# The Role of Waste to Energy in the Circular Economy

Waste to Energy

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# Abstract

Since the world population and the amount of waste produced continue to grow, sustainable waste management is becoming increasingly essential. A circular economy provides solutions to the challenges of traditional waste management by emphasizing waste prevention, reuse and recycling. If prevention, reuse or recycling is not possible, one option is to treat the waste for energy recovery. Waste-to-energy (WtE) includes processes that transform waste into different forms of energy. The objective of this report was to explore the role of WtE in the circular economy. Literature was studied to understand the link between WtE and circular economy. Moreover, case studies of Germany, Latvia, and China were analyzed to see how WtE is implemented in different countries. WtE enables the treatment of waste that cannot be feasibly recycled. It also decreases the amount of waste that ends up in the landfills and contributes to renewable energy production. However, WtE should be utilized according to the waste hierarchy, so after waste prevention, reuse, and recycling. WtE does not compete with recycling but rather offers an alternative to landfill. Germany has one of the highest recycling rates of the EU countries. There are over 150 incineration plants in the country. Germany also has a landfill ban for untreated waste. Latvia, where over 50 % of municipal solid waste is landfilled and only 3 % is used for energy recovery, has implemented high landfill taxes in order to reduce landfilling and motivate the use of other waste treatment methods. China has made progress with its waste management since the 1980s but its landfill rate remains high so there is still room for improvements.

**Key-words:** Waste; Energy; Circular economy.

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# 1 INTRODUTION

Just like water, health and freedom, it is correct to say that in modern times, we can also refer to “energy” as a fundamental asset for quality of life, a vital force that drives nations. Without it, there is no industry, let alone technological and economic development. Worldwide, there has been an “awakening” of minds regarding matters related to sustainability and ensuring a habitable world for future generations. This has created, as never observed before, a pressing need to promote and encourage the use of cleaner, more efficient and sustainable forms of energy.

One such efficient form is known as Waste-to-Energy (WTE), which plays a fundamental role in waste treatment by driving the purification of waste disposal and maximizing the use of energy contained in exhaust gases. It encompasses various waste treatment processes that produce energy in the form of electricity, heat and fuels, with varying environmental impacts and circular potential. It is essentially defined as the process of transforming something that no longer has utility into a useful resource [1] [2].

At the same time this “awakening” and technological evolution emerged, the global population was directly impacted, experiencing rapid growth. As of 2023, the world population has surpassed 8 billion, bringing about environmental challenges as well as issues related to the waste produced. This compels us to rethink how waste is managed, discarded and reused, as traditional methods such as landfills have become unsustainable due to space limitations, greenhouse gas emissions, wastefulness, and soil and water contamination. It is estimated that by 2050, the population will reach 9.7 billion people and 11 billion by the end of the century. Urgent measures are needed as it is projected that the amount of waste produced daily around the world will increase to about 3.5 million tons per year, and this figure is expected to reach 6.1 million tons annually by 2025, as illustrated in Figure 1. Figures 2 and 3 show how population growth has directly impacted the increase in CO2 emissions associated with waste. Part of these emissions originates from inadequate waste management [3] [4].

