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Waste-to-Energy in the Circular Economy Transition and Development of Resource-Efficient Business Models

Dzintra Atstaja [1,2,*], Natalija Cudecka-Purina [2,*], Viktor Koval [3], Jekaterina Kuzmina [2], Janis Butkevics [2] and Hanna Hrinchenko [4]

1 Faculty of Social Sciences, Rīga Stradiņš University, LV-1007 Riga, Latvia
2 Department of Management, BA School of Business and Finance, LV-1013 Riga, Latvia; jekaterina.kuzmina@ba.lv (J.K.); janis.butkevics@ba.lv (J.B.)
3 Department of Business and Tourism Management, Izmail State University of Humanities, 68601 Izmail, Ukraine; victor-koval@ukr.net
4 Department of Automation, Metrology and Energy Efficient Technologies, V. N. Karazin Kharkiv National University, 61022 Kharkiv, Ukraine; hrinchenko@uipa.edu.ua
* Correspondence: dzintra.atstaja@rsu.lv (D.A.); natalija.cudecka-purina@ba.lv (N.C.-P.)

Abstract: The consistent rise of the per capita waste generation rate has led to an escalation of waste quantities and the need to expand waste disposal methods. Efforts to develop clean and affordable energy systems are increasingly linked to waste-to-energy as part of the transition to a circular economy (CE). A resource-efficient waste-to-energy business model within a CE offers a variety of environmentally friendly waste management options based on their overall environmental impacts but also makes efficient use of available resources and technologies to convert different types of waste into energy, which helps reduce the adverse effects on the environment and create additional energy sources. This research aims to identify innovative waste management solutions to foster the implementation of CE and a more resource-efficient business model. The research methodology is based on qualitative and quantitative research, triangulation, material flow assessment, and systems dynamics. The value of this study is within the analysis of existing waste-to-energy plant case studies to identify a set of recommendations and appropriate business models for the countries that are at an early stage of evaluation of such facilities. This study found that waste-to-energy plants are critical to achieving the EU's waste disposal targets by 2035. The findings highlight the importance of supporting mechanisms in the waste sector, such as structural funds, as the industry primarily focuses on societal health and safety and environmental protection, alongside resource efficiency and circularity potential.

Keywords: business models; circular economy; sustainable development goals; waste to energy

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1. Introduction

Achieving the Sustainable Development Goals (SDGs) requires all countries, stakeholders, businesses, and individuals to create a sustainable social, economic, and environmental future and to ensure that commitments are translated into action. The SDGs include a variety of topics and indicators, such as water, energy, climate, transport, urbanization, health, and others. Companies worldwide embrace sustainability and integrate the SDGs into their core strategy to drive growth, mitigate risks, attract investment, and focus on achieving their goals. In this case, sustainability indicators serve as a roadmap for businesses to take action to achieve global goals.

Companies that incorporate the SDGs into their operations usually have an advantage over their competitors, ensuring their growth and prosperity. Among the sustainable development indicators, waste management plays a significant role in achieving global goals and can be seen in all 17 SDGs [1]. This is not surprising, as more than two billion tonnes of municipal solid waste (MSW) are generated globally every year. In addition to household waste, human activity generates significant amounts of agricultural, construction, industrial, commercial, and healthcare waste. This waste is generated on farms and at construction sites, factories, and hospitals. Thus, decision-making at every level of the 'individual–enterprise–country', in terms of production, consumption, and waste management, is inextricably linked to crises on a global scale, such as climate change, pollution, and biodiversity loss.

In accordance with Resolution 2/7, adopted at the second session of the UN Environment Assembly and reaffirmed by Resolution 4/7 at the fourth session [2,3], data on solid waste management worldwide and energy and raw material use were analyzed. Forecasts for the development of the global economy and the environment, provided that approaches to waste generation and management remain the same, are disappointing. Currently, the priority for all European countries is to find ways to reduce waste and improve its management, in line with the waste hierarchy, to treat all waste as a resource, and much has already been done in this direction.

Environmentally sound waste management and using recycled materials contained in waste are crucial elements of the EU's environmental policy. The waste policy of the EU (European Union) aims to develop CE by maximizing the recovery of quality resources from waste. The European Green Deal (EGD) aims to promote sustainable development and growth in the EU by transitioning to a modern, resource-efficient, and competitive economy. To this end, the Waste Framework Directive [3] was introduced, which is the legal framework for waste management in the EU, establishing a prioritization order known as the "waste hierarchy". Some categories of waste require particular approaches, so, in addition to the general legal framework, many laws in the EU regulate diverse types of waste and their management. Thus, the analysis of the existing statistical economic indicators in the EU shows that the European Union's Green Deal is a topical issue, especially with regard to improving the efficiency of the energy sector, both the industrial sector and the provision of municipalities [4,5].

For the last 30 years, Latvia and EU countries have experienced an immense transformation in the sector of waste management–a shift from numerous illegal dumpsites and a total re-design of the system. As a result, until 2015, Latvia has developed a system with 10 sanitary landfills, waste sorting infrastructure, and mechanical–biological treatment of unsorted waste. Therefore, for the past 15 years, the pattern of increasing waste volumes and significant reliance on disposal (~49% in 2022) has been the decrease in population and the rate of trash creation per capita [6].

When examining the regions that comprise the European Union's major countries, it is essential to give special attention to Ukraine, whose waste management policies serve as a model for the country's dedication to sustainable development and adherence to the European Green Deal. While Ukraine has yet to join the EGD formally, it has expressed its intention to participate in its implementation. The country is progressively aligning its legislative framework with the European one, demonstrating a solid commitment to sustainable development. Ukraine is developing a long-term strategy for climate neutrality and mechanisms for financing the 'green transition', integrating novel approaches to environmental management and waste management technologies, etc. Thus, the main focus is to ensure efficient energy management of existing capacities, which requires significant economic costs to achieve environmentally friendly use of resources and is a strategic direction for the transition from a traditional energy economy to a renewable one. In this area, the main focus is on ensuring safety and risk assessment of the technical condition of equipment, which will help maintain the energy balance during the transition to a green course [7].

