparity in economic status, regulation systems, and acceptance among the population. Advanced waste management systems can be easily assumed by developed countries whereas simple anaerobic digestion systems can be employed by developing countries. The impact of WtE technology on the environment is complex, given the minimization of greenhouse gas emissions due to traditional energy production with fossil fuels. Nevertheless, all of these technologies are not eco-friendly (Figure 1) [1, 2, 5–7].

Figure 1. WtE technology [1]

New developments in WtE technology have rendered them more viable to be implemented in developing economies. For example, thermal and enzymatic pre-treatment systems could be taken in consideration to provide a better anaerobic digestion system for producing more methane and modular incinerators to be introduced in areas with poor infrastructure. The plasma arc types of gasification system are becoming more popular because it has the capacity to process mixed and unsorted waste streams with minimal emissions. Together with a falling price per sensor and control system, these improvements are making WtE more affordable to low and middle-income countries. Such developments will be described in detail in Section 5.1, and their practical implementation will be discussed in Section 7 by means of international case studies.

Technological Advancement (Year 2020–2024)

Incineration: Modern incinerators have often combined heat and power (CHP) and real-time monitoring of emissions into the atmosphere. For example, Sysav in Sweden has been fitted with scrubbers and dioxin filters to comply with the stricter European Union air quality standards.

Anaerobic Digestion: Effective pre-treatment technology (e.g., thermal hydrolysis) reduces the yield of methane by disaggregating inaccessible organic matter. AI and smart sensors are optimizing the process of digestion.

Gasification and Pyrolysis: Plasma arc gasification has proven to be a highly effective technology which has the capability of treating mixed waste with reduced emissions.

Biochar: Pyrolysis-Based biochar is currently being appreciated as a carbon sequester and soil improver owing to its financial benefit.

Economic Feasibility of Third World Countries

Capital costs are barriers to be overcome, as elaborated further in Table 1.

Table 1. Economic insights for policymakers or engineers in developing nations

Technology	Trends of Recent Adaptation in Developing Nations
Anaerobic Digestion	Widely adopted due to low setup cost and availability of local feedstock (e.g., agricultural waste in Kenya, India). Governments offer subsidies for small-scale biogas units.
Modular Incinerators	Containerized WtE plants are being trialed in rural parts of Southeast Asia (e.g., Indonesia), to offer affordable and scalable solutions.
Pyrolysis for Plastics	Some startups in Nigeria and Bangladesh are converting plastic to oil with low-cost pyrolysis units, which have promising return on investment (ROI) and low greenhouse gas (GHG) impact.

2.2 Conversion Processes

2.2.1 Incineration

WtE technology involves the use of MSW, which is transformed into thermal energy by controlled burning. Modern incineration plants employ superior technology to control the level of emission and burning, in order not to contravene environmental regulations. The waste is then passed on to a burning chamber with very high temperatures up to 2 000 degrees Fahrenheit to eliminate harmful emissions and to provide an opportunity for burning organic materials fully. This process involves the generation of electricity using turbines associated with generators. Incineration reduces up to 90% of waste; thus prolonging landfills.

Nonetheless, challenges to incineration are related to emission control because of sophisticated air pollution control units. Continuous emission monitoring systems are used to comply with the environmental requirements. The incineration plants have been made greener and efficient due to technological development and efforts in contemporary designs. Pollutants left are minimized by secondary refinement; technological monitoring tools enable the operators to deal with possible pitfalls and inconveniences.

WtE incineration is a fast-growing industry in the world because of the urbanization process and the necessity of waste management sustenance. It produces a lot of energy through more than 800 facilities operating in 40 countries. The burnt ash could be utilized as building materials or metal polish. To conclude, incineration is a good WtE method to be used as a source of energy recovery in an ecologically aware world (Figure 2) [1, 2, 4, 6, 8, 9].

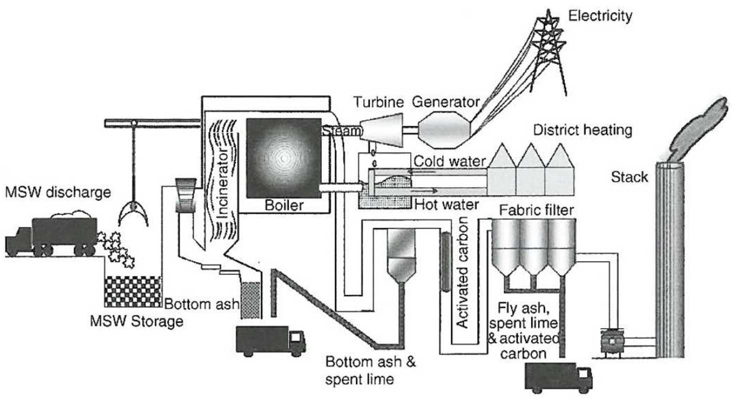

Figure 2. Diagram of typical WtE for the generation of power and heat [10]

2.2.2 Anaerobic digestion

Anaerobic digestion is a digestive process used to break organic substances without oxygen, thus producing renewable energy by taking on anaerobic digesters. Methane and carbon dioxide are the major components of biogas which could be burnt to release heat or electricity; the resulting by-product, digestate, contains nutrients to be adopted as fertilizer in agriculture. Nevertheless, anaerobic digestion technology incurs expensive initial investments to counter complicated conditions and non-reliability in biogas production. Community perception and communication are essential in advertising anaerobic digestion systems and regulation regimes that might not follow the technological solutions. Programs by the government are capable of enhancing the feasibility of anaerobic digestion as a long-term solution of disposing organic waste.

Anaerobic digestion systems could also generate permanent innovations geared towards improving efficiency and efficacy. Appropriate pre-treatment techniques could maintain and enhance the quality of feedstock through the removal of complex materials that can undergo fermentation in the digester, resulting in an increase in the rate of biogas production. Biogas can be wholly exploited, and the complexity of anaerobic digestion can be used through a combination of technologies, such as the CHP system.

The foreseeable future of anaerobic digestion can be envisaged in the advantages of anaerobic digestion, which includes fewer landfills and high quality fertilizers, since the world requires more clean energy sources (Table 2) [11–15].

Table 2. Different WtE generation technology [11]

Conversion Process	Technology	Process	Feedstock	Residues	Output
Thermo-chemical	Incineration	Mass burn at temperature $>1000^\circ$C	Mixed waste, refuse-derived fuels (RDF)	Metals, fly ash, bottom ash, and air pollutants	Heat and electricity energy
	Gasification	Standard temperature: 750°C; plasma arc temperature: 4000 to 12000°C	Mixed waste, RDF	Bottom ash, air pollutants	Syngas, methane, and hydrogen converted to energy (electricity)
	Pyrolysis	At temperatures ranging from 300 to 800°C, under extreme pressure, and without oxygen	Sorted waste (e.g., plastics), organic waste	Air pollutants	Gases, aerosols, syngas, pyrolysis oil, and char all contribute to the production of electricity
Bio-chemical	Fermentation	Without oxygen: Bacteria-Treated dark fermentation occurs when there is no light present, whereas photo fermentation occurs when light is present	Organic waste that has a lot of sugar	Wastewater, digestate, and liquid residues	Energy from biodiesel, hydrogen, and ethanol
	Anaerobic Digestion	Microorganisms that are treated without oxygen	Organic waste, green waste	Wastewater, digestate, liquid leftovers, and nonbiodegradable materials such as plastics and metal	Electricity energy from methane
	Landfills with gas capture	Natural decomposition of waste	Green garbage and organic waste	Compost	Methane converted to power
	Microbial fuel cell	Catalytic interaction between bacteria a nd microorganisms	Organic waste	CO_2, water	Electricity energy
Chemical	Esterification	An ester is produced by a chemical reaction between acid and alcohol when an acid catalyst is present	Waste oil such as leftover coconut oil	Water	Biodiesel and ethanol produced energy

The mass adoption of anaerobic digestion has to combat a number of challenges. The biggest problem is that establishing and operating the digester entails large capital investment, especially in the developing world. Effective regulatory frameworks are lacking and this obscures the political environment. Such operational risks as keeping digesters in an optimum condition may reduce the yield of gas and depend on the reliability of the system. Investments in anaerobic digestion are less appealing when it is subsidized, and tax credits or even feed-in tariffs are applied. The community perception, especially odor associated with land use, may deter the new anaerobic digestion facility sites. There is a need for free communication and early involvement in order to increase the acceptance and encourage the use of anaerobic digestion.