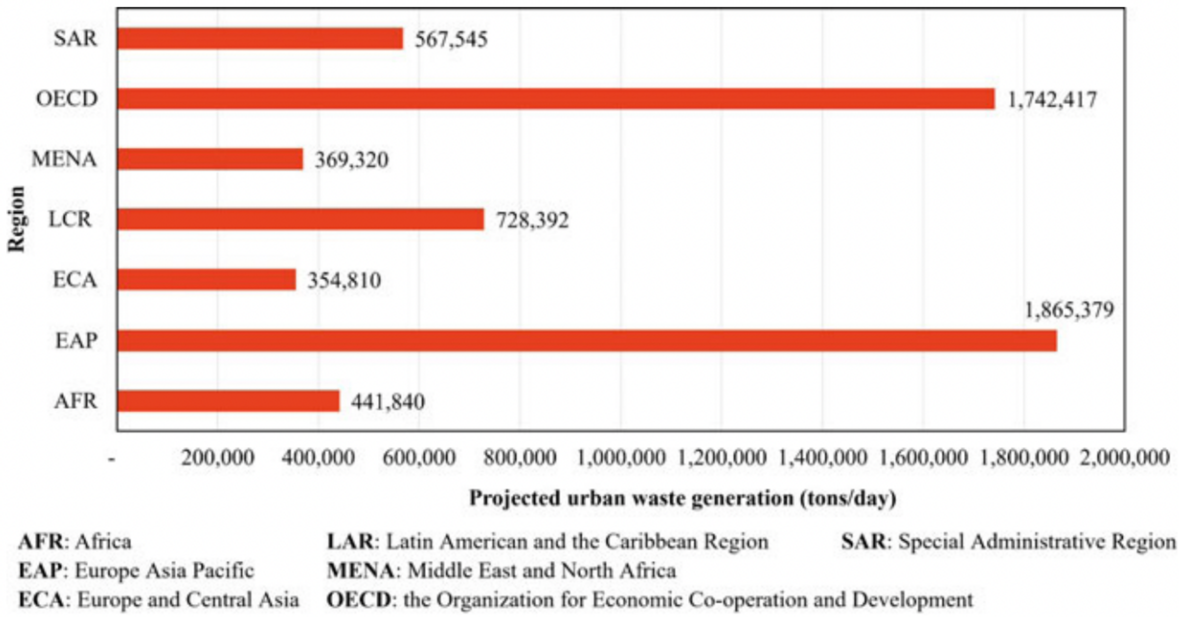


*Figure 1: World waste generation by 2050 (regions) [4]*

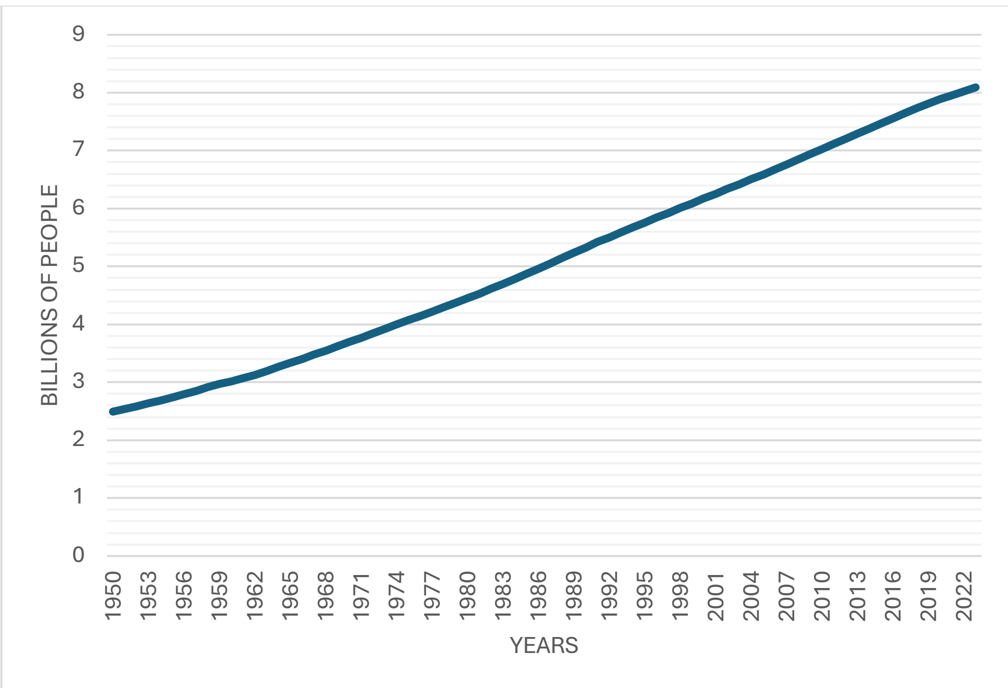


*Figure 2: World population over the years [3]*

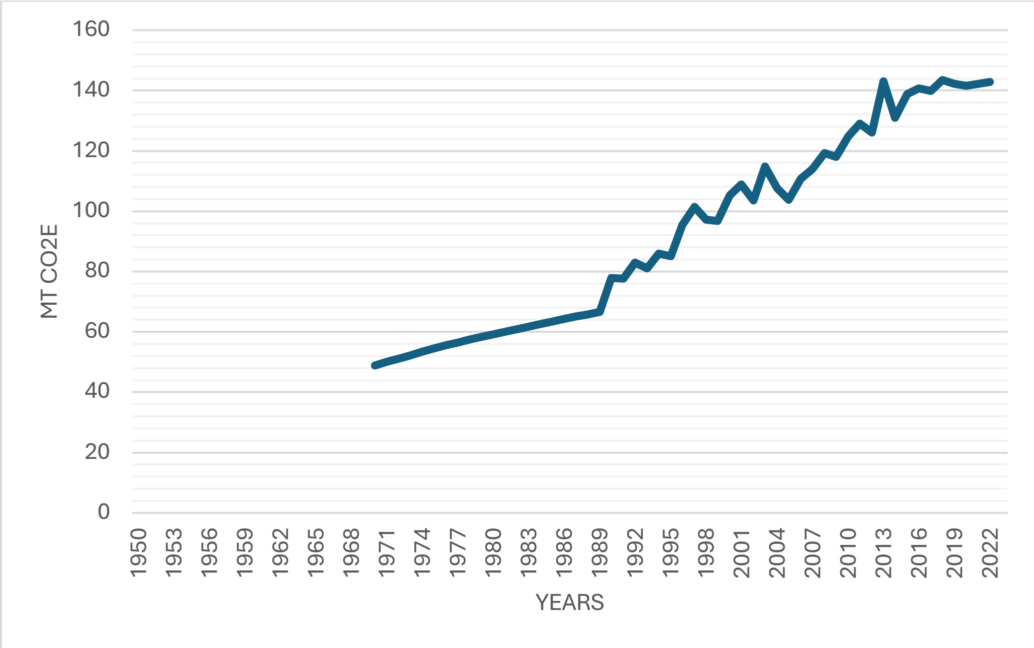


*Figure 3: CO2 emissions from Waste [5]*

Of all the waste generated worldwide, approximately 44% consists of organic waste (food and vegetation), 33% of recyclable materials (paper, cardboard, plastic, glass and metals) and 18% of materials such as wood, rubber, leather and others. However more than a third of all this is improperly discarded, especially in emerging countries, where 93% is either openly burned or disposed of in vacant lots, roadside areas or waterways [2].

In 2015 the European Commission introduced an action plan for the circular economy that aimed to create new jobs, foster economic growth and promote more sustainable production and consumption patterns aligned with the 2030 Agenda for Sustainable Development. This plan significantly emphasized that achieving a circular economy and reducing emissions requires interventions at all stages of a product's lifecycle (from production to creating markets for secondary raw materials derived from waste). The plan highlights the importance of increasing waste prevention, reuse and recycling, establishing a waste hierarchy based on sustainability [6].

Waste-to-Energy (WTE), one of the options for reusing the increasing volume of waste, is divided into several processes [6]:

- Co-incineration of waste in combustion plants;
- Waste incineration;
- Anaerobic digestion of biodegradable waste;
- Production of solid, liquid or gaseous fuels derived from waste;
- Other processes such as indirect incineration following pyrolysis or gasification steps.

These processes occupy different positions in the waste hierarchy established by European Union legislation, as shown in Figure 4. For example, anaerobic digestion is considered a recycling operation, whereas waste incineration with low energy recovery is regarded as final disposal.

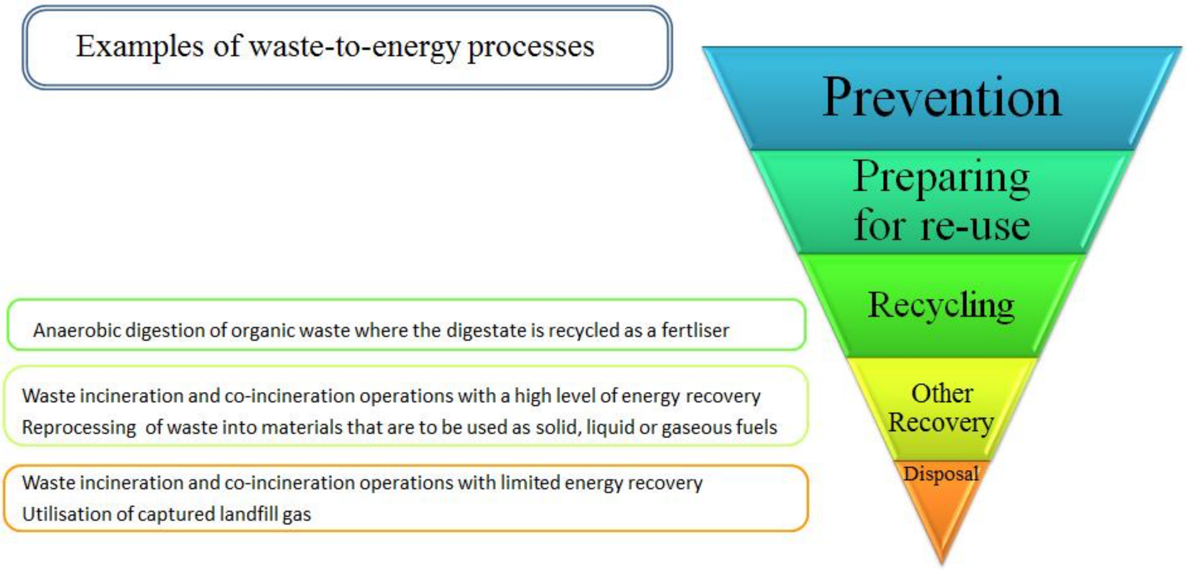


*Figure 4: Process of WTE process in the waste hierarchy [6]*

It is thus confirmed that Waste-to-Energy (WTE) plants are becoming the most effective solution for closing the circular economy loop, as they recover resources even from waste that cannot be recycled, preventing it from being sent to landfills and generating energy from the organic matter present in the waste [7].

In Figure 5, which includes steps such as collection, recycling, material recovery and waste-to-energy conversion, the integration of the main processes in the circular economy can be observed. Meanwhile, Table 1 shows the various contributions.


*Figure 5: Representation of the Circular Economy in the Waste Management Sector [8]*

*Table 1: Contribution of Waste-to-Energy to the Circular Economy [7]*

| Contribution of Waste to Energy to the Circular Economy | Description |
|---|---|
| Hygienic service to the community | Ensures the treatment of non-recyclable and polluting waste, preventing its disposal in landfills and the associated environmental impacts. |
| Recovery of secondary materials | Allows the extraction of useful resources, such as metals and minerals, from the ashes resulting from the incineration process, reintegrating them into the production chain. |
| Local energy production | Converts waste into stable sources of electricity, heat, and fuels, reducing dependence on fossil fuels. |
| Carbon capture and reuse | Uses carbon capture technologies to reduce emissions and produce new materials and fuels, promoting environmental sustainability. |

Basically, in the traditional linear economy, natural resources are extracted to meet consumption and production demands, generating emissions and waste that harm the environment. In contrast, the circular economy proposes a more efficient approach, reducing waste and reusing materials, which minimizes emissions and consumption. Figure 6 illustrates the differences in the context of waste. By way of example, solid waste, such as bottom ash composed of metals and minerals, can be used in construction to replace cement, sand and gravel. Biodegradable waste can be diverted from landfills to processes like anaerobic digestion, which produces biogas and fertilizers [4].