For example, the 'Energia' waste incineration plant recycles 25% of municipal solid waste (MSW) in Kyiv (Ukraine) and converts it into heat for 300 high-rise buildings in the capital. The plant produces heat and electricity using the most advanced environmental technologies. At present, this type of plant remains the only alternative and most environmentally friendly solution for solid waste disposal that uses modern flue gas chemical treatment systems and meets European environmental standards.

Increasing interest in Waste to Energy (WtE) is driven by the fact that it creates a potential alternative energy source that, depending on the feedstock, can provide a reduced carbon footprint while complementing fossil fuels. The proposed approach to converting waste into energy can help reduce the disposal of waste, which is a highly long natural decomposition period. However, if the approach must be corrected when reducing recycling, converting waste into energy can lead to increased emissions of harmful substances. In this regard, waste-to-energy conversion should be based on appropriate technologies and control measures to minimize the risks of increased emissions of harmful substances. A resource-efficient waste-to-energy business model is only possible through an integrated approach that includes the development of appropriate technologies, effective waste management strategies, and compliance with certain safety and environmental standards and regulations.

2. Materials and Methods

The research is based on qualitative and quantitative research, triangulation, material flow assessment, and systems dynamics. The concept of society's development is based on the principles of 'production–consumption' aimed at meeting the multifaceted needs of people through various economic activities, the main type of which is production. This inevitably creates contradictions between the social and environmental components, between production and natural ecological systems.

Changes in the global population lead to an increase in consumption. Moreover, these values are not proportional to each other. Consumption is growing faster than the population (Table 1). Objective reasons for this are the expansion of the range, quality, and quantity of goods consumed. Even though some countries have experienced a demographic decline in recent years, production and consumption rates have not slowed down. Production growth, in turn, affects the environmental component and leads to negative consequences.

Table 1. Statistics on trends in population, consumption, pollution, and waste generation (2011–2021). Source: by authors based on [8–10].

Year		Population [8]	Primary Energy Consumption * [9]	Carbon Dioxide Emissions from Energy [10]	Packing Waste Generation, Kilogram per Capita [10]
2011		6,985,603,105	520.90	31,904.6	157.15
2012		7,161,697,921	528.18	32,241.1	154.77
2013		7,250,593,370	537.56	32,710.9	156.57
2014		7,339,013,419	543.52	32,820.2	161.18
2015		7,426,597,537	548.14	32,837.4	165.16
2016		7,513,474,238	555.91	33,020.6	168.66
2017		7,599,822,404	566.66	33,426.4	173.84
2018		7,683,789,828	582.38	34,148.5	173.25
2019		7,764,951,032	587.43	34,095.8	177.49
2020		7,840,952,880	564.01	32,078.5	177.87
2021		7,975,105,156	595.15	33,884.1	188.69
Growth rate per annum	2021	0.87%	5.8%	5.9%	6.08%
	2011–2021	0.14%	1.3%	0.6%	0.2%

* primary energy comprises commercially traded fuels, including modern renewables used to generate electricity.

These growing needs can only be met by increasing production, which is unthinkable without using nature and its resources. This explains the contradictions between humans and nature, between production and natural ecological systems. Let us consider some negative aspects of human impact on nature in production growth.

Firstly, every year, humanity takes away tens of billions of tonnes of natural substances from nature [7], which includes oil, gas, coal, water, natural resources, etc.

Secondly, and perhaps most importantly, is environmental pollution from production and consumption waste, which in many parts of the world has reached critical levels for ecosystem sustainability and human health [6,11].

Ensuring the sustainability of the socio-ecological and economic system requires the development of an effective strategy for balanced environmental management. The requirements of ecological development and the subordination of the economy to the principle of balanced nature management can be most fully realized within the framework of a natural and economic complex that forms a balanced ecological and economic system (EES).

The ecological and economic system is interpreted as an environmentally oriented socio-economic formation on the global level. However, globally, the organization of an EES is a distant and abstract prospect. For the practical implementation of the principle of balanced environmental management, it is crucial to understand the EES at the territorial level in individual regions and industrial complexes.

Industrial development has never been aimed at creating a balanced EES. The mechanisms of environmental regulation economic activities that have been actively developed in recent years, such as the assessment of foreseeable environmental impacts, licensing, and environmental impact assessment of programs and projects, cannot ensure the practical implementation of the sustainability requirements. For this purpose, effective science-based practical mechanisms for implementing sustainability in certain sectors and enterprises must be developed, forming the basis for the EES model.

Ecological and Economic System Models: Structure and Flows

There have been many attempts to model the EES. As a rule, they analyze the connections, but there needs to be approaches to quantitative analysis. Below is a simplified flow diagram of a territorial EES (Figure 1). The economic and environmental systems are seen as parts of a whole and are denoted as subsystems. The boundary between them is conditional since the entire sphere of biological life support and human reproduction belongs to both subsystems. The EES combines jointly functioning ecological and economic systems and has emergent properties.

The economic subsystem is an organized set of productive forces that transforms natural and production resources' input material and energy flows into output flows of consumption items and production waste.

Thus, some of the material elements of the ecological system, including elements of the human environment, are used as a resource of the economic system.