2.2.3 Gasification and pyrolysis

In big syngas, waste is currently being translated into energy with advanced thermochemical techniques which include gasification and pyrolysis. Gasification refers to the partial combustion of organic substances in high temperatures and in enclosed places, which form simpler gaseous substances such as hydrogen, carbon monoxide, and traces of carbon dioxide. This gas can be injected in a gas turbine power generator or can be utilized in the production of synthetic fuel such as methane or methanol. Pyrolysis, conversely, is a low oxygen reaction, which occurs at controlled temperatures with the by-products of solid char, liquid bio-oil and gas. The resultant bio-oil may be refined to use in place of the conventional oils in heating or processed into usable transportation fuels.

Along with every advantage that the gasification and pyrolysis processes have compared to the traditional processes, both methods make the usage of fewer resources per volume of waste, as well as unlocking more potential energy. But gasification is less polluting than incineration as per environmental conditions. These technologies are in line with the circular economy whereby the resources are converted to productive resources, strain on landfills is minimized, and other energy is produced. Their scale-up however has been problematic because of the enormous capitals as well as community issues.

The presence of proper regulatory framework is essential in introducing gasification and pyrolysis conversion to the existing waste management systems. Surveillance systems based on AI can enhance the gasification processes and stabilize the system and reduce the number of emissions during energy generation [2, 11, 15–18].

3 Types of Waste Utilized for Electricity Generation

3.1 Municipal Solid Waste

There is also an increasing concern in MSW in the world as a result of population increase and urbanization. MSW is estimated to be 3.40 billion tons by 2050 and it is quite diverse both in terms of geography, economy and culture with more than half of the waste being organic. This offers a huge potential in energy conversion of WtE approaches. Methane CH_4 is a greenhouse gas emitted by the landfills and is a cause of climate change. Another way of reducing the emissions is through renewable energy generation technologies such as gasification and anaerobic digestion. As an illustration, Chandigarh, India, produces 350 tons of MSW in a day and more than half of it is biodegradable. State-of-the-art WtE technology will be able to transform organic waste into biogas or biomethane in order to decrease the landfill practices and GHG emissions.

Nevertheless, owing to the heterogeneity of MSW, there is so far no common solution. A high level of 90% of waste can be minimized with the help of thermal treatment and incineration, but it requires emission control and air control. The presence of the stakeholders is essential to reduce the level of concerns and create a supportive environment within the population. The WtE solutions must encompass energy recovery, resource recycling along with material recycling so that a circular economy is realized.

The effective WtE solutions would also involve the development of technologies that would help to increase the efficiency and minimize the adverse effects of the traditional waste disposal. Maximization of the value of MSW must be conducted through research and innovation. The creation of infrastructure to sort different MSW materials will provide the communities with the opportunity to combat waste generation and take action on climate (Figure 3) [3, 19–22].

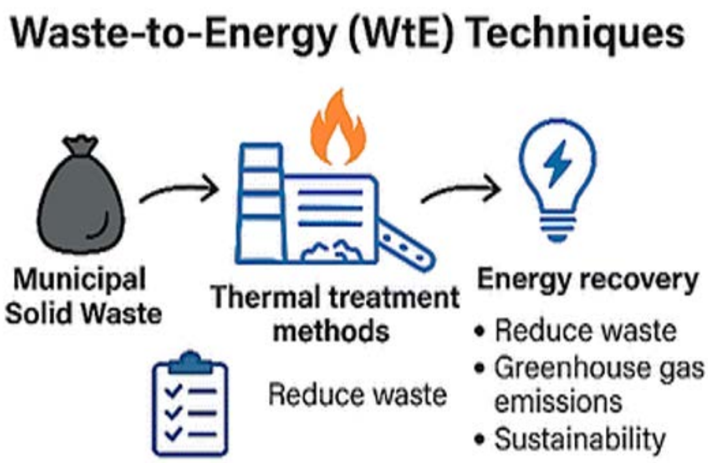

Figure 3. WtE technologies: An environmentally friendly route to material management and resource recovery [3]

3.2 Agricultural Residues

The process of WtE projects is applied to turn agricultural waste into renewable energy to help environmental concerns with waste disposal. Straw and husk are by-products which could be used to generate energy by anaerobic digestion, gasification, and pyrolysis. The organic matter is digested anaerobically to generate biogas that can be utilized in heating or even in cogeneration systems as heating or electricity. Biomass is taken to solid biomass and transformed into syngas that may be utilized as electricity or biofuels. Best feedstocks are wood chips and stover corn. Pyrolysis burns organic materials at elevated temperatures, which comprise biochar and bio-oil gases. WtE projects enable agricultural societies to save on the expense of disposing waste materials, and become more sustainable as the waste minimizes the emission of greenhouse gasses. The use of agricultural residue to fuel has such benefits as recovery of resources and reduction of landfill waste, which are in line with the circular economy. But geographical changes due to season and logistical problems are challenging. Government incentives and policy support may support the investment in the agricultural processing infrastructure waste. The scientists are looking into high conversion efficiencies and new technologies into all wastes produced by agriculture, which leads to more sustainability rules and regulations. The use of agricultural waste can meet the energy requirements of the world as well as provide jobs in the rural nations [18, 23–25].

3.3 Industrial Waste

Byproducts of industries would be of importance in WtE business as they could be transformed into electricity and other sources of energy. This encompasses trash like assembly of mass productions, food processing among other industries. Another way in which industrial waste can be utilized involves generation of power, the reduction on landfills use, and establishment of sustainability through the conversion of potentials of wastes into valuable products.

Industrial wastes are consistent and contain high nutrients thus a good option in WtE technology. An anaerobic digestion, gasification or incinerators can be used in the digestion of organic products. The food processing plants produce organic wastes such as peels of fruits and vegetable peels, which can be utilized in biogas production, electricity, or heat production.

The other alternative is industrial waste gasification that subjects the organic materials to high temperature and low oxygen conditions and this produces synthetic gases, which may be utilized to produce electricity or chemical and fuel precursors. Industrial waste that consists of hydrocarbons particularly petrochemical industries is gasifiable.

The paper sector produces off-grade products and sludge that can be operated in WtE systems to minimize the impact of landfills. The textile business produces additional fabrics and scraps, which can be subjected to pyrolysis to get liquid fuels or other sources of energy. Nevertheless, it is necessary to treat these wastes with caution because of the possible heavy metals or poisonous elements.

The policy of the government is very important in the inclusion of industrial wastes in WtE systems, so that businesses adopt cleaner technologies that can minimise their carbon footprint. With the technological change, ecologically friendly industries have been in a position to emerge as the victors of the sustainability competition [1, 26, 27].

4 Environmental Impacts and Sustainability Considerations

4.1 Emissions and Air Quality

WtE solutions may be used as a way of waste treatment and energy production, yet they have environmental concerns as well. Production of Methane in landfills is a major contributor of greenhouse gas emissions. WtE systems can minimize these emissions by taking waste that would otherwise decompose to produce poisonous gases that include carbon dioxide, nitrogen oxides, sulfur dioxide, and particulate matter. Recent transformation in WtE technology is based on efficiency in the process of combustion and reducing harmful gases. Plants that have superior emission reduction initiatives are in a position to cut NOx emissions and SO_2 emissions considerably. WtE has carbon capture and storage characteristics in the majority of its practices to reduce almost zero or negative emissions.

Systematic plant set-ups may attain the further performance of emissions, e.g. the highest feedstock processing and sorting. Incinerators have to be properly loaded with materials to reduce the development of dioxins and other wastes that are toxic. The life cycle assessment (LCA) model can offer an overall picture of the overall impact of the WtE technology on the environment.

Nevertheless, the most significant issue is the attitude to WtE plants that sometimes encounters certain obstacles associated with the air quality in the area. To address the challenge of air quality, policymakers and stakeholders should be able to open to communities regarding changes in technology, in order to encourage a domesticated consumption of fossil fuels and solid wastefulness policies. A significant concern in developing countries is also waste problems since they either cannot afford ultra-modern WtE technology because of the lack of facilities or money (Figure 4) [5, 7, 10, 28].

Approximately 1.2 tons of CO_2/ton of waste processed are the emissions of MSW incineration, especially because of the burning of fossil-based materials such as plastics. By comparison, anaerobic digestion emits about 0.5 tons of CO_2-equivalent per ton, as a result of residual methane leakages, and energy consumption—this is the more relatively clean technology as far as greenhouse gas emissions are concerned.