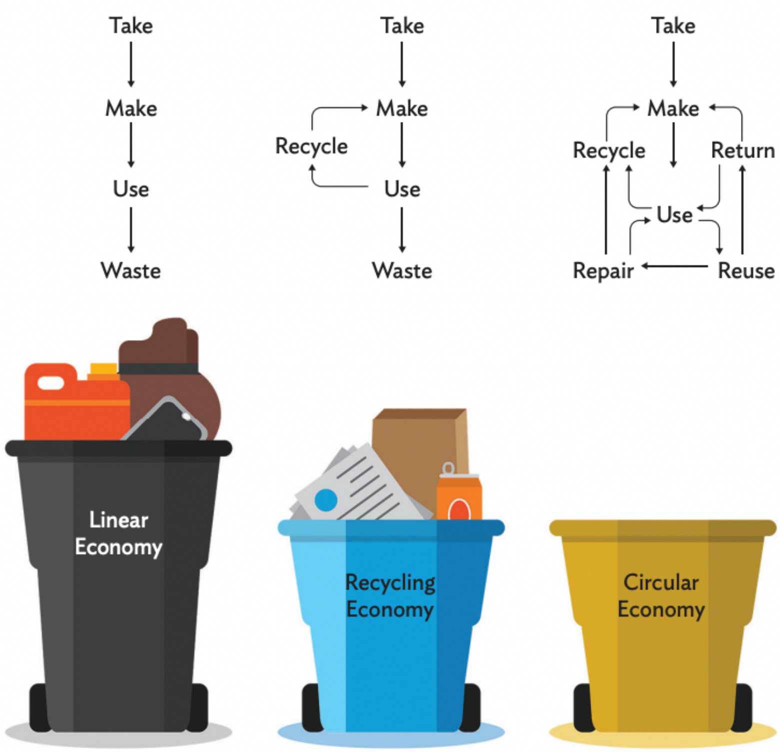


*Figure 6: Economy types [2]*

On the other hand, when analyzing how final energy is consumed worldwide, a significant growth in the transportation sector has been observed and cannot be ignored. This growth is also a result of increasing urbanization and societal development. Over the last 32 years, this sector has grown by approximately 77.58%, as shown in Figure 7. This exponential growth highlights additional environmental problems, presenting yet another opportunity for Waste-to-Energy to help decarbonize this sector [9].

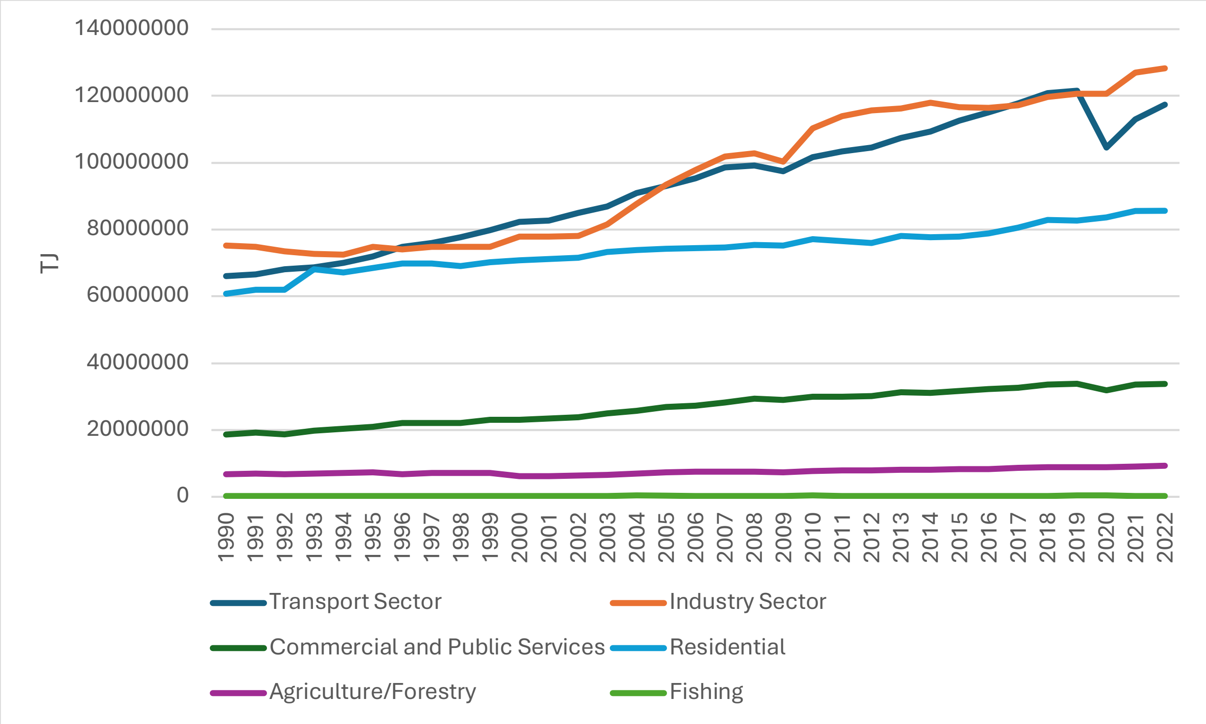


*Figure 7: World total final consumption by sector [9]*

The energy generated in the European Union from waste is used in urban systems as a replacement for fossil fuels, enhancing the integration between waste management and energy [4].

Throughout this work, the different Waste-to-Energy technologies will be explored, along with their link to the circular economy, benefits, challenges and case studies from around the world to concretely observe their real-world functioning.

# 2 Circular Economy

## 2.1 Definition and Key Principles

The circular economy (CE) represents a transformative economic model that prioritizes the sustainable management of resources by shifting from a linear system ("take, make, dispose") to a regenerative cycle. It seeks to address critical global challenges, including resource depletion, environmental degradation, and economic instability, by rethinking how materials and energy flow through the economy.

The CE is defined by three guiding principles, as outlined by the Ellen MacArthur Foundation [10]:

1. **Eliminate waste and pollution** – Redesign systems and products to prevent waste from being generated.

2. **Circulate products and materials** – Maximize the utility of materials by keeping them in use through repair, reuse, and recycling.
3. **Regenerate natural systems** – Support ecosystems by restoring natural resources rather than depleting them.


*Figure 8: Principles of circular economy [11]*

The CE moves beyond traditional recycling by incorporating systemic changes to product design, production processes, and consumer behavior. Unlike linear systems that treat waste as an endpoint, the CE integrates waste as a valuable input for other processes, creating closed-loop cycles.