The total input of production—the sum of production material resources R_p—consists of resources imported into this system R_1 (including non-renewable local resources) and renewable local resources R_n. The latter includes part of the bioproducts of the ecological subsystem, including the products of agrocenoses and humans themselves—both as a resource and as a subject of production (1) and consumption (2).

$$R_p = R_1 + R_n \tag{1}$$

Consumption C consists of a part of the local net output of production P_C that is consumed (the flow of products returning to the production cycle and the secondary production cycle is not shown in the diagram), as well as a part of local bioresources C_p and imported products C_1.

$$C = P_c + C_p + C_1 \tag{2}$$

Local production and consumption resources together form a flow of resource withdrawal from the ecological subsystem: $U_n = R_n + C_n$.

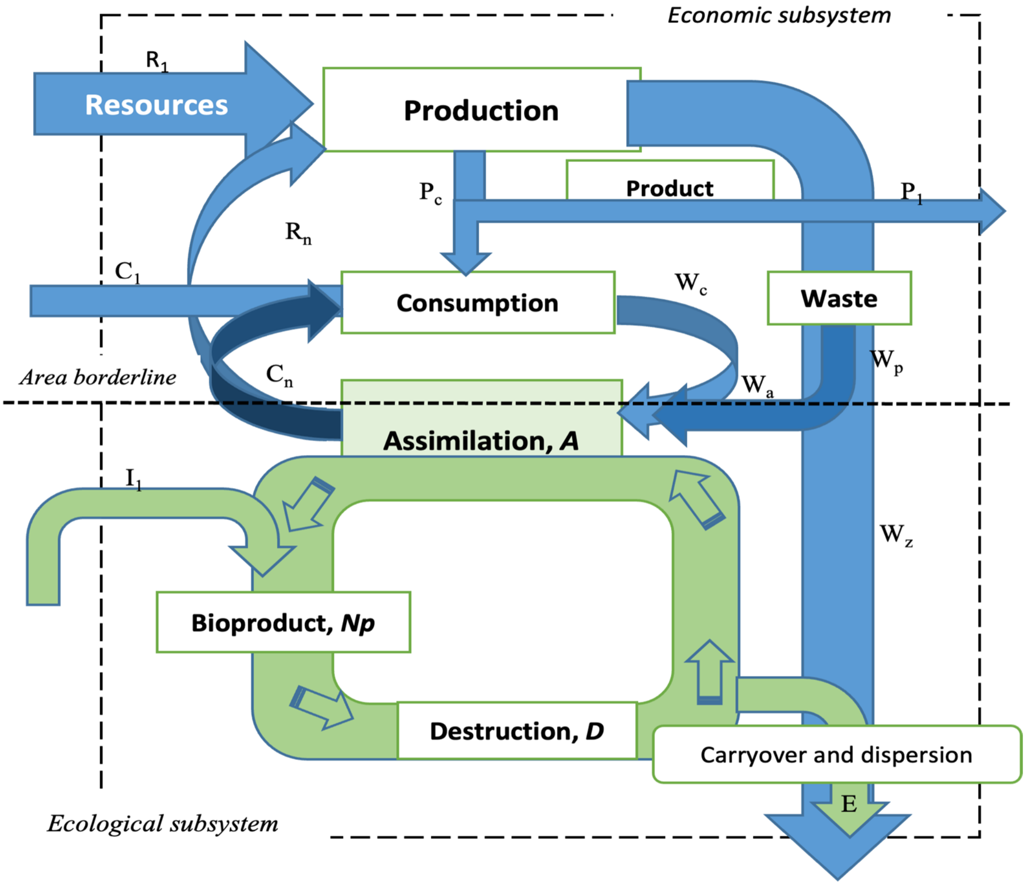


Figure 1. Scheme of main material flows in the ecological–economic system. Source: by authors.

The production efficiency is determined by the ratio P/R_p, where $P = P_1 + P_c$, and the production waste is determined by the ratio $(R_p - P)/R_p = W_p/R_p$.

Waste from production W_p and consumption W_c is released into the environment as the sum of the economic subsystem's waste:

$$\begin{cases} W = W_p + W_c \\ W_p = W_a + W_z \end{cases} \quad (3)$$

Part of waste from production W_p is included in the biogeochemical cycle of the ecological subsystem (Wa) and the other part is accumulated and dissipated with partial removal outside the system (Wz).

Part of the Wa waste stream undergoes assimilation and biotic neutralization in the process of destruction; the other part, after biological and geochemical migration, joins the W_z fractions and undergoes immobilization, dispersion, and removal together with them.

Thus, part of the waste acts as anthropogenic pollution $M = K - W$, where K is the overall coefficient of aggressiveness or harmfulness of waste for the system. In turn, the damage caused by environmental pollution to system objects can be represented as an indirect withdrawal of a part of the resources of the ecological subsystem, similar to U_n. Then, $U_t = LM$, where L is the integral coefficient of the 'pollution-damage' relationship.

$$\sum U = U_n + U_t \quad (4)$$

The above equation represents the total damage to the ecological subsystem caused by its interaction with the economic subsystem.

The ratio between intermediate and final pollution flows and their cumulative harmful effect depends not only on their mass and chemical composition, but also on species composition, biomass, recipient density, productivity, and ecosystem resilience, in particular, regarding anthropogenic impacts. These qualities depend to the greatest extent on the input flow of renewal of the biogeochemical cycle I_1, its productive capacity, and the scale of destruction D.

The cycles of both subsystems of the EES together form a kind of technobiogeochemical cycle, and the entire EES can be designated as a technobiogeocenosis. Equilibrium and velocity constants can be assigned to the flows of matter in the EES, which makes it possible to carry out a kinetic analysis of the system and identify the conditions for its equilibrium and stability.