LCA is a technique which is utilized to determine the environmental impact of system including the conversion of waste, distribution of feeding stock, the construction of plants and energy recovery. There is a potential to have net-negative emissions by existing WtE facilities, especially those that are linked to district heating or renewable grids, in substituting fossil fuels. The quality of feedstocks and sorting is also taken into consideration by LCAs because the mixed or contaminated waste streams can result in the increase of particulates and dioxin, which will counterbalance the positive changes to the environment. Positioning LCA in the policies of the national WtE may guarantee superior assessment of the trade-offs affecting the environment and technology choices towards the most sustainable systems that would provide maximum sustainability payoffs. The significant examples of LCA analysis that can be applied to WtE are in Table 3.

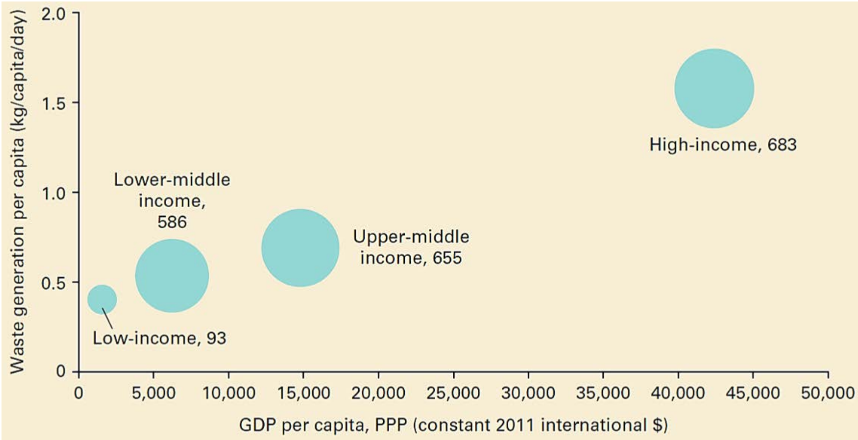

Figure 4. Waste generation per capita by income group [10]

Table 3. LCA analyses applied to WtE

Study/Source	Key Finding
US EPA (2021) [28]	WtE incineration with modern flue gas treatment emits 35–55% less GHGs than landfilling with methane capture over a 100-year timescale.
European Environment Agency (EEA, 2020) [10]	WtE systems that displace fossil-fuel electricity show net negative GHG emissions, especially when combined with district heating.
IEA Bioenergy Task 36 (2022) [22]	Transport and preprocessing contribute up to 15–20% of total emissions; localization of feedstock supply significantly improves net environmental benefit.
World Bank (2018) [5]	In developing countries, poor sorting increases emissions due to combustion inefficiencies and dioxin formation—underscoring the need for source separation policies.

4.2 Resource Recovery and Recycling Potential

WtE systems play a vital role in terms of resources management and minimization of waste since they can transform the waste into electricity, heat or fuel. The systems are useful in reducing the amount of waste in landfills, as well as improving the process of extracting reusable items that can be reused and recycled. Sustainable waste management processes include incinerations, anaerobic digestions and gasification with a recovery rate of up to 90% of having been able to recover valuable waste materials including metals. Through anaerobic digestion, renewable energy is produced in biogas and organic fertilizers, which can help in agriculture and diminish the utilization of substitutes.

WtE systems are concerned with sustainability because they minimize waste and ill impacts and result in new waste resource reuse and recycling behaviour. Yet, such issues as dependency on MSW and the possible opposition of the community are present. Research and development to recover more of the resources should be done which entails refined separation techniques in the pre-processing stage, and better sorting techniques in the collection areas.

There is a necessity to address the issue of sustainable behavior on a large scale and include technological advances and community involvement in the process of waste management. Contamination can be avoided by educating citizens on correct separation of recycling separation and therefore improves recycling. Although there are many opportunities to extract useful materials in garbage using the WtE systems, there is no need to use strict energy recycle solutions (Table 4) [3, 7, 11, 29].

Table 4. Comparing open dumping and landfills without gas recovery with the effects of WtE generation on sustainability in the developing world [11]

Sustainability Dimensions	Positive Impacts	Negative Impacts	Dominant Impact Type
Social	Enhancement of public health Decrease of odor; Waste reduction; Local production of renewable energy; Advantages for the neighborhood.	Enhanced dust and noise levels brought on by garbage transportation trucks	Positive
Economic	Development of the local economy; Creation of new jobs; Avoiding the expense of disposal.	The value of local land may rise	Positive
Environmental	Decreased air pollution; Decreased pollution from odors; Reduced reliance on fossil fuels; Production of renewable energy; Utilizing leftovers as fertilizer.	Plant emissions from WtE	Positive

5 Technological Advancements and Efficiency Improvements

5.1 Innovations in WtE Systems

WtE systems are increasingly becoming sophisticated in order to support the increased requirement in waste management and energy creation. Efficiency, environmental sustainability in addition to the integration of renewable energy in the models of WtE has been engineered using new technology.

The incineration technology has been improved, so that it produces the minimal emissions and improves the quality of air. Efficient boilers with flue gas purification systems have recorded satisfactory combustion levels as well as lowered adverse gaseous emissions. The gasification technologies have been improved as well to achieve high grade of syngas whose thermal processes are optimized. Purest form of this syngas may be combusted to generate electricity or make production chemicals and fuels.

Another innovation that can be used to improve the resource recovery of various waste streams is anaerobic digestion, which can be used with other types of WtE. It is possible to convert organic waste into biogas and non-organic should be subjected to gasification or incineration. Hybrid systems enhance efficient feedstock utilization, generate more energy buffet and minimize green campaigns.

The new intelligent technologies, like the IoT, that can be used in WtE to monitor and gather data on the logistics of waste collection are also undergoing development and enhance the efficiency of waste processing. This data-driven method can have variable parameters and a dynamic process operator, which results in improved maintenance and the decision to change operations.

Plasma arc gasification and torrefaction are new processes that bring new processes in the WtE industry. Plasma arc employs high temperature plasma torches to transform the organic matter to syngas with less solid wastage and therefore can be used in MSW management as well as hazardous waste management. Torrefaction yields dense biomass that is pre-treated without the use of oxygen.

Scientific research will be done in future in the field of producing biohydrogen through microbial fuel cells which have the capability of directly producing electricity through the conversion of organic material without reducing it. It is a science that is concerned with holistic solutions that would maximize energy recovery of various wastes [1, 2, 12, 29–31].

5.2 Smart Grid Integration and Energy Storage Solutions

The use of smart grid technology has a lot to offer when it comes to the supply and demand of energy as it can be used to incorporate WtE systems. The smart grid employs the internet of things technique in regulating the amount of released electricity by different sources to enhance the efficiency of the generation. The integrated solution will be able to overcome the anomalies of power production in WtE systems because of the waste and conversion technologies. The smart grids are able to deliver power at any rate thus making the grid powerful and stable. The storage systems such as batteries or pumped hydroelectric storage can equalize the energy storage whereby it will not produce waste and can optimize energy. Ancillary services can also be created through storage systems including frequency regulation by WtE plants.

The management of the processes can be conducted with the help of data analytics to address the existing energy needs and supply. The use of historical data to extrapolate the past trends of electricity demand can enable predictive analytics that will enable production practices to be prepared by the WtE facilities. A new trend, associated with smart grids, is virtual power plants (VPPs), which collect a collection of distributed energy resources to form one participant in wholesale electric markets. This plan is more robust in outages and helps in making the environment sustainable by making its resources efficient in terms of consumption by alternative sources of generation.

The implementation of smart meters at homes and corporate sites can assist the customer to make intelligent choices on the usage of energy and switch to high power consumption during low and abundant seasons. To manage the demand, it is important to increase consumer engagement, which will reduce peak loads to the grid. The intersections of smart grids and WtE systems can enable the development of cities to be more sustainable and reduce the intermittency of renewable energy sources and the dependence on fossil fuels [2, 30, 32, 33].

5.3 Integration of WtE with Renewable Energy + Smart Grids

WtE systems combined with wind and solar power provide a hybrid energy model that has the potential to react to various intermittency aspects in smart grids. Such systems stabilize the grid through the creation of baseload power, and the grid capabilities of the smart grid, e.g. computer-aided prediction and VPPs, can intelligently deliver WtE based electricity. Denmark and Japan integrations have made it possible to dispatch more WtE at the times of low renewable generation, which has made the system more resilient and energy-independent. WtE systems may also be a perfect complement to non-persistent renewable energy such as wind and sun providing baseload power instead of solar or wind. Smart grids can adjust grid posts at peak time whereby when the solar/wind power consumption is low (reduced) intelligent smart grids like VPPs with solar rooftops and battery plants can adjust the grid posts.