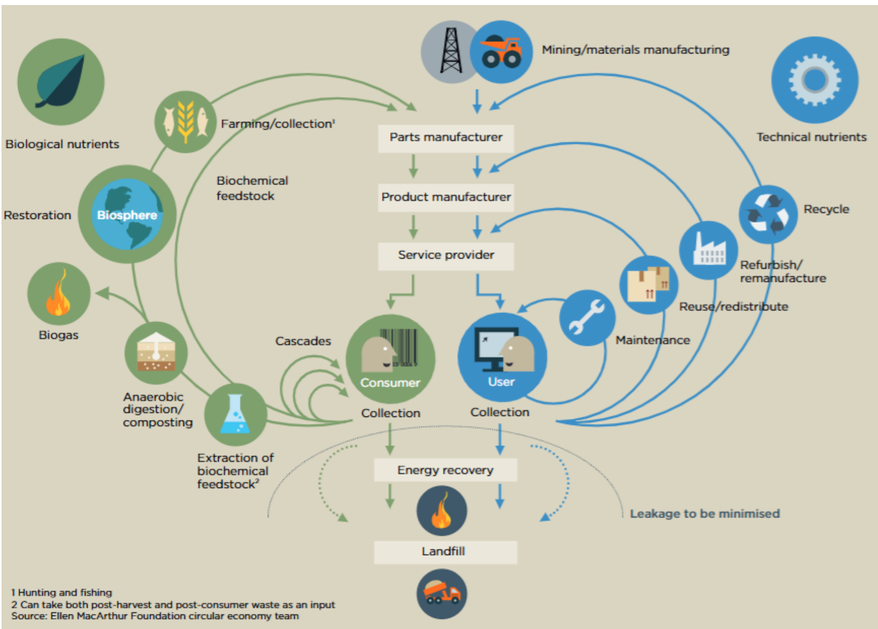


*Figure 9: Material flow in a circular economy [11]*

The push to transition the material composition of consumables from technical to biological nutrients, ensuring they cascade through multiple applications, reflects a core principle of the restorative circular economy. This process involves extracting valuable feedstock and ultimately reintroducing nutrients back into the biosphere.

Figure 9 demonstrates how products and materials based on technological and biological nutrients cycle through the economic system, each following distinct pathways and exhibiting unique characteristics.

## 2.2 The Role of Waste in the Circular Economy

In the CE, waste is reconceptualized as a resource with intrinsic value, integral to new cycles of production. Waste streams, once destined for landfills, are now seen as opportunities to recover materials, extract energy, and regenerate ecosystems. For example:

**Biological and Technical Waste Streams**

- **Biological Materials**: Organic waste such as food, agricultural residues, and yard trimmings can be composted or converted into biogas. This approach regenerates nutrients in the biosphere and mitigates methane emissions from landfills.
- **Technical Materials**: Metals, plastics, and glass are treated as secondary raw materials, reducing the dependency on virgin resources. Advanced recycling technologies enable the efficient recovery of these materials for reintroduction into production processes [12].

Waste management systems play a pivotal role in closing material loops. Effective systems reduce resource extraction, mitigate environmental impacts, and create secondary raw material markets.

**Challenges and Opportunities**

**Challenges:**

- **Economic Barriers**: Transitioning to circular systems requires significant investment, particularly in infrastructure and innovative technologies [12].
- **Policy Gaps**: Many regions lack cohesive policies to support circular initiatives, such as extended producer responsibility (EPR) schemes.
- **Consumer Behavior**: Shifting public attitudes towards reuse and repair remains a persistent challenge.

**Opportunities**:

- **Resource Efficiency**: By extending the lifespan of products, the CE reduces the demand for virgin resources.

- **Job Creation**: Industries such as recycling, remanufacturing, and waste-to-energy (WTE) contribute to employment growth.
- **Innovation**: Designing for circularity fosters innovation, such as modular smartphones and recyclable packaging.

Regarding these challenges and opportunities, OECD [12] did a survey in the countries and cities represented in Figure 10, showing the main obstacles and the primary drivers to the circular economy, represented in Figures 11 and 12.

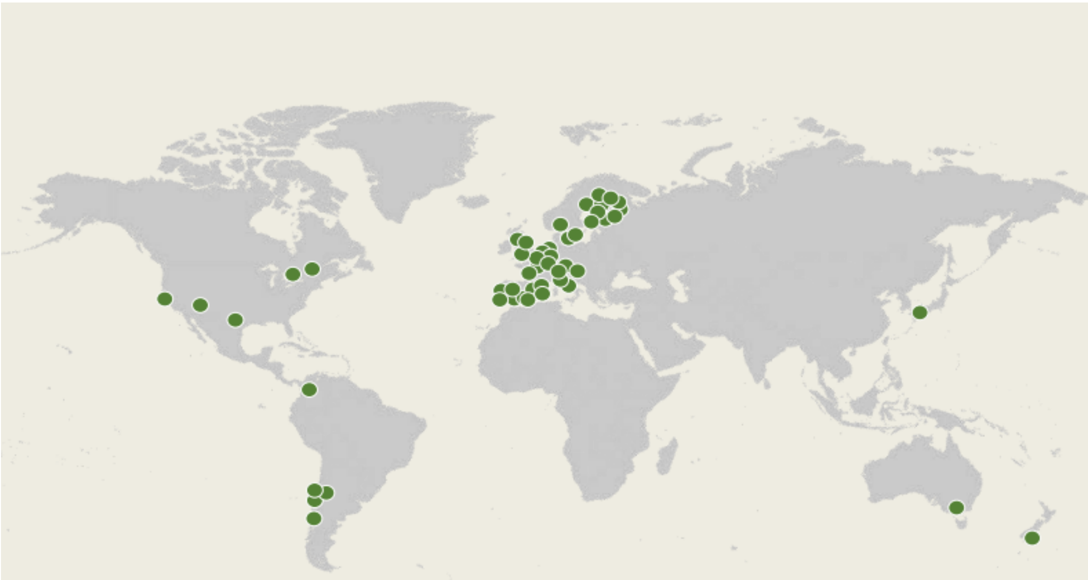

*Figure 10: Map of cities and regions surveyed [12]*

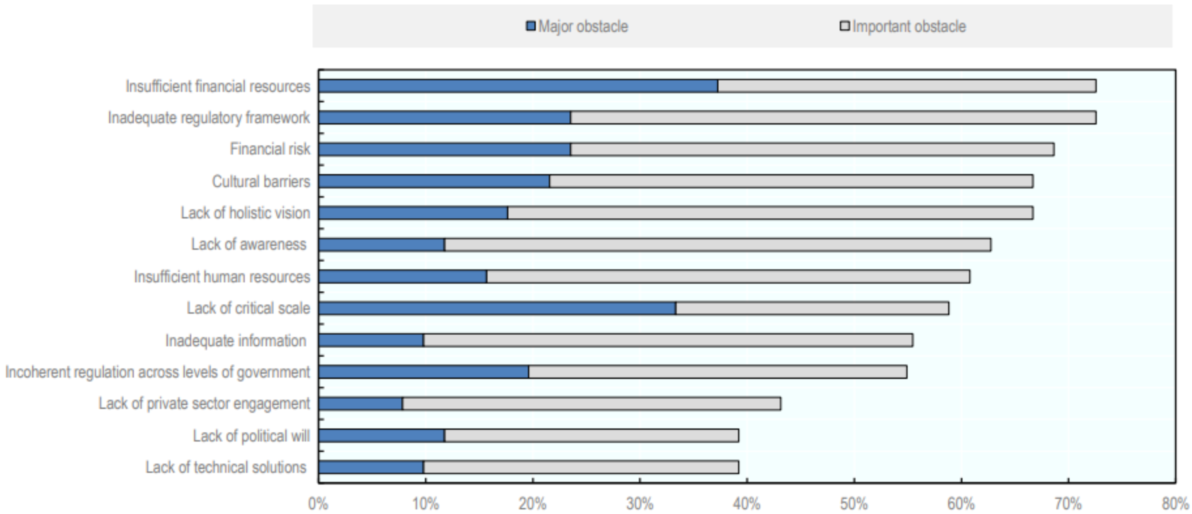


*Figure 11: Main obstacles to the circular economy in surveyed cities and regions [12]*