In a balanced ecological and economic system, the total anthropogenic load should not exceed the self-healing potential of natural systems. In this regard, it is proposed to develop waste management mechanisms to ensure the balance and sustainable development of the EES. Of course, this requires preliminary measures to reduce waste production, but statistics [6,12] show that an increase in solid waste generation is an integral part of the country's economic growth. Therefore, the existing problem of solid waste growth needs to be addressed, and this can be achieved in several ways: controlled waste disposal (landfilling), waste-to-energy, and recycling.

3. Results

3.1. Status Quo of European Countries towards the Achievement of UN SDGs (Sustainable Development Goals)

Within the discussion of waste-to-energy challenges on the CE transition path, it is necessary to determine Latvia's and Ukraine's status quo based on the progress achieved towards the UN SDGs. The assessment is based on the latest data of the report published in 2023 [7] and highlights the existing gaps to be closed and the potential for success and future progress towards the 2030 goals. The brief evaluation of the data and comparison of the Latvian and Ukrainian scores to the European countries selected as a pear group (consisting of a group of 39 countries with valid data) suggest the following conclusions:

- Latvia's overall 2023 SDG index score is 80.7, above the median of 79.4, demonstrating the slightly better results within the broad European universe; nevertheless, the result is still below the 75th percentile of 81.7, meaning the existing potential to achieve better results. Ukraine's overall 2023 SDG index score is 76.5, below the median and the 25th percentile of 77.4, demonstrating the considerable gap and call for action to achieve the pre-defined sustainability goals (follow Figure 2). It is worth considering that both countries demonstrated sufficient progress over time, while the Latvian overall score increased from 78.84 in 2015 to 80.47 in 2020 and 80.70 in 2023; Ukraine is moving on a lower trajectory, but taking a similar direction, from 71.51 in 2015 to 77.08 in 2020 and 76.5 in 2023, due to geopolitical reasons. Both countries indeed show progress over the given timeframe, but with some notable differences, like starting points: Latvia began at a higher score in 2015, indicating it was already more developed or economically stable than Ukraine; rate of progress: Ukraine showed more rapid improvement between 2015 and 2020, increasing by 5.57 points compared to Latvia's 1.63-point increase. This comparison highlights how countries can make progress at different rates and how external factors, particularly geopolitical events, can impact a nation's development trajectory.
- UN Goal number 7 claims to ensure access to clean and affordable energy, which is critical to developing all the other business segments. As this goal is intricately connected to the CE transition path, the overall evaluation is necessary: Latvia, according to the latest data, demonstrates sufficient progress equal to an index score of 88.9, which is above the median level of 76.9 for the same pear group as above. Moreover, it is worth considering that the result is above the 75th percentile of 83.3, demonstrating a country's sufficient progress towards sustainability. Ukraine also

reveals sufficient progress equal to an index score of 80.2. Nevertheless, actions that contribute to developing an affordable and clean energy system would allow for better results and evaluation of the SDG score that is below the 75th percentile (follow Figure 3). The analysis over a longer time period demonstrates that both countries achieved some progress, while the Ukrainian success rate is high. The Latvian SDG 7 index increased from 85.4 in 2015 to 88.5 in 2020 and 88.9 in 2023, while the Ukrainian SDG 7 index demonstrated an increase from 68.3 in 2015 to 70.7 in 2020 and 80.2 in 2023. Ukraine's success rate is indeed higher, especially considering its lower starting point and more substantial percentage increase. Moreover, Ukraine's rapid progress in the 2020–2023 period is particularly noteworthy, suggesting recent policy changes and/or investments in sustainable energy.

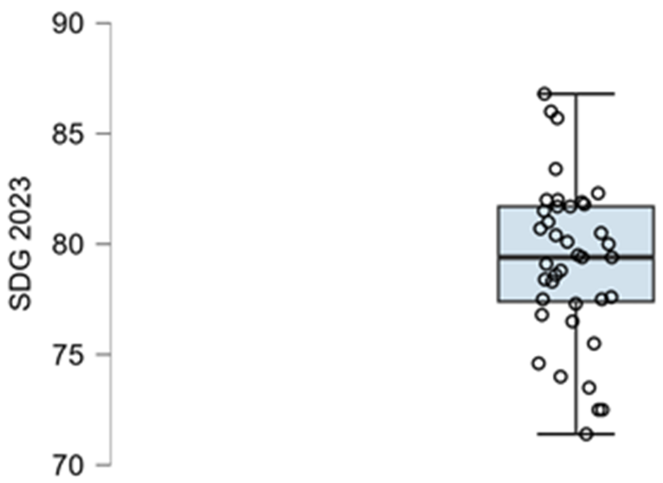
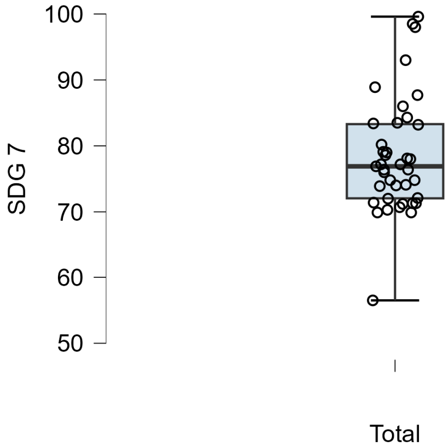
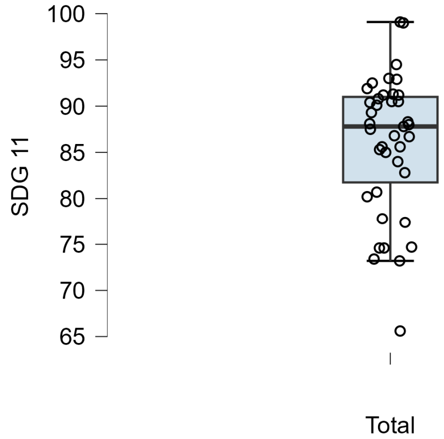


Figure 2. Boxplot of 2023 SDG Index Score for the selected European countries based on the data published in [11]. Median: 79.4; 25th percentile: 77.4; 75th percentile: 81.7.