5.4 Efficiency Improvements in Emerging Technologies

There are emerging WtE systems that are increasing the energy conversion efficiency. Gasification using syngas can be enhanced by plasma-aided fuel reactors and oxygen-enriched combustion to produce high calorific value syngas. Pyrolysis systems are enhanced by catalytic distillation to enhance the usability of bio-oil in transport fuels. The production of methane by anaerobic digestion rises due to heating and breaking down by means of living organisms. Such inventions with the help of the Combined Heat and Power recovery work can raise the total energy efficiency of the WtE systems to more than 80%, which will make it a feasible high-yield renewable energy source, especially in urban environments. To give further discourse on the technological changes, it will drown itself in how technological improvements are improving within newer WtE systems displayed on Table 5.

Table 5. Efficiency enhancements

Technology	Efficiency Enhancements
Gasification	Plasma arc reactors reach up to 80% syngas recovery, and the use of oxygen-blown systems instead of air increases heating value
Pyrolysis	Coupled with catalytic upgrading and bio-oil distillation, can yield transport-grade fuels
Anaerobic Digestion	Thermal hydrolysis pre-treatment and two-stage digestion improve methane yield by 20–35%
CHP Integration	Modern Combined Heat and Power units now recover up to 85–90% of energy from incineration

Real-World Efficiency Case: In Singapore, the Keppel Seghers Tuas WtE plant enjoys net electrical efficiency of greater than 60% through simultaneous operation of a high temperature combustion system, a flue gas condensation system and a CHP system—an exemplar of small-space facilities in crowded urban areas.

6 Economic and Policy Drivers of WtE Adoption

6.1 Cost-Benefit Analysis of WTE Projects

WtE projects play a vital role in determining the feasibility and sustainability of the projects, cost and benefit evaluation, and short-term financial impacts. In emerging countries, the cost of start-up capital, technology, infrastructure, and set-up of operation can be excessive because of the financial shortage. The cost of operation of the WtE projects depends on the energy requirements, staffing and the maintenance of a sophisticated machinery.

Most of the revenues generated by the WtE projects are realized by selling electric power, waste tipping and by-products. These charges can be used to generate income due to adequate waste management. The WtE processes contribute to the production of renewable energy hence financially viable.

WtE conversion has such benefits outside, as fewer landfills, greenhouse emissions, recovered resource, and adherence to the climate action and sustainable development objectives. Nonetheless, these advantages do not quantify since there are conflicts in environment, laws as well as demographic choice. WtE systems need standardization of measuring processes.

WtE investments are attractive and can be determined using sensitivity analytics and internal rate of return (IRR). Incentives provided by the government, including subsidies or tax exemption, may have a considerable effect on the economics of a WtE project since the start-up cost is reduced. With the promotion of renewable energy across different parts of the world, new ventures of waste energy generating may be established.

WtE strategies can only work after personal economic situations and governmental subsidies. The developing nations usually possess inferior infrastructure as compared to the developing nations particularly in systems that are difficult to logistically reach. A general cost-benefit evaluation of the WtE project preparation phases would give the stakeholders the information about the costs and scope wide consequences of sustainability measures in the regions (Table 6) [3, 12, 20, 34].

Table 6. Comparing WtE technology based on technological and socioeconomic criteria [20]

Process Type of Factor	Capital Cost (USD/ton of MSW)	Operation Cost (USD/ton of MSW)	Energy Conversion Efficiency (%)	Complexity	Skill Level	Geographical Location
Incineration	14.5–22	1.5–2.5	50–60	Low	Low	Urban
Pyrolysis	17–25	2–3	70	High	Intermediate	Industrial urban
Gasification	17–25	2–3	70–80	High	Intermediate	Industrial urban
Anaerobic Digestion	7.5–11.5	<0.5	50–70	Low	Low	Rural
Trans-Esterification	35	20–25% of total cost	80–98	Low	Low	Urban

Table 7. Comparative economic profiles

Country/ Project	CAPEX (USD/ton)	OPEX (USD/ton)	Energy Revenue (USD/MWh)	Breakeven Time	Public Support Mechanism
Germany (Typical MSW Incinerator)	\$15,000–\$20,000	∼\$2,500/year/ton	∼\$110/MWh (with CHP)	∼12 years	Feed-in tariff, landfill tax
Shenzhen East WtE Plant	\$12,000–\$14,000	∼\$2,000/ton/year	∼\$90/MWh	∼10 years	Green energy subsidy
Pune, India (Planned RDF Plant)	\$7,500–\$9,000	∼\$1,200/ton/year	∼\$60–70/MWh	∼15 years	Viability gap funding (VGF)
Quezon City, The Philippines	\$8,000–\$10,000	∼\$1,500/ton/year	∼\$65/MWh	∼14 years	CDM credits, PPP framework

Table 8. Political implications

Areas of Policy	Recommendations	Benefits
Tariff Support	Introduce Feed-in Tariffs or Power Purchase Agreements (PPAs) for WtE	Guarantees ROI for investors
Capital Subsidies	Apply Viability Gap Funding (VGF) for infrastructure	Lowers upfront cost burden
Landfill Tax or Ban	Enforce landfill disincentives	Shifts waste toward WtE
Mandatory Waste Segregation	National legislation + enforcement	Improves WtE efficiency and reduces emissions
Carbon Credits/ CDM	Register WtE under Clean Development Mechanism	Attracts international climate finance
PPP Guidelines	Streamlined Public-Private Partnership frameworks	Encourages investment from private operators

Economic feasibility of the WtE projects is established, but country-specific statistics are required to estimate the viability of the project. As an example WtE facilities in Germany produce an average of \$110/Mwh in case of district heating included, even and even in 10–12 years. It however has longer ROI period than other plants in India and Philippines because the other plants are cheaper in terms of energy and policy compliance. In order to make WtE investments possible, developing countries are expected to design tailor-made policy initiatives, solve waste separation issues, promote public-private partnership (PPP), and take steps at landfills, as in Table 7.

The National Renewable Energy Policy (2008) of Bangladesh already includes waste valorization in the format of biogas and compost—this can be further expanded to WtE incineration and pyrolysis under official government PPA and subsidy frameworks. Table 8 exemplifies a list of concrete and practically applicable policy modifications that might be considered.

6.2 Government Incentives and Regulations Impacting WtE Adoption

The importance of WtE technology is critical to the government incentives and regulatory system, which influence investment and operations. The policymakers should plan policy to increase the investment into WAST programs and to create a joint-public-private action to spur the circulation of funds. Proper regulatory environment will promote entry into the industry by the private sector, which boosts creativity and efficiency in the industry. Tax reliefs, subsidies, and feed-in tariffs can be used to increase the economic viability of WAST initiatives to encourage the use of cleaner technology as well as competition among energy producers. The policy frameworks should include the nature of local wastes in order to simplify the operations and enhance the quality of feedstock. The implementation of Waste Elimination projects requires coordination of the different ministries in the government.

The awareness campaigns on the positive attributes of WtE technology should make them be accepted by the community to ensure that landfills and greenhouse gases are reduced. Citizens should be educated about waste technology and the impact it has on the local economy and environmental wellbeing.

The issue of resource shortage is a challenge to the developing countries, and the international assistance programs have the potential to create government institutions and advance regulation systems. Investment into Waste technologies needs research and development and governments must provide funds towards innovative energy production by other wastes. Successful implementation of waste requires constant government policies, encouragement by the state, and quality regulations (Tables 9–11) [3, 11, 22, 35].