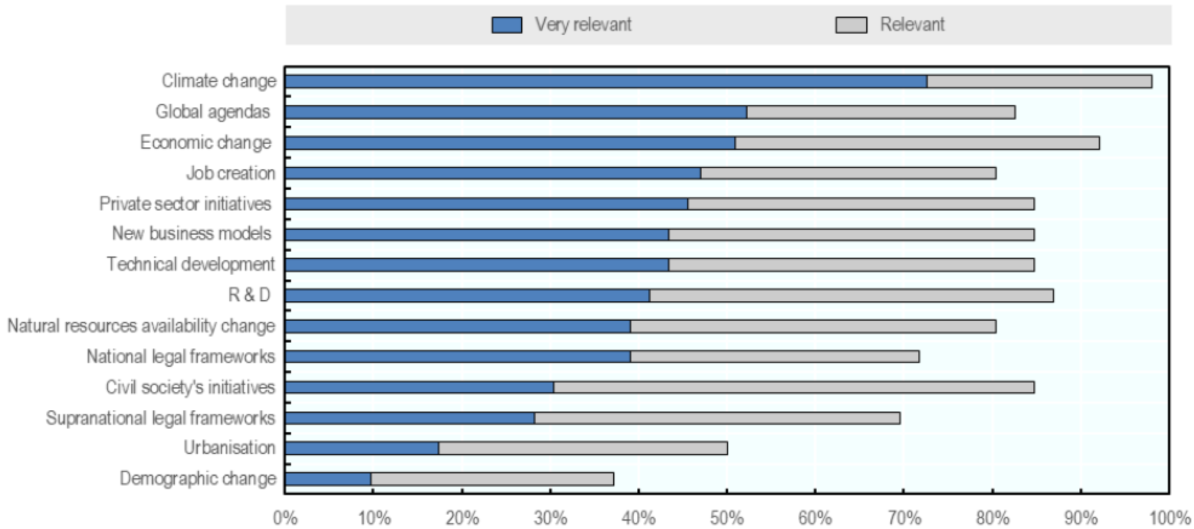


*Figure 12: Drivers of the circular economy in surveyed cities and regions [12]*

**Circular Economy and Waste-to-Energy (WTE)**

A unique aspect of the CE is the integration of waste-to-energy technologies to handle non-recyclable waste. These technologies bridge the gap between material recovery and energy production. [13]

This means that Waste-to-energy (WtE) technologies play a particular role in a circular economy. These technologies convert solid waste materials that would otherwise be destined for landfill into heat, electricity, or fuel. By doing so, waste-to-energy can reduce the volume of waste, generate energy, and save on traditional waste disposal costs. However, it's important to remember that in a truly circular economy, the goal is to keep materials in use as long as possible and reduce waste to a minimum. Therefore, waste-to-energy should be seen as a last resort for dealing with waste after options for reduction, reuse, repair, and recycling have been explored [11].

# 3 Waste to Energy (WTE)

## 3.1 Overview of Waste-to-Energy Technologies

Waste-to-Energy (WtE) technologies involve the process of generating energy in the form of electricity, heat, or fuel from waste materials. These technologies play a crucial role in waste management, energy creation, and resource recovery. Fig. 13 shows the categories and types of some key waste-to-energy technologies [11]:

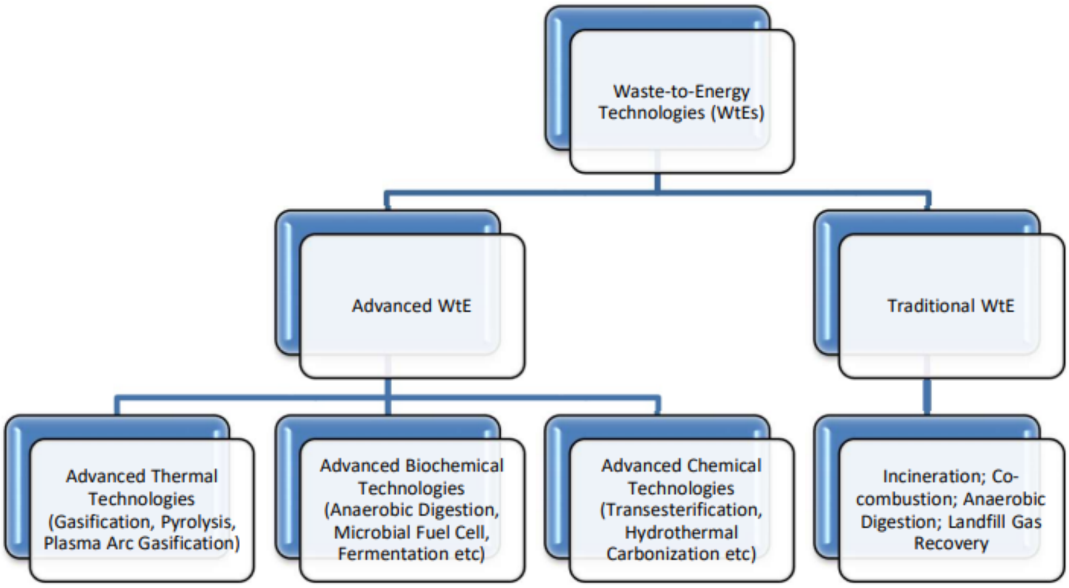


*Figure 13: Broad Categories of Waste-to-Energy Technologies [11]*

## Traditional Waste-to-Energy Technologies

Traditional Waste-to-Energy (WtE) technologies involve the conversion of non-recyclable waste materials into usable heat, electricity, or fuel. These technologies can play a key role in waste management, reducing the volume of waste sent to landfills and generating energy [11].

Several well-established WtE technologies are commonly used today:

**Incineration:**

Incineration remains the most widely adopted WtE method, involving the combustion of waste at high temperatures to produce energy. The heat generated during the process is used to create steam, which drives a turbine to generate electricity. Modern incineration facilities are equipped with advanced pollution control technologies to minimize emissions, although concerns about air quality and residual ash persist [11].

The process typically operates at temperatures exceeding 850°C, reducing waste volume by approximately 90%. The residual ash, accounting for 10-15% of the original waste volume, can often be repurposed in construction or disposed of in landfills [11].

- **Energy Production:** Incineration provides a reliable energy source independent of weather conditions, unlike other renewable energy technologies.
- **Waste Reduction:** It significantly decreases waste volume, conserving landfill space and reducing transportation and handling needs.

However, within the framework of a circular economy, incineration poses certain challenges [11]:

- **Air Pollution and Greenhouse Gases:** Despite modern emission controls, pollutants like dioxins, furans, heavy metals, and particulates can still be released. Additionally, carbon dioxide emissions contribute to climate change.
- **Waste Hierarchy:** In a circular economy, waste prevention, reuse, and recycling are prioritized. Incineration should only be considered for materials that cannot be feasibly reused or recycled.
- **Energy Efficiency:** Recycling materials often saves more energy than incineration can produce. For example, recycling aluminum conserves over 90% of the energy compared to producing new aluminum, while incinerating it for energy is far less efficient.

While incineration has its place in managing waste and generating energy, it should be utilized judiciously to support broader efforts in waste reduction and recycling [11].

**Co-Combustion or Co-Firing:**

This method involves the simultaneous use of waste materials and conventional fuels, such as coal, in industrial boilers or kilns. Co-combustion reduces fossil fuel consumption and emissions while providing an alternative use for certain waste streams [11].

**Anaerobic Digestion (AD):**

Anaerobic digestion is a biological process in which microorganisms decompose organic waste, such as food waste, manure, or sewage sludge, in an oxygen-free environment. The process generates biogas, primarily methane and carbon dioxide, and a nutrient-rich residue known as digestate [11].

- **Biogas Utilization:** Biogas can power combined heat and power (CHP) plants or be upgraded into biomethane for use as renewable natural gas.
- **Digestate Use:** The digestate can serve as a soil conditioner or fertilizer, reducing reliance on synthetic alternatives.
- **Environmental Benefits:** AD mitigates greenhouse gas emissions by capturing methane, a potent greenhouse gas, and offers a renewable energy source that supports the transition away from fossil fuels.