- UN Goal number 11 and number 12 are tightly connected to the CE, and the progress in the domains of safety, resilience, and sustainability of cities and human settlements, as well as sustainable consumption and production patterns, cannot be ignored. In the first case (UN Goal number 11), Latvia demonstrates a score of 86.7 vs. a median of 87.8 (but is above the 25th percentile). In the second case (UN Goal number 12), there is a below-median result of 58.8 vs. 62.8 (also above the 25th percentile). In both cases, progress is necessary. At the same time, considering that the overall score regarding sustainable production and consumption (including waste management) is low and signals an insufficient effort to reduce the enormous environmental footprint (follow Figure 3). The numbers describing the Ukrainian's efforts are slightly different: in the first case the score is 80.2 (below the 25th percentile) and in the second case is 84.5 (above the 75th percentile). As a result, there is a serious gap in sustainable cities and community management and considerable success in sustainable production and consumption. Similar conclusions could be drawn with regard to SDG 11 and SDG 12: both countries demonstrate some progress over time, while Latvia's slower progress might be due to already being at a high level, making further improvements more challenging, and Ukraine's rapid recent progress could be linked to reforms, increased focus on sustainability, and/or improvements in efficiency.



(**a**)



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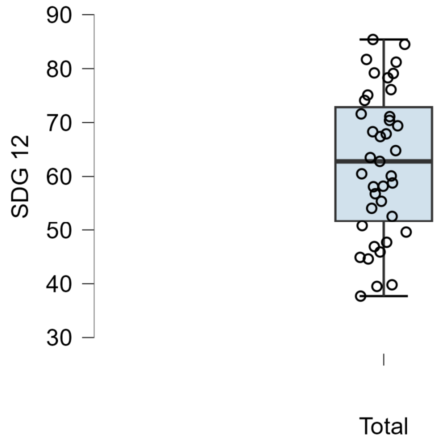

(**c**)

Figure 3. Boxplot (**a**) of 2023 SDG Goal 7 for the selected European countries based on the data published in Sustainable Development Goals Report 2023 [13]. Median: 76.9; 25th percentile: 72.1; 75th percentile: 83.3. Boxplot (**b**) of 2023 SDG Goal 11 for the selected European countries based on the data published in Sustainable Development Goals Report 2023. Median: 87.8; 25th percentile: 81.8; 75th percentile: 91.0. Boxplot (**c**) of 2023 SDG Goal 12 for the selected European countries based on the data published in Sustainable Development Goals Report 2023 and Supplementary Materials [11,13]. Median: 62.8; 25th percentile: 51.7; 75th percentile: 72.9. The brief analysis of the data allows us to conclude that the necessity for action in the field of the CE transition is evidence-based and requires considerable effort from all the relevant parties.

3.2. Trends and Development of Waste-to-Energy in the EU and in Latvia

It has become evident recently that, within the European Union countries, EGD and CE are the general directions of the economy that will last for many decades. The EGD delineates the principal objectives of the European Union's sustainable development strategy, prioritizing the transition from a linear to a CE and the decarbonization of Europe by 2050 [14]. Although waste management within the framework of CE is considered to be an end-of-pipe solution, it still has a variety of possibilities for managing waste in environmentally sound ways and creating benefits for society. The waste management sector has achieved significant advancements over the past decades, although the waste management hierarchy still lies at its core [15,16]. According to the Waste Framework Directive, the EU member states shall take measures to encourage waste management options that deliver the best overall environmental outcome. The hierarchy applies as a priority order in waste prevention and management legislation and policy:

- Prevention;
- Preparing for reuse;
- Recycling;
- Other recovery, e.g., energy recovery;
- Disposal [2].

Waste-to-energy (WtE) incineration plays a crucial role in modern waste management and is a critical waste treatment method in Europe. Energy recovery, also called WtE, follows recycling and converts non-recyclable waste into usable forms of energy, such as fuel or heat. The EU acknowledges WtE as a technology that can aid the transition to CE, provided that the waste management hierarchy—prioritizing waste management practices—is adhered to [17]. Despite the challenging economic conditions of recent years, the WtE industry has demonstrated remarkable resilience. It ensures waste treatment that meets high ecological, health, and hygienic standards and stabilizes growth and employment in Europe. The EU appears to be taking the implementation of a circular economy seriously (taking into account that at the end of 2024, it is foreseen that the EU will start to work on the 3rd Circular Economy Action Plan), as evidenced by recent initiatives like the Ecodesign Regulation, the End-of-Life Vehicles Regulation, and the Packaging and Packaging Waste Regulation. The new developments foresee that, in the future, the produced goods will be more durable, there will be less packaging, and, as a result, the volume of waste will decrease, and the waste generated will be easier to recycle. However, the effects of these EU regulations will not be fully realized until after 2030. The legislative debates reveal the challenges of engaging all stakeholders in this significant transformation. If industries produce items that cannot be recycled into high-quality materials, technically or economically, society requires a dependable way to handle the leftover waste. WtE, which meets the highest ecological standards, offers this crucial solution and is considered indispensable for sustainable waste management, at least for a certain period [18,19]. In the Figure 4 shown Waste-to-energy trends in Europe 1) "Hazardous waste plants" Gradient Legend Entry: 1 (Light Blue), 117 (Dark Blue) and 2) "Residual waste thermally treated" Gradient Legend Entry: 0 (Light Orange), 30 (Brown).