Table 9. Environmental and socioeconomic effects of the WtE method [3]

WtE Techniques					
Parameters	Anaerobic Digestion	Landfill Gas Recovery Technology	Incineration	Landfill Gas	Pyrolysis
Types of Waste	Organic Fraction	Mixed Waste	Mixed Waste	Homogeneous Waste	Homogeneous Waste
Technical					
Technology maturity	Very high	Very high	Extremely high	Emerging	Emerging
Waste volume reduction	45–50%	Low	75–90%	75–90%	50–90%
Technology complexity	Low	Low	Low	High	High
System efficiency	50–70%	10%	50–60%	70–80%	70%
Residence time	15–30 days	Years	2 s	10–20 s	Seconds to weeks
Requirement of labor skills	Low	Low	Low	High	High
Land requirement	Large	Very large	Small	Small	Small
Pre-treatment	Required	Not required	Not required	Required	Required
Future potential	High	High	Moderate	High	High
Economic					
Capital cost	Medium high	Low	Medium high	High	High
Operation and maintenance costs	Medium high	Low	Medium high	High	High
Pre-treatment cost	Medium	None	None	High	High
Social and Environmental					
GHG emissions	Least	High	Extremely high	Low	Low
Dioxin and furan emission	Extremely low	Extremely low	Very high	Very low	Very low
Social opposition	Very less	Less	Extremely high	High	High

Table 10. The current and maximum production capacity of the Integrated Landfill and Resource Recovery Center (Jashore) [11]

Product Type (Unit)	Maximum Production Capacity	Present Production Capacity
Fertilizer (t/d)	4	1–1.5*
Biogas (m^3)	720	450
Electricity (KW)	550–600	200

Table 11. Bangladeshi laws and policies pertaining to waste management [11]

Year	Policies/Acts	Comments
1995	Bangladesh Environmental Conservation Act	Suggests guidelines for the proper disposal of various waste kinds.
1998	Urban Management Policy Statement	Suggests the privatization of services to be rendered by the municipalities and prioritizing of amenities among the slum dwellers such as water supply, sanitation and disposal of solid wastes.
1998	National Policy for Water Supply and Sanitation	As per this policy, the government will initiate recycling of waste to the best extent and utilize the organic waste products to make compost and biogas.
1999	National Agriculture Policy	Under this policy, the government will encourage the farmers to adopt compost/organic fertilizer that will enhance food security and productivity of the soil.
2005	National Industrial Policy	It is advisable in the policy that there would be the use of environmental management systems and cleaner production systems amongst industries.
2006	Fertilizer Act	The government has set a standard of compost by promoting compost with the help of this act.
2006	National Urban Policy	This policy has stressed on clean development mechanism (CDM) and recycling.
2008	National Renewable Energy Policy	This policy is encouraging the generation of biogas and other green energy by waste and encouraging incentives such as CDM to encourage green energy activities.

7 Global Perspectives: Case Studies from Leading Countries

7.1 European Union Initiatives on WtE Technology

The European Union itself is aggressively advocating WtE technology like the European green deal that is geared towards turning the EU into a climate neutral state by 2050. The vision of a round economy action plan is based on sustainable waste management methods that aim at reducing the level of waste, increasing the recycling process, and using non-recyclable waste residues. Funding of EU waste management initiatives is done using structural funds and renewable energy investment schemes with the European Investment Bank actually funding some of the most widely built undertakings in member countries. The EU also provides guidelines on how to build waste infrastructure according to environmental guidelines. Germany has more than 70 incineration plants to produce vital energy and regulation of high efficiency incineration plants with high emission control is eminent. Sweden and Netherlands are the earliest to adopt waste management practices in which sorting technology has been invented in the recycling plant and the pay-as-you-throw programs encourage waste reduction. The most intensive investor in waste technologies research and development is Europe where Horizon Europe is concerned with green innovation. There should be campaigns with people to deal with pollution and health risks of incineration [36].

7.2 Successful Models from Asia-Pacific Countries

The Asian-Pacific region is one of the key players in the adoption of the WtE technologies, as such countries as China, Indonesia, and Vietnam have introduced new methods of dealing with waste management issues and fulfilling the energy demands. By 2022, China has established more than 300 Waste treatment facilities with a total power of above 10 gigawatts as an example to the developing world that waste should be treated in a responsible manner using sustainable methods.

Waste management in Indonesia and Vietnam is also interested in the WtE so the countries can overcome increasing waste management problems and solve the dependence on fossil fuels. The government of Indonesia has been setting up twelve WtE plants with capacity of 234 megawatts of electricity by 2022. Vietnam intends to introduce WtE systems in order to diversify its energy production and reduce over dependence on power plants that use coal.

Thailand is enhancing the effectiveness of the existing waste management systems and making popular the public-private partnerships in WtE development. Incentives that enable investments in renewable energy projects like WtE initiatives are a few of the measures put in place by the Thai government to entice investments into the sector by the private sector. To cut the emission by 27% by the year 2030, Cambodia is coming up with a new solid waste management plan which incorporates the Waste Energy Technology.

Other technologies that countries of Asia-Pacific are considering as an alternative to the traditional incineration include gasification and pyrolysis. More efficiencies and reduced emissions can be attained by using sophisticated processes that are able to use different feedstock other than MSW.

There is an increasing cooperation between local governments and international technology companies and it is through workshops and conferences that knowledge can be shared. In a long-term perspective, appropriate research and implementation of better Waste disposal technologies in the national policy can be able to resolve the recently experienced waste disposal issues and resolve the environmental targets such as low carbon production and renewable energy development within a nation [22, 29].

Here, the worldwide WtE technologies have proven to be very successful in other regions. Green WtE systems are used in Sweden where nearly a quarter of the district heating systems have been covered, and more than 6.5 million tons of waste is destroyed each year. The Tuas waste management facility is able to transform 3,000 tons of waste per day to 1 TWh of electricity, which will save 800,000 tons of CO_2 emission annually, in Singapore. The Shenzhen East WtE plant in China is of capacity 5000 tons/day and produces more than 160 MW in the grid each day. Decision-makers should take these performance metrics into consideration in order to establish the possibility of the replication of such systems in other regions. Table 12 provides quantitative performance snapshot of key WtE projects.

Table 12. Quantitative performance snapshot of key WtE projects

Country/Facility	WtE Type	Energy Output	Waste Treated	CO_2 Offset
Sweden (Nationwide)	Incineration + CHP	14 TWh/year (≈20% of district heat)	∼6.5 million tons/year	∼2.2 million tons CO_2 saved annually
Germany (Multiple Plants)	Incineration + Energy Recovery	∼7 TWh/year electricity	∼14 million tons/year	∼4.5 million tons CO_2-eq offset
Singapore (Tuas WtE)	Incineration	2,688 MWh/day (≈982 GWh/year)	3,000 tons/day (∼1.1 Mt/year)	∼800,000 tons CO_2-eq/year
China (Shenzhen WtE Plant)	Largest incinerator	168 MW capacity	5,000 tons/day (∼1.8 Mt/year)	∼1.5 million tons CO_2-eq/year
Japan (Osaka)	Incineration + district heat	∼100 GWh/year	500,000 tons/year	∼220,000 tons CO_2 saved
Netherlands (ARN Plant)	High-efficiency incineration	∼700 GWh/year	1 million tons/year	∼1 million tons CO_2-eq saved

8 Challenges and Barriers to WtE Deployment

8.1 Public Perception and Acceptance Issues

WtE projects will never succeed without the consent and opinion of the people. Nevertheless, even with the development of technologies and the ecological agenda, some degree of plan distrust exists among the population. The problem of mistrust to waste disposal technology, especially waste incineration plants, due to the previous negligence in waste products handling is one of the major ones. They need educational channels of communication to fight the misconception and ensure that people agree by discussing the safety, health implications and environmental implications of safety.

Another major consideration is community resistance to the location of WtE, where most communities are resisting it because of fear of noise, odor and traffic. On site selection, policies must take into consideration the concerns of the community and consult with the local residents and the stakeholders at the initial level. Attitude towards waste management also has cultural implications on levels of acceptance. Sustainable practices create a chance that the Waste minimization projects will be more tolerable in areas that have sustainable practices and strongly unwelcoming in areas that do not have efficient waste recycling.