While anaerobic digestion is essential for managing organic waste and producing sustainable energy, challenges include waste sorting, digestate management, and economic viability. In a circular economy, the focus should remain on waste prevention, with AD complementing efforts to reduce food and organic waste [11].

**Landfill Gas Recovery (LGR):**

As organic waste decomposes in landfills, it produces a gas primarily consisting of methane and carbon dioxide. Landfill gas recovery systems capture and utilize this gas for energy production, reducing greenhouse gas emissions and fossil fuel dependency [11].

- **Economic and Environmental Benefits:** Capturing and using landfill gas can provide additional revenue for operators, reduce local air pollution, and create jobs. However, reducing, reusing, and recycling waste should remain a priority to minimize landfill dependency.

Traditional WtE technologies play a significant role in waste management and energy production. However, their use should align with a comprehensive waste management strategy that prioritizes waste reduction, material reuse, and recycling. These technologies should only be applied to non-recyclable materials and designed to minimize environmental impacts [11].

## Advanced Waste-to-Energy Technologies

Advanced Waste-to-Energy (WtE) technologies have evolved to provide more efficient and environmentalfriendly methods for converting waste into energy. These technologies address some of the environmental concerns associated with traditional WtE methods, particularly around emissions and residues [11].

### Thermal Technologies (Gasification, Pyrolysis, Plasma Arc Gasification)

Advanced thermal technologies involve the processing of waste in low-oxygen or oxygen-free environments, converting it into energy-rich products like syngas. These methods generally produce fewer emissions compared to traditional incineration and can handle a wide variety of waste materials. For instance, waste plastics, which pose significant disposal challenges, can be transformed into energy through pyrolysis [11].

**Gasification and Pyrolysis**

Gasification and pyrolysis are advanced thermal processes designed to recover energy from diverse waste types, including municipal solid waste, industrial waste, biomass, and certain hazardous materials. These technologies have been used to process various waste streams, such as garden waste via hydrothermal gasification, printed circuit boards through microwave pyrolysis, municipal solid waste and waste tires are some of the examples [11].

- **Gasification:** This process heats waste at high temperatures in a controlled, low-oxygen environment, preventing combustion. The primary output is **syngas, a mixture of hydrogen, carbon monoxide, and sometimes carbon dioxide**. Syngas is a versatile energy carrier that can be used to generate electricity, heat, or as a precursor for other fuels.
- **Pyrolysis:** This process involves heating waste in an oxygen-deprived environment, breaking it down into three main components: syngas, bio-oil, and char. Syngas and bio-oil are widely used in electricity and heat generation or as chemical feedstocks. Char may be utilized as a soil amendment, though its application depends on its properties and potential contaminants.

These technologies are particularly suited for handling waste materials that are difficult to recycle, reducing landfill dependency while generating energy and valuable byproducts. However, several factors must be considered [11]:

- **Energy Demand:** Both processes require significant energy inputs to heat waste, and the overall energy efficiency depends on the waste type, technology used, and how the resulting products are utilized.
- **Environmental Impact:** Emissions and residues must be managed carefully. Syngas typically requires cleaning to remove impurities, and char from pyrolysis may contain heavy metals or other contaminants.

**Plasma Arc Gasification**

Plasma arc gasification employs a plasma torch to subject waste to extreme temperatures ranging from 10,000°C to 25,000°C. This process converts waste into syngas and produces minimal solid residue (slag), which can potentially be repurposed for construction if uncontaminated. Plasma arc gasification is noted for its ability to handle a broad range of waste types and achieve significant volume reductions [11].

While advanced thermal technologies provide an effective solution for non-recyclable or non-compostable waste, their adoption should be part of a comprehensive waste management strategy emphasizing waste prevention, reuse, and recycling. Furthermore, the energy efficiency, environmental footprint, and economic feasibility of these technologies vary widely, necessitating careful optimization to suit local conditions and specific waste streams [11].

**Biochemical Technologies (Anaerobic Digestion, Microbial Fuel Cell, Fermentation)**

Biochemical technologies utilize microorganisms to transform waste into usable products, including various forms of energy. Advanced approaches in anaerobic digestion (AD) and fermentation address the limitations of conventional systems, enhancing efficiency and output [11].

### Advanced Anaerobic Digestion (AD)

Advanced anaerobic digestion employs optimized biological processes where microorganisms decompose organic materials in oxygen-free environments. This results in improved biogas production, with higher methane content and reduced carbon dioxide, along with nutrient-rich digestate. The biogas can be used for heat and electricity generation, while the digestate serves as a soil conditioner or fertilizer [11].

Enhanced anaerobic digestion is versatile, processing a wide range of organic waste streams such as food waste, agricultural residues, and sewage sludge. Techniques like co-digestion and the use of additives or nanoparticles further enhance performance. AD technology plays a critical role in advancing the circular bioeconomy and achieving carbon neutrality. By converting organic waste into valuable bioenergy and biosolids, it provides a cost-effective and sustainable method for valorizing agricultural biomass and food waste through stages such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis [11].

### Microbial Fuel Cells (MFCs)

Microbial fuel cells are bio-electrochemical systems that harness the metabolic activity of microorganisms to generate electricity by oxidizing organic matter. These innovative devices simultaneously provide sustainable energy and treat wastewater or organic waste, making them a dual-purpose solution [11].

### Fermentation

Fermentation leverages microorganisms, typically yeasts or bacteria, to convert organic compounds such as sugars and starches into alcohols and gases. In waste-to-energy applications, fermentation is often used to produce bioethanol, a renewable fuel for transportation. Additionally, the process generates carbon dioxide and other byproducts, which can be captured and repurposed [11].

The implementation of biochemical technologies is being refined to suit diverse waste streams and local conditions. Key considerations include optimizing energy balances, minimizing environmental impacts, and ensuring economic feasibility [11].

## Chemical Technologies (Transesterification, Hydrothermal Carbonization)

Chemical technologies involve reactions aimed at transforming waste into energy or other valuable products. Within the waste-to-energy (WtE) sector, two prominent technologies include transesterification and hydrothermal carbonization [11].

**Transesterification**

Transesterification is a chemical process used to convert fats and oils into biodiesel. This reaction involves mixing lipids (fats and oils) with an alcohol, typically methanol or ethanol, in the presence of a catalyst, usually a strong alkali. The process produces esters (biodiesel) and glycerol as byproducts. The biodiesel obtained can directly fuel diesel engines [11].

This method is commonly employed to transform waste cooking oil and animal fats into biodiesel, offering a sustainable solution for recycling these waste streams into renewable fuel. Recent advancements have focused on converting plant-based feedstocks into biodiesel. For instance, non-edible plant oils such as castor bean and jatropha have been successfully utilized. Furthermore, nanocatalyst-assisted transesterification has enabled the conversion of microalgae into biodiesel, showcasing its versatility [11].

**Hydrothermal Carbonization (HTC)**

Hydrothermal carbonization is a process that transforms organic waste into a coal-like material known as hydrochar. This is achieved by treating waste with water under conditions of high pressure and temperature. Hydrochar serves as a versatile product, functioning as a solid fuel or as a soil amendment [11].

HTC can process a wide range of organic waste types, including sewage sludge, food waste, and agricultural residues [11].

## 3.2 Criteria for Evaluating the Efficiency of Advanced Waste-to-Energy Technologies

Assessing the effectiveness and efficiency of advanced Waste-to-Energy (WtE) technologies involves an evaluation encompassing both their technical proficiency and their environmental, economic, and social implications. The parameters used to evaluate these technologies were [11]:

**Energy Efficiency**

The overall energy efficiency of a WtE technology can be evaluated by comparing the energy content of the input waste to the usable energy output. This includes the heat and electricity generated or the energy content of any fuels produced [11].