WtE technologies contribute to waste reduction and provide an alternative to fossil fuel-based energy generation, reducing greenhouse gas emissions and promoting sustainability. Furthermore, energy extraction from waste can simultaneously increase the lifespan of existing landfills and reduce the emissions of GHGs into the atmosphere since the energy produced from waste may replace the sum of energy produced from fossil fuel resources [20].

The choice of WtE technology is influenced by various factors, such as the composition of the waste stream, energy demand, regulatory frameworks, and environmental considerations. WtE technologies include incineration, gasification, and pyrolysis, each with its unique benefits and considerations. Cost considerations, including capital investment, operational and maintenance costs, and potential revenues from energy sales, significantly influence technology selection. Also, stringency of regulations may favor technologies with lower emissions and better waste residue management. Bjelic et al., 2024, have suggested the following aspects to consider for the application of WtE technologies: the environmental aspect, technical aspect, political aspect, social aspect, and economic aspect [14].

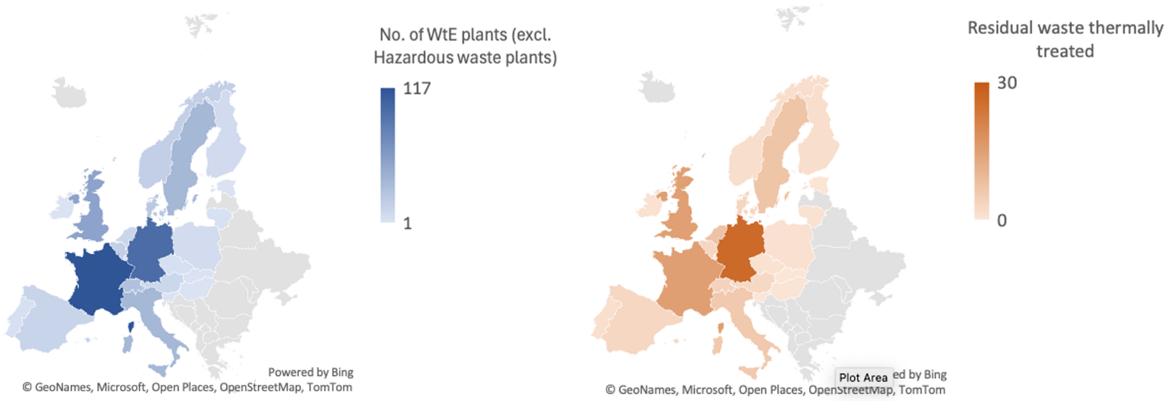

Figure 4. Waste-to-energy trends in Europe. Source: by authors, based on CEWEP and Eurostat.

Around 500 WtE incineration plants across the continent process approximately 100 million tonnes of municipal, commercial, and industrial waste annually. Currently, WtE plants in Europe can provide electricity to 21 million citizens and heat to 17 million. This is based on treating 103 million tonnes of residual household and similar waste in 2021. By using WtE plants instead of conventional power plants, Europe could avoid the use of from 10 to 56 million tonnes of fossil fuels (such as gas, oil, hard coal, or lignite), thereby preventing the emission of from 22 to 44 million tonnes of CO_2 [17,19]. When analyzing the upcoming periods, it has been forecasted that the capacity needs for waste treatment in Europe in 2035, taking into consideration that the 65% recycling target of municipal waste would be met and, even more ambitiously, that 68% of non-hazardous commercial and industrial waste would be recycled. Under this scenario, CEWEP calculated that around 142 million tonnes of residual waste treatment capacity would still be needed by 2035 (calculations have been peer-reviewed by Prognos) [20,21].

The graph below (Figure 5) illustrates the proportions of municipal waste that are recycled (including composting), converted to energy through Waste-to-energy processes, and landfilled in each EU Member State, as well as Iceland, Norway, and Switzerland, organized by the percentage of waste landfilled. It also highlights any data gaps, such as discrepancies between the waste generated and the waste treated in each country.

The overall data for European Union countries show that, in those countries where waste is recovered, waste recycling is also effectively implemented. Some examples include Belgium (57% recycled, 44% recovered), Germany (68% recycled, 31% recovered), and the Netherlands (41% recycled, 58% recovered). In these countries, the amount of waste sent to landfills has been reduced to nearly zero. Unfortunately, Ireland *—data available for 2021, Greece **—data available for 2022

In addition to environmental protection, waste management has a significant impact on economic and social aspects. Under economic it impacts regional development, creation of new and green jobs, increase in income tax in particular regions for the municipalities, etc. With respect to social aspects, waste management positively fosters environmental awareness and education of the inhabitants with respect to the effective and sustainable treatment of resources, and their conservation. However, social impacts also have a reverse impact on waste management, for instance, in the case of social opposition regarding one or another waste management infrastructure element. One of the best visualizations of social impact is the strong opposition in a range of countries of the society towards waste incineration with energy recovery (WtE) plants. Some of the main concerns raised by the opponents in the WtE discussion in Latvia are as follows:

- WtE is not endorsed by the EU-level policy planning documents as a solution in the CE cycle;
- The introduction of large-capacity WtE facilities might lead to a decrease in sorted waste volumes to feed the capacity of constructed plants;
- Pressure to increase the volume of recyclable materials might lead to a decrease in volumes of non-recyclable waste, and, consequently, to the importing of waste for incineration;
- Disposal of ashes and slags remains an issue in practice;
- Negative effects on the environment due to increased transport flows to facilities, possible smells, pollution, etc.