Table 13. WtE transition key challenges list in developing countries [37]

Challenges	Code	Sub-Challenges	Descriptions
Operational challenges (OC)	OC1	Weakness in sorting at the source of waste	Urban areas do not follow segregation of waste in the household, thus leading to lot of wastes to pile on in open fields, drains and roadsides.
	OC2	Inability to handle the process of waste collection and transportation at a high rate	Without effective storage of the waste, collection, transfer, processing, and disposal, the whole WtEd system may fail.
	OC3	Unacceptable ways of waste recovery and disposal	It encompasses the open burning of wastes, open dumping of waste materials in an unapproved place like in the water bodies, landfills lacking liners and leachate systems to collect the leachates, as well as unregulated or unlicensed waste incinerators or waste pyrolysis facilities.
	OC4	Proper site selection	Qualitative measures are an assessment of flood risks, road structure, population, climate situation, power grid, and industry. The decision making of land acquisition within the government has to deal with these problems and the foul odor of waste is one factor that is the matter of concern in site selection.
	OC5	Heterogenous mixture of garbage in the garbage site	It is very rare to have a use of any type dustbins related to a certain waste like having a blue dustbin to dispose paper, green dustbin to dispose glass, yellow dustbin to dispose plastic, and red dustbin to dispose metal because of the ignorance of people and lack of publicity.
Technical challenges (TC)	TC1	Lack of cutting-edge and state-of-art technologies	The non-renewable waste processing is made difficult without the presence of advanced modern technologies, hence, the environmental and health damage cannot be minimized
	TC2	Knowledge and awareness of the operational personnel absence of operational personnel	Insufficient research and development are not able to present new projects and to advance the existing plants.
	TC3	A low calorific power in comparison with the traditional fuels	The foods, vegetables, paper, plastic, etc. are different types of MSW whose calorific value is less than the oil, gas, coal, etc.
	TC4	Lack of combined information on waste	The problematic issue with the information gathering and accumulation is the waste that is being used to generate energy. Data concerning the average annual production of waste by the city corporations and municipalities is not complete. Information is lacking in terms of the solid material totality.
	TC5	Damage of atmosphere in the plant regions	The byproduct of the energy creation process undermines the ambiance of the areas where the plant is established.
Managerial challenges (MC)	MC1	Poor training and training and support	The project is being stagnated by the lack of expertise in the WtEt technology to design, construct and put in operation the technology.
	MC2	There existed a communication without communication between the government and researchers	There is a slight linkage between researchers and the policymakers and so the projects cannot be optimized. The researchers should provide information and guidelines on the composition of wastes in order to implement the projects.
	MC3	Lack of adequate financial support by the government and the investors	Local governments, who are the municipalities and the city corporations, are in charge of the waste management system. They thus need financial support of sufficient levels by the government and other investors.
	MC4	Poor involvement and collaborative effort of stakeholders	Because of the little inclusion of all the concerned communities, most projects are uneventfully complete with the possibility of doing bigger projects in future proving hard.
	MC5	The necessity of a high-quality planning and motivated policy-making	WtE power plants are not built up as needed because of the proper planning and policy. The electricity production in such plants highly requires government paybacks.
	MC6	Complication in the procurement buying process	Once the planning has been done, the acquisition of equipment is immediately an issue and it slows the process of completing the WtE project.
	MC7	Insufficient complete legislation and suitable enactment	The absence of thorough legislation, as well as their adequate implementation, leads to the establishment of obstacles in the way of fast-growing WtE plants.
Economic challenges (EC)	EC1	The challenge to carry out the project within time and within budget	Most of the projects are not completed because of the few involvement of all the respective communities and therefore it is hard to undertake bigger projects in the future.
	EC2	Cross-subsidizing costs of installation, maintenance and infrastructure development is high	The initial investment required in primary installation as well as development of the basic infrastructure is also huge Emerging economy is faced with a big challenge in taking the responsibility of maintenance and operational cost.
	EC3	Lack of monitoring of the released budget	Poor budget overhauling would cause a project to financial crunch particularly in an emerging economy where deficit budget is prevalent.
	EC4	Lack of the right quantity of waste in time	Construction of a WtE facility is complicated without having adequate waste into consideration within a certain facility. Since most of the municipalities lack adequate waste treatment facilities, these factories are dumping their waste in the rivers, canals and other water supplies, thus leading to lack of waste to be used and also pollution.

Urbanization has also contributed to the fact that people in Kenya have changed their minds towards Waste Incineration Power Plants (WIPPs). However, at first people did not favor them because of pollution, these days people see the projects as a chance to obtain new energy and better systems of waste management. Public perception can be influenced by media pronunciation, political debates on the sustainability and personal experience of the facilities available. It is possible to create trust in Waste treatment systems through updating information about improved air quality and success stories.

The decision-making processes need to be fair in order to be acceptable. When they have heard their voices, projects provide communities with more reasons to support them. Long term relationships founded on trust can be created through fair procedures that involve different stakeholders. Economic elements are also a contributory factor to the skepticism of the people because they might not have positive economic results such as employment or reduced costs of sanitation.

A multi-layered policy which incorporates educating on the advantages and disadvantages of technology, involvement in planning, responsiveness to input, cultural orientation, openness of how operations affect performances, performance improvements, fair judgement, and awareness of the economic viability of Waste disposal operations are required to manage these sentiments (Table 13) [37, 38].

The socio-political resistance and an existing state of distrust and perception of WtE incinerators are leading to low-income populations. In Campania of Italy and Los Angeles of the USA, the fact that the air quality, transparency in governance, and eco-social justice have been under pressure by citizens has led to postponements in propositions. To overcome these problems, nations have proposed enthusiastic engagement plans such as participative siting, live tracked emission boards and community benefit-sharing programs. Such practices do not only enhance trust but also make residents feel that they own such projects which is essential towards long-term sustainability of WtE projects. With the aid of education, it is possible to support these practices and eliminate the popular myths concerning the modern WtE management. Table 14 presents real cases actually experienced when social-political resistance overshadowed the way WtE was paralyzed by the wider opinion.

Table 14. Examples indicate the impacts of perceived fairness, transparency, and inclusiveness regarding WtE acceptance

Location	Outcomes	Public Concerns
Campania, Italy	WtE facility delayed for over a decade	Linked to mafia-controlled waste systems; public feared toxic pollution and corruption
Los Angeles, USA	Abandoned WtE proposal in 2013	Health risks cited by environmental groups; emphasis on zero-waste instead
Melbourne, Australia	Protests in 2021 over proposed incinerator	Feared impact on recycling targets and air pollution near residential areas
Manila, Philippines	National ban on incineration (RA 8749)	Public opposition based on air quality and incineration'sclash with cultural norms of waste separation

Strategic advice on public outreach and engagement can be seen in Table 15.

Table 15. Evidence-based engagement strategies

Strategy	Descriptions	Examples
Participatory Siting	Include local stakeholders early in site selection	Sweden's Malmö plant held 30+ town halls pre-construction
Transparency Portals	Real-time emissions monitoring published online	Germany's WtE plants publish emissions hourly
Community Benefits Packages	Share benefits (e.g. jobs, local energy discounts)	Singapore's Tuas South WtE gives locals utility rebates
Third-Party Environmental Audits	Independent validation of compliance	Used in Belgium's Mechelen WtE facility
Targeted Education Campaigns	Science-backed outreach on health/safety	UK's WRAP campaigns increased acceptance by 40% in surveyed areas

8.2 Technical Challenges in Implementing WtE Systems

Introduction of WtE systems has a lot of technical issues especially in the developing nations where it is evident that organic wastes are the largest portion of the waste products. These wastes are wetter and less calorific in nature hence it is hard to get maximum power output of a WtE plant. These issues are further complicated by the fact that incomplete source separation of waste adds to the problem since complex waste mixtures may result in inefficient generation of energy.

Most of the areas also do not have adequate waste collection and management systems, which adds to such challenges. Cities use the old-fashioned approaches to waste collection, which do not introduce the adequate sorting and recovery of waste, which results in the lack of proper feedstock in WtE plants and the high expenses of the collection process and sorting. The technological hindrance is also not an easy task as the existing technologies are not applicable or economical in the developing nations. Unavailability of key staff having special skills and absence of systematic training programs are also obstacles to the effectiveness of the work.

WtE technologies also have environmental concerns in that the thermal emission profile of some treatment processes such as incineration may have the harmful elements released into the atmosphere. New methods such as gasification have fewer demands on emission with a high quality of syngas. Another obstacle to a successful policymaking is the lack of a connection between researchers and policymakers concerning the advantages and disadvantages of WtE technologies.

The other significant challenge is social acceptance since the community would be reluctant to accept WtE projects because it might be viewed as contamination or a threat to their well being. Such socio-political impediments are paramount in building trust among the stakeholders by efforts of stakeholder engagement.

Another problem in WtE projects is financial uncertainty, and most cities have financial constraints that act as barriers to investing in infrastructure or technology. Governance systems do not allow adapting WtE on different levels, and local administrations of low experience and knowledge levels regarding the functioning of the WtE do not encourage the inclusion of different stakeholders engaged in managing waste.