- Thermal Systems: Gasification efficiency ranges from 60%-80%, influenced by feedstock type, operational parameters (temperature, pressure), and reactor design. Integrating advanced systems like solar-assisted gasification boosts efficiency (up to 74%).
- Biochemical Systems: Anaerobic digestion (AD) efficiency depends on the feedstock, pre-treatment, and transportation distances (feedstock transported from places). Co-digestion offers higher energy balances (34.1%-55%) compared to single-feedstock digestion.
- Transesterification: Ultrasound-assisted methods (e.g., with KOH catalyst) improve reaction efficiency and reduce energy requirements for biodiesel production.

**Waste Reduction**

A key measure of the efficiency of WtE technologies is the degree to which they reduce the volume and mass of waste that would otherwise need to be disposed of in landfills. Gasification and pyrolysis can reduce waste volume by 85%-95%, converting organic matter into syngas, bio-oil, or biochars. AD waste reduction varies with feedstock type and pre-treatment [11].

**Environmental Impact**

Lifecycle assessments evaluate emissions, residues, and benefits like reduced landfill use and fossil fuel substitution [11].

**Economic Feasibility**

Costs are balanced against revenues from energy/products and landfill savings [11].

**Social Impact**

Includes job creation, community effects (e.g., traffic, noise), and health considerations from emissions [11].

**Integration with Waste Management**

Technologies must align with local waste characteristics and complement reduction, reuse, and recycling efforts. A thorough evaluation of advanced WtE technologies should consider all these aspects and involve a wide range of stakeholders, including local communities, waste management authorities, and environmental organizations. It should ideally be supported by detailed data and analysis, using tools such as life cycle assessment and cost-benefit analysis [11].

# 4 Benefits and Challenges of WTE in the Circular Economy

This chapter discusses the benefits and challenges in implementing WTE technologies from a circular economy point of view.

## 4.1 Benefits

WtE enables the recovery of energy and materials. Therefore, it is a tool to close material cycles, which contributes to circular economy. It also contributes to energy security, providing a renewable energy source and decreasing dependance on fossil fuels. One major benefit of implementing WTE practices in transitioning towards the circular economy is the reduction of landfill waste. For instance, incineration can decrease the volume of waste by approximately 90 %. This is especially an advantage in regions where area for waste disposal is limited. WtE plants also create job opportunities and therefore also have a social impact [11] [14].

WtE practices also have potential to significantly reduce greenhouse gas emissions. Rezania et al. stated that incineration, pyrolysis, and gasification have significantly lower impact on the environment compared to landfilling waste. In addition, methane emissions originating in landfills are reduced when utilizing WtE technologies rather than landfilling the waste. This can be achieved for example by utilizing anaerobic digestion or landfill gas recovery [11] [14] [15].

WTE technologies can be applied to hazardous waste, which can mitigate harmful impacts caused by hazardous waste and produce renewable energy. Applying WtE to hazardous waste can be used as a tool to remove toxic substances from the material cycle [16].

## 4.2 Challenges

Although implementing WtE practices towards a circular economy has many benefits, it also faces some challenges. Developed and developing countries have different challenges regarding implementing WtE technologies towards a circular economy. A significant problem in developing countries is the lack of funding and technologies. On the other hand, the challenges of the developed countries include changing consumer behaviour towards a more sustainable manner, transitioning towards a circular economy with government support, and creation of economic opportunities by international collaboration [15].

Another challenge is the varying composition of waste. This is relevant especially considering municipal solid waste. The variability can have an impact on the operation of WtE facilities. Scaling up of some technologies, such as pyrolysis and gasification, is also a challenge [11].

Some WtE technologies have harmful environmental impacts since they produce air emissions, such as particulate matter and nitrogen oxides, and greenhouse gas emissions, such as carbon dioxide. Thus, they can contribute to climate change and air quality. The flue gases can be treated with Carbon Capture and Storage technologies or other pollution prevention technologies, but implementation of such processes is expensive and therefore increases the investment costs. Emission control systems can also be challenging from a technical point of view [11] [14] [16].

Some technologies require a steady feed of waste to operate properly. Trying to ensure a steady waste stream could potentially hinder the incentives to aim at waste reduction. Thus, WtE should be considered after waste prevention and recycling, or in other words waste hierarchy should be followed [11].

There are also some economic challenges, since capital and operational costs of the WtE plants can be high. This is especially a problem when there is lack of policy support for implementing WtE technologies [11].

Another challenge is the management of residues produced for instance in incineration, pyrolysis, and gasification. These technologies are also energy intensive [11].

Social acceptance and regulatory issues are also challenges. People are skeptical about WtE plants due to environmental and health issues, and odor and noise that the plants produce and therefore do not necessarily want WtE plants in their backyards. One reason for this is the lack of awareness about the possible impacts on humans and the environment. It is crucial to raise public awareness about benefits of WtE technologies in order to strengthen social acceptance. Implementing WtE facilities might not be economically feasible without policy support [11] [14] [17].

# 5 Case Studies

While there has been an international interest using waste-to-energy technologies to move towards a circular economy, the waste management systems are implemented at a national level, leading to variations in effectiveness, policies, and practices depending on the country’s regulations, infrastructure, and resources. Figure 14 showcases that in countries where WtE technologies are widely used, they do not compete with recycling but rather serve as an alternative to landfilling. This aligns with the EU’s target for member states to reduce landfilling to 10% of generated household waste by 2035, and to recycle at least 65% of collected household waste. If these targets are also applied to industrial waste, WtE plants could produce 189 billon KWh of energy per year [15] [18] [19] [20].

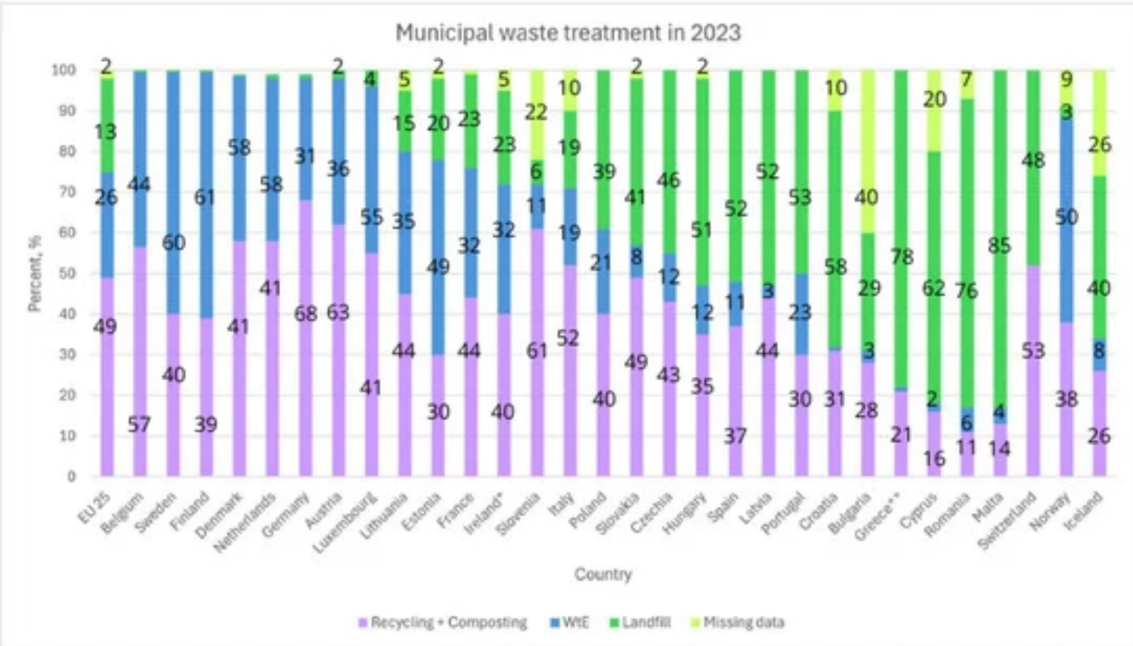


*Figure 14: MSW management in the different EU member states in 2023 [19]*

This chapter provides an overview of case studies based on Germany, Latvia and China.