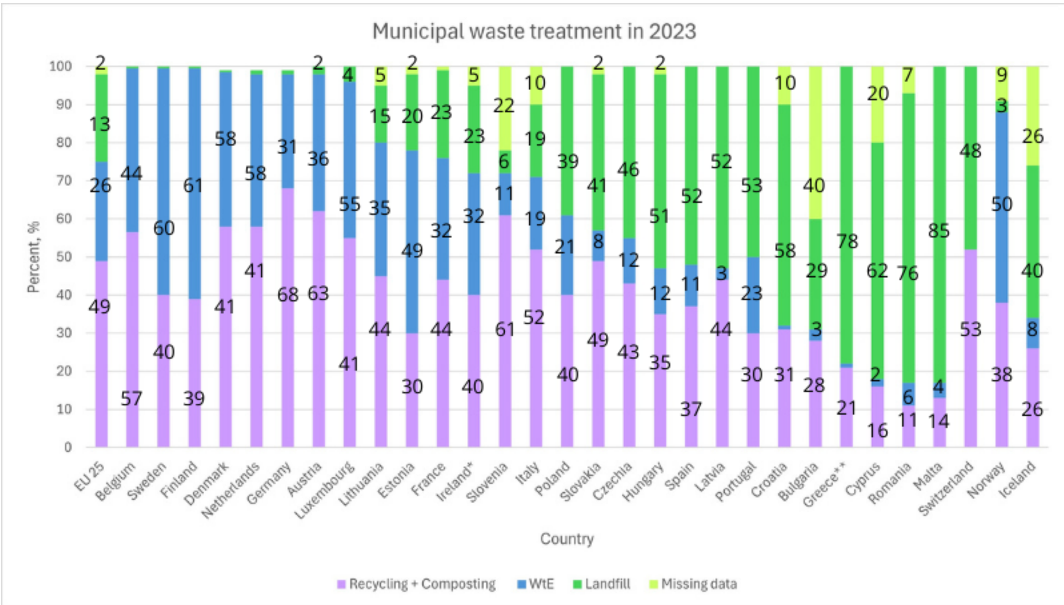

Figure 5. Municipal waste treatment in 2023. Source: by authors, based on CEWEP and Eurostat.

The WtE discussion in Latvia also highlighted arguments used by proponents of energy recovery from waste:

- In terms of climate change mitigation, the WtE produces less CO_2 compared to landfilling waste and serves as a more climate-neutral fuel compared with other fuels;
- EU requirements to minimize the landfilled household waste to 10% of total volume by year 2035 vs. the 52% which is landfilled today;
- The landfilling capacity is diminishing, and more sustainable alternatives should be in place to address non-recyclable waste management issues;
- Strengthening the independence from imported fossil energy resources (in particular, for heat energy) and the diversification of energy resources;
- The attraction of new investments into the country and further economic benefits (new workplaces, taxes, etc).

The arguments above may contribute to further academic and professional research to provide a comprehensive and well-grounded basis to evaluate the development of WtE projects globally. With respect to CO_2 emissions and the potential increase of CO_2 taxation, it has to be noted that WtE plants are dependent on the material that is sent for incineration. For instance, plastic waste contributes significantly to fossil CO_2 emissions from waste incineration. Fees should be imposed based on the polluter pays principle, targeting the source of pollution rather than the final step in the treatment chain, which is waste incineration. One more thing has to be taken into consideration, in the case that waste incineration is the only treatment method charged with a higher CO_2 tax, this could lead to the system turning back to landfilling, despite the decreasing landfilling capacities, with the choice driven by economic aspects [20–22]. Another key aspect is that, with more than 39 TWh of electricity and 90 TWh of heat produced in Europe annually, WtE has the potential to prevent the production of up to 50 million tons of CO_2 emissions that would otherwise be generated by fossil fuels [21,23,24].

4. Case of Latvia

4.1. Waste Management Overview

In Latvia, households generate around 869,000 tons of waste per annum. The volume of generated household waste per capita in Latvia is still below the OECD average (respectively, 478 kg in Latvia vs. around 500 kg in OECD vs. 505 kg of municipal waste in the EU average per annum); the statistics demonstrate a constant increase in waste generation. Of the total generated household waste volume, 45% is recycled, 3% is used for energy production at the "SCHWENK" cement factory, but the majority—52% or 456,000 tonnes of household waste—is currently disposed of in landfills (Figure 6).

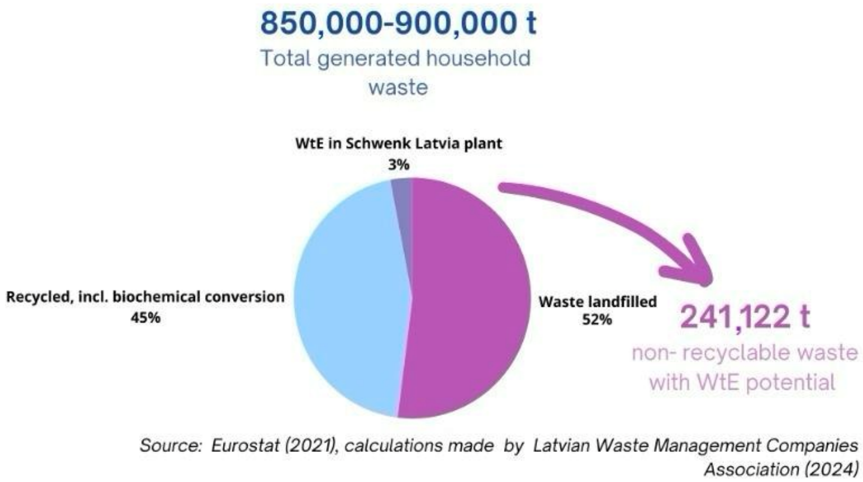

Figure 6. Waste-to-energy resources availability in Latvia (tonnes per annum).

In addition, three household waste landfills collect and treat landfill gas to produce electricity and heat [25].

Since the European Union has set a target for member states to landfill no more than 10% of generated household waste by 2035, and to recycle at least 65% of collected household waste, Latvia is among the EU countries at risk of not meeting the landfill waste volume target [26].

The Latvian Waste Management Plan 2021–2028 estimates that around 220 thousand tons of waste per annum, which are currently landfilled and are unsuitable for recycling, have high energy content and could be utilized as energy resources 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 [27].

Latvia's National Energy and Climate Plan 2021–2030 [28] defines an action item for the coming year as reducing the amount of waste to be landfilled, including via the incineration of waste/residues for energy production. To reduce the volume of landfilled waste, especially considering the established landfilling restrictions for 2035, and to ensure effective waste management by the waste management hierarchy set out in Latvian and EU regulations, the Waste Management Plan 2021–2028 calls to explore the possibilities of constructing waste regeneration facilities with energy recovery [27]. It may be concluded that energy and waste management policy planning documents at the national level endorse energy recovery from waste as a viable solution to reach the objectives. While these documents endorse waste-to-energy initiatives, they do not provide specific directives or obligations for constructing "waste-to-energy" facilities, particularly incinerators for municipal solid waste (MSW) with energy recovery.

The Waste Management Law 2010 [29] defines recovery of waste as any operation the principal result of which is waste serving a useful purpose in the production processes or in the national economy by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function.

The EU acknowledges WtE as a technology that can aid the transition to a CE, but this is contingent upon adherence to the waste management hierarchy, which dictates the order of priorities in waste management practices [30,31]. Waste management hierarchy is incorporated also into the Waste Management Law 2010 where recovery of waste by acquiring energy follows recycling in the management priority list.

Latvian legislative regulations require the Environmental Impact Assessment (EIA) for the construction of any waste management-related facilities, including WtE plants. EIA is one of the initial steps, but not the only one–environmental procedures continue until the project's implementation and during the operation of the facility:

- Environmental Impact Assessment: Its goal is to verify whether the proposed solutions are suitable for the specific location and if the environmental capacity allows for the project's fundamental implementation.
- Building Design: Based on the EIA's conclusions, the State Environmental Service will issue environmental technical regulations or precise conditions for design, after which specific solutions and technologies will be selected.
- Obtaining a Polluting Activity Permit: This is a time-consuming and complex process following the receipt of the EIA conclusion to obtain an A-category polluting activity permit. Based on the technical design results, parameters and emission limits under which the facility can operate will be precisely defined–these may be stricter (lower) than in the EIA process, but not higher.
- Monitoring During Operation: Environmental inspection not only checks compliance with existing regulations but can also impose stricter requirements and ensure that companies invest in and strive for continuous improvements.

4.2. WtE Biochemical Conversion in Latvia

While the environmental benefits of WtE technologies are well-recognized, their economic viability and business models have received significant attention in recent years in Latvia. WTE techniques are divided into biochemical and thermochemical conversion processes [31,32]. Biochemical processes, like anaerobic digestion, direct combustion, hydrothermal liquefaction, transesterification, pyrolysis, thermal gasification, and fermentation, are a few technical methods for generating renewable energy [33]. Organic waste is one of the main sources of biochemical conversion. In Latvia, organic waste is defined as biodegradable garden and park waste, food and kitchen waste of catering establishments (restaurants, canteens, etc.), households and offices, wholesale and retail food outlets, and other similar waste from food industries [27,29].

Landfills and biogas stations operate WtE biochemical conversion across the different regions of Latvia. More than 500 thousand tons of biodegradable waste are generated in Latvia per annum, and more than 40 biogas stations operate across the country. Six of them are located in landfills [34]. Biogas technologies integrated into all stations allow the conversion of organic waste to biogas [35–38]. To mention an example of a biogas facility, the operator Getlini EKO of the largest landfill in Latvia located in the Riga region obtains biogas from the biodegradable waste processing complex and waste disposal cells. In 2023, the company processed 91,000 tons of biodegradable waste at the biodegradable waste processing complex, of which 80,000 tons were mechanically separated waste and 11,000 tons were separately collected waste. In the power unit, gas is burned in internal combustion engines, obtaining electricity and heat in the ratio—40% electrical and 46% thermal energy. Annually, the company produces around 30 GWh of electricity, mainly sold in the open market, and 20 GWh of heat energy, used primarily for the company's economic activity, such as heating greenhouses and the recirculation pool.

Starting in 2022, at least 40 percent of organic waste and production residues shall be used as raw material in biogas stations to decrease the amount of waste and greenhouse gas emissions. As of 1 January 2026, this proportion should be 60 percent, and, as of 1 January 2030, at least 80 percent. The national legal framework is creating pressure on biogas station operators to search for opportunities to attract more organic waste for biogas production, and in coming years, increasing volumes of organic waste will be diverted from landfills to biogas stations.

In parallel to WtE, in the biogas stations located outside the landfills and operated by private companies, in recent years, around EUR 90 million in investments has been made into landfills to divert organic waste from landfills to regeneration. This shift not only contributes to environmental sustainability but also creates potential job opportunities in the WtE sector. The State Audit Office estimated that the total available organic waste processing capacity in Latvia is around 380 thousand tonnes per year, including processing capacities available at composting sites and biogas stations, i.e., approximately 2–2.5 times higher than the estimated amount of organic waste generated by households. One of the reasons for the excessive capacity for organic waste biochemical conversion is indicated poor data quality on generated waste volumes to make informed decisions, such as those regarding investments and infrastructure capacity.

4.3. WtE Thermochemical Conversion in Latvia

Thermochemical processes, including incineration, gasification, and pyrolysis, employ heat and chemical reactions to produce energy. New waste-to-energy (WtE) plants create opportunities for new employment, enhance the