To sum up, these technical issues suggest the difficulty of transitioning to sustainable waste management systems particularly in emerging economies that have not yet secured improved energy security under the environmental pressures [3, 11, 37, 39].

9 Policy Recommendations for Accelerating WtE Adoption

In order to hasten the implementation of WtE systems, the policy platform must be holistic to cover different problems associated with these systems. Another issue that the decision-makers ought to consider is coming up with friendly regulations that will encourage the WtE project investment such as incentives to participate in both publicly and privately owned industry and the establishment of partnerships with financial risks.

It is necessary that local communities should be involved in supporting WtE projects by creating awareness among people regarding the advantages of WtE, waste management, energy generation, and greenhouse reduction. Governments are supposed to put control mechanisms, such as strict environmental standards, to make the WtE plants operate responsibly and make technological innovations.

Other important parts of policy recommendations include stimulation of research and development. Governments ought to invest on research and development operations to upgrade the technologies and develop new technologies, including the advanced gasification or anaerobic digestion. Pilot projects will prove the advantages of innovational technologies and will draw more investments and the interest of the stakeholders.

The barriers to the economy can be opened to encourage the use of WtE by providing favorable financing facilities such as the low-rate lending or special financing to the target cities that intend to construct WtE. This can enable the local governments to invest in WtE solutions with low start-up capital investments.

The economics of WtE projects can be enhanced by a transparent market model that will enable the operators to sell and buy the produced energy with the help of fee-in tariffs or power purchase contracts and encourage the usage of renewable energy sources. When regional waste compositions are analyzed properly, the relevant WtE technologies to be applied to the community can be determined and thus this will enhance operational efficiency and effectiveness and minimize the effect on the environment.

The synergies of successful WtE projects can be formed by the constant communication with the government agencies, non-governmental companies, universities, and civil society groups. Issues of health and environmental impact should be taken care of in getting the population on board. An integrated approach involving regulation models, economic incentives, participative cultures, emerging technologies, local evaluations, cross-sector collaborations, and openness coordinated will be significant in the enhancement of the application of WtE technologies throughout countries [3, 20, 37–39].

9.1 Actionable WtE Recommendations

In order to encourage the use of wind turbines (WtE), the governments of the countries must offer feed-in tariffs (FITs) of WtE power where the price of electricity generated in the WtE plant is guaranteed to be higher than it is in the market. The source should begin with waste separation as households and commercial waste should be separated on organic, recyclable and residual waste. Mechanisms of Viability Gap Funding (VGF) must be made to lower the cost of capital in low-income regions, which will encourage the use of private funds. All WtE offers should be subjected to LCAs and environmental audits in order to enhance transparency and environmental utility maximization.

Nationally Determined Contributions (NDCs) should contain WtE and must be a part of the climate commitments of countries to the Paris Agreement. This will enable the access of carbon finance, the clean development mechanism (CDM) and the international climate investment. The optimisation of WtE processes and the possibility of university-industry collaboration should be facilitated by the creation of special research centres.

In order to continue the uptake of WtE, high-level policy needs to be converted into concrete, enforceable policies. These are the introduction of feed-in tariffs, source segregation, in the direct form of subsidies (viability gap funding), lifecycle analysis as an element of environmental regulation, and the introduction of WtE in climate policies. This will aid in accelerating the practice of WtE and bringing it closer to sustainable development and decarbonization goals.

9.2 Future Directions and Research Gaps in the Field of WtE Technology Development

The research in the Waste Treatment and Empowerment technology should aim at streamlining it and making it more sustainable in the future. This includes adjusting to the changing policies and climate change where the models should be flexible and capable of responding to the nature of waste. This will raise the sustainability of the WtE technologies and the long-term economic and environmental impacts should be taken into account.

The current multi-criteria decision analysis (MCDA) procedures usually fail to consider the locality, hence tailor-made applications must be done in accordance with local waste profile, infrastructural capacity and regulatory capacity. This will result in improved considerations of WtE technologies, as opposed to technical feasibility or socio-cultural appropriateness only.

Some of these promising opportunities that can be provided to the stakeholders include new technologies like carbon capture and incineration optimization or integration of different WtE processes. These have the potential of increasing the flexibility of the selection models and allow the stakeholders to select the most successful strategies.

The collaboration between the government and the business world may assist in sharing of knowledge, promote best practices, and retain consistency in the processes of recycling. The impact of various activities on the environment can be captured in holistic lifetime assessment which enhances responsibility in the generation of gains in the long-term.

In order to establish WtE on large scale, it is necessary to analyze the dynamics of societies in areas where WtE facilities are situated. The resistance to new technologies can be minimised through sustained monitoring and engagement and a platform created where all parties interested can strive to achieve some form of sustainability.

There is also an opportunity that the researchers should look into to consider the possibilities to transfer or scale up the good WtE practices in different locations, taking into account logistic issues, economic gains, and environmental impact effects. An answer to these problems through partnership, technological improvements, policy changes, participation of general population and in-depth research enables the interested parties to come up with sustainable energy projects that will aid the health of the environment and help in addressing the needs of locals [3, 21, 37, 40].

10 Conclusions

WtE technology provides an essential solution to waste management and helps maintain a stable energy supply for the growing global population. The quantities of waste generated increase along with the expanding urban population, thus requiring new disposal and energy generation strategies. WtE technology converts different types of waste into energy sources, resulting in fewer landfills and accelerating renewable energies. However, their implementation is impeded by serious economic, technical, and social obstacles.

The emerging economies have difficulty in adopting WtE system, including a lack of developed infrastructure and stringent regulation systems. Inefficiency in its operation is caused by inappropriate source segregation and a high capital investment cost. The industry has a potential to explore state-of-the-art technology such as gasification and pyrolysis, to comply with the principles of sustainability to preserve air quality and human health.

WtE program cannot be successful without the consent of people. Through successful outreach, the community should be educated about the environmental benefits of WtE compared to land filling and non-energy recovery incineration. It is important to build relationships with the local authorities, the community members, and the leaders in the industry when it comes to partnership in WtE projects.

The European and Asian-Pacific case studies showed that there were successful integrated strategies of WtE technology. As the European Union follows the principles of circular economy, the strategy of policy systems encourages investments in sustainable practices, resulting in carbon neutrality.

There are still issues faced by the world in terms of citizen perception and technology adoption. To make WtE solutions more acceptable, the stakeholders should collaborate; the governments should stipulate all-round policies;

researchers should pioneer; non-profit organizations should advance community interest; and private organizations should invest in new technology.

Future research should aim to understand the specificity of a region and its impact on WtE implementation under different cultural and economic conditions. Exploring decentralized forms could reveal alternative approaches to communities that cannot commit to large-scale systems targeting sustainability.

Smart grid technology, coupled with energy storage, provides customized solutions to the various socio-economic environments. Although there are some risks involved in the implementation of WtE programs on the international level, the benefits derived from the new initiative to waste management and renewable energy generation cannot be overestimated. The combined actions of all concerned parties are required to handle the immediate environmental challenges and make a positive step towards the achievement of sustainable development goals.

Author Contributions

Conceptualization, H.M.M. and M.S.K.; formal analysis, K.A.A.; investigation, M.S.K.; writing—original draft preparation, M.S.K.; writing—review and editing, H.M.M.; supervision, M.S.K.; project administration, M.S.K. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] A. Tabibi, "Introduction to Waste to Energy (WtE) Technology," 2024. https://green.org/2024/01/30/introduction-to-waste-to-energy-wte-technology/

[2] I. U. Rahman, H. J. Mohammed, and A. Bamasag, "An exploration of recent waste-to-energy advancements for optimal solid waste management," *Discov. Chem. Eng.*, vol. 5, no. 1, 2025. https://doi.org/10.1007/s43938-025-00079-8

[3] A. Soni, S. K. Gupta, N. Rajamohan, and M. Yusuf, "Waste-to-energy technologies: A sustainable pathway for resource recovery and materials management," *Mater. Adv.*, vol. 6, no. 14, pp. 4598–4622, 2025. https://doi.org/10.1039/d5ma00449g

[4] A. Gomstyn and A. Jonker, "What is waste-to-energy?" 2019. https://www.ibm.com/think/topics/waste-to-energy

[5] B. Dastjerdi, V. Strezov, R. Kumar, and M. Behnia, "Environmental impact assessment of solid waste to energy technologies and their perspectives in Australia," *Sustainability*, vol. 14, no. 23, p. 15971, 2022. https://doi.org/10.3390/su142315971

[6] Y. Luo, M. Ye, Y. Zhou, R. Su, S. Huang, H. Wang, and X. Dai, "Assessing the environmental impact of municipal waste on energy incineration technology for power generation using life cycle assessment methodology," *Toxics*, vol. 12, no. 11, p. 786, 2024. https://doi.org/10.3390/toxics12110786

[7] Babcock and Wilcox, "What is Waste-to-Energy (WtE)?" 2025. https://www.babcock.com/home/renewable/waste-to-energy/waste-to-energy-technology

[8] Ecomaine, "Waste-to-Energy Power Plant." https://www.ecomaine.org/our-facility/waste-to-energy-plant/

[9] U. S. Energy Information Administration (EIA), "Waste-to-energy (MSW) in depth," 2024. https://www.eia.gov/energyexplained/biomass/waste-to-energy-in-depth.php

[10] Global CCS Institute, "Waste-to-Energy with CCS: A pathway to carbon-negative power generation," 2019. https://www.globalccsinstitute.com/publications/waste-to-energy-with-ccs-a-pathway-to-carbon-negative-power-generation/

[11] I. Khan, S. Chowdhury, and K. Techato, "Waste to energy in developing countries—A rapid review: Opportunities, challenges, and policies in selected countries of Sub-Saharan Africa and South Asia towards sustainability," *Sustainability*, vol. 14, no. 7, p. 3740, 2022. https://doi.org/10.3390/su14073740

[12] M. A. Alao, O. M. Popoola, and T. R. Ayodele, "Wastetoenergy nexus: An overview of technologies and implementation for sustainable development," *Cleaner Energy Syst.*, vol. 3, p. 100034, 2022. https://doi.org/10.1016/j.cles.2022.100034

[13] Winno Energy, "Waste-to-Energy: Turning Trash into Power," 2024. https://winnoenergy.com/waste-to-energy-turning-trash-into-power/

[14] T. W. Kirchstetter, C. D. Scown, A. Satchwell, L. Jin, S. J. Smith, C. V. Preble, J. Amirebrahimi, M. D. Sohn, N. J. Brown, S. Nordahl, and et al., "Enabling Anaerobic Digestion Deployment to Convert Municipal Solid

Waste to Energy," *California Energy Commission*, 2020. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-011.pdf
[15] Perch Energy, "Advancements iin Waste-to-Energy Technology: Anaerobic Digestion to Gasification," 2024. https://www.perchenergy.com/blog/innovation/waste-to-energy-technologies-benefits-challenges
[16] S. A. Ali Shah, C. Longsheng, Y. A. Solangi, M. Ahmad, and S. Ali, "Energy trilemma based prioritization of waste-to-energy technologies: Implications for post-COVID-19 green economic recovery in Pakistan," *J. Clean. Prod.*, vol. 284, p. 124729, 2021. https://doi.org/10.1016/j.jclepro.2020.124729
[17] Wikipedia, "Waste-to-energy," 2025. https://en.wikipedia.org/wiki/Waste-to-energy
[18] United Nations Climate Change, "Waste to energy technologies." https://unfccc.int/technology/waste-to-energy-technologies
[19] S. Mor, K. Kaur, and K. Ravindra, "Methane emissions from municipal landfills: A case study of Chandigarh and economic evaluation for waste-to-energy generation in India," *Front. Sustain. Cities*, vol. 6, p. 1432995, 2024. https://doi.org/10.3389/frsc.2024.1432995
[20] A. Farooq, P. Haputta, T. Silalertruksa, and H. Shabbir Gheewala, "A framework for the selection of suitable waste to energy technologies for a sustainable municipal solid waste management system," *Front. Sustain.*, vol. 2, no. 2, p. 681690, 2021. https://doi.org/10.3389/frsus.2021.681690
[21] S. C. Patil, C. Schulze-Netzer, and M. Korpås, "Current and emerging waste-to-energy technologies: A comparative study with multi-criteria decision analysis," *Smart Energy*, vol. 16, p. 100157, 2024. https://doi.org/10.1016/j.segy.2024.100157
[22] M. M. Tun, P. Palacky, D. Juchelkova, and V. Sítař, "Renewable waste-to-energy in Southeast Asia: Status, challenges, opportunities, and selection of waste-to-energy technologies," *Appl. Sci.*, vol. 10, no. 20, p. 7312, 2020. https://doi.org/10.3390/app10207312
[23] S. Sharma, S. Basu, P. Nagaraj Shetti, M. Kamali, P. Walvekar, and M. Tejraj Aminabhavi, "Waste-to-energy nexus: A sustainable development," *Environ. Pollut.*, vol. 267, p. 115501, 2020. https://doi.org/10.1016/j.envpol.2020.115501
[24] M. Rios and M. Kaltschmitt, "Electricity generation potential from biogas produced from organic waste in Mexico," *Renew. Sustain. Energy Rev.*, vol. 54, pp. 384–395, 2016. https://doi.org/10.1016/j.rser.2015.10.033
[25] S. Zafar, "What Type of Waste Can Be Converted into Renewable Energy," *EcoMENA*, 2024. https://www.ecomena.org/renewable-energy-from-wastes/
[26] U. S.Department of Energy, "Waste-to-Energy." https://www.energy.gov/eere/bioenergy/waste-energy
[27] I. Gergel, "Waste to Energy Technologies Overview," *Waste to Energy International*, 2021. https://wteinternational.com/news/waste-to-energy-technologies-overview/
[28] A. R. Pfadt-Trilling, T. A. Volk, and M. O. P. Fortier, "Climate change impacts of electricity generated at a waste-to-energy facility," *Environ. Sci. Technol.*, vol. 55, no. 3, pp. 1436–1445, 2021. https://doi.org/10.1021/acs.est.0c03477
[29] A. Tabibi, "Waste-to-Energy Technologies and Their Environmental Impact," *ThemeSphere*, 2024. https://green.org/2024/01/30/waste-to-energy-technologies-and-their-environmental-impact/
[30] SBNsoftware, "What technological advancements are changing waste management practices?" 2025. https://sbnsoftware.com/blog/what-technological-advancements-are-changing-waste-management-practices/
[31] S. Sharma, S. Basu, P. Nagaraj Shetti, M. Kamali, P. Walvekar, and M. Tejraj Aminabhavi, "Waste-to-energy nexus: A sustainable development," *Environ. Pollut.*, vol. 267, p. 115501, 2020. https://doi.org/10.1016/j.envpol.2020.115501
[32] UN-Habitat, "Urban Energy." https://unhabitat.org/topic/urban-energy
[33] Vermont, "Institute for Energy and the Environment," 2025. https://www.vermontlaw.edu/academics/centers-and-programs/institute-for-energy-and-the-environment
[34] T. Michael, "Environmental and social impacts of waste to energy (WTE) conversion plants," in *Waste to Energy Conversion Technology*. Woodhead Publishing, 2013, pp. 15–28. https://doi.org/10.1533/9780857096364.1.15
[35] Y. Lv, "Transitioning to sustainable energy: Opportunities, challenges, and the potential of blockchain technology," *Front. Energy Res.*, vol. 11, p. 1258044, 2023. https://doi.org/10.3389/fenrg.2023.1258044
[36] V. Weghmann, "Waste to energy: A privatized false solution," 2024. https://www.tni.org/en/article/waste-to-energy
[37] Md. Ruhul Ferdoush, R. A. Aziz, C. L. Karmaker, B. Debnath, M. H. Limon, and A. B. M. Mainul Bari, "Unraveling the challenges of waste-to-energy transition in emerging economies: Implications for sustainability," *Innov. Green Dev.*, vol. 3, no. 2, p. 100121, 2024. https://doi.org/10.1016/j.igd.2023.100121
[38] Y. Xie and B. Lin, "Understanding the dynamic changes in public support for waste incineration power plants in China's first-tier cities," *Renew. Energy*, vol. 247, p. 123064, 2025. https://doi.org/10.1016/j.renene.2025.12

3064

[39] N. R. Longfor, L. Dong, T. Sudo, and X. Qian, “A systems approach to analysing drivers and barriers to waste-to-energy utilization in the Global South: The case of Cameroon,” *Sustain. Prod. Consum.*, vol. 58, pp. 30–45, 2025. https://doi.org/10.1016/j.spc.2025.06.004

[40] World Economic Forum, “How technology designed to help us reach net zero can also leave zero waste.” https://www.weforum.org/stories/2025/03/why-a-net-zero-world-must-also-be-zero-waste/