## Case 1: Germany

Germany adapted a new waste management policy called German Closed Cycle Management Act (Kreislaufwirtschaftsgesetz, KrWG) in 1996. It is built on the concept of closed loop recycling, placing the responsibility for product disposal on manufacturers and distributors, also reducing land usage for waste disposal simultaneously. In 2005, thermal treatment saw a big increase following the ban on landfilling untreated waste and still to this day is dominating the WtE market with over 150 thermal waste incineration plants all over the country [21] [22].

Germany has also focused on moving from disposal to prevention and recycling, which will eventually restrain the incineration market. However emerging WtE technologies, such as Dendro Liquid Energy (DLE) are expected to help WtE market growth [22].

## Case 2: Latvia

Latvian households generate around 869 000 tons of waste annualy. 45% of that is recycled, 3% is used for energy production at the “SCHWENK” cement factory but the rest of the waste is landfilled [19].

To meet the EU targets The Latvian Waste Management Plan 2021–2028 was published, which estimates that around 220 000 tons of waste annualy that is unsuitable for recycling and is being landfilled could actually be utilized for energy production. However, Latvia is still one of the EU countries where waste incineration has yet to be used as one of the types of waste management [19].

Though, Latvia is using biochemical technologies, such as anaerobic digestion and fermentation, with more than 40 biogas stations processing organic waste, including six located in landfills. Biogas facilities like Getlini EKO, convert waste into electricity and heat. In 2023, Getlini processed 91 000 tons of biodegradable waste, producing 30 GWh of electricity for sale and 20 GWh of heat. Since 2022, regulations mandate increasing organic waste use in biogas production, targeting 40% by 2022, 60% by 2026, and 80% by 2030 [19].

Schwenk Latvija, a innovative cement plant is the country’s only facility that co-incinerates specially prepared waste—Refuse-Derived Fuel (RDF) or Solid Recovered Fuel (SRF) in its production process. Cement clinker kiln operates at over 1500°C, using ash as a raw material in the final product and creating a completely closed-loop production process, that uses about 15 000 tons of waste annually, about 3% of Latvia's total [19].

Multiple similar WtE facilities are in various stages of planning and development across the country. With one of the highest landfilling taxes, 95€ per ton, businesses are motivated to seek alternative waste management solutions [19] [23].

## Case 3: China

Since the 1980s, China has undergone significant advancements in waste management At that time the MSW collection rate was only about 30% and consisted mainly of open dumping. In 2003, it raised to 70% and about 85% of the collected waste was landfilled, 10% composted, and 5% incinerated. A decade later, in 2013, the MSW collection rate reached 90%, with 68% landfilled, 2% composted or recycled, and 30% incinerated. This period also saw a rapid growth in Waste-to-Energy (WtE) infrastructure, with the number of WtE plants increasing from 47 in 2003 to 268 in 2015. This was mainly driven by limited space availabilty for landfilling in in the eastern provinces, which are more developed and have higher level of urbanization. Though, this rapid expansion caused continuous public criticisms and even protests, which are partly caused by high NOx, SO2, and HCl emissions and not releasing transparent data to the public. Higher pollution levels show that East Asia's dietary habits contribute to higher moisture content in MSW due to the mixing of vegetable debris and cooking liquids [24] [25].

Though, Taiwan, which shares the same dietary habits shows the impact of waste management policies with the combustible ratio of MSW increasing from about 33% to nearly 40%, driven by the implementation of a waste management hierarchy. Policy making should consider ongoing implementation of waste recycling and also optimizing used technologies. Actually, recycling targets are set for key materials such as scrap steel, non-ferrous metals, paper, agricultural wastes and more [25] [26].

The primary challenges for developed countries like Germany and Latvia include changing consumer behavior, transitioning to a circular economy (CE) with government support and ensuring the efficient use of waste hierarchy. In comparison, developing countries encounter challenges mainly due to limited financial resources, infrastructure. These challenges show the need for public awareness programs, investments by government agencies, optimizing technologies and knowledge sharing from developed nations [15].

In summary, waste-to-energy technologies play pivotal role in moving towards a resource-efficient, low-carbon, circular economy. Countries should adopt various strategies for waste-to-energy, such as prioritizing investments in waste reduction, establishing efficient waste collection systems, promoting material recovery and recycling, evaluating the environmental and economic impacts of existing technologies and raising public awareness about the benefits of circularity [20] [15].

# 6 Conclusion

The aim of this work was to explore the role of waste-to-energy in the circular economy. The focus was on case studies from Germany, Latvia and China. The goal was to see which countries have adopted successful practices and provide suggestions for improvements.

Circular economy is based on three key principles: elimination of waste and pollution, circulation of materials and products, and regeneration of natural systems. In circular economy, waste generation is minimized, and products are kept in use as long as possible through reuse, repair, and recycling. The waste is seen as a resource for other processes rather than something that must be discarded.

Waste-to-energy plays a crucial role in the circular economy. It contributes to waste management and can reduce greenhouse gas emissions originating in waste management. Especially the possibility to treat non-recyclable waste is an advantage of WtE since it enables energy recovery from waste that would otherwise be destined to landfills. It is important to note that waste-to-energy should be utilized following the waste hierarchy, so it should be considered after waste prevention, reuse and recycling.

Waste-to-energy has many benefits but there are some challenges as well. WtE can reduce the amount of landfilled waste which contributes to waste reduction. Utilizing WtE can also reduce GHG emissions since WtE technologies release less GHG emissions compared to landfilling waste. WtE also contributes to renewable energy production and can be applied to hazardous waste. However, some technologies, especially incineration, produce GHG emissions and other pollutants which affect air quality. The operation of some technologies requires a steady feed of raw material, which should not hinder the aim for waste prevention. There are also economic issues: some technologies require high investments so WtE may not be economically feasible.

It is important to understand that WtE does not compete with recycling: in countries where WtE is widely used, recycling rates tend to be high as well. Germany has one of the highest recycling rates of the EU countries. Currently, incineration is the most widely used WtE technology.

In 2023 in Latvia, 52 % of the MSW was landfilled and only 3 % treated for energy recovery. Latvia has a waste management plant to meet EU's target to reduce landfill to 10 %. One way of decreasing the landfill rate in Latvia is high landfill taxation. This motivates to find alternative solutions and could make utilization of WtE technologies more economically viable option. The taxation system is new so it is difficult to evaluate its efficiency but if it has a positive impact, taxation could be used elsewhere as well to promote more environmentally friendly waste management solutions.

China has made progress with its waste management. The motivation behind this has been to find a solution for limited landfill space. Incineration is the most common technology. However, China’s landfill rate is still quite high so there is room for improvements.

International collaboration is important to achieve sustainable waste management in a global scale. Developed countries can help developing countries. Also EU countries that struggle in meeting the EU targets can learn from countries that have implemented successful waste management practices.

Incineration is still the most common WtE technology. For future research, it would be beneficial to study how advanced WtE technologies can be made into more economically attractive options compared to landfill and traditional technologies like incineration.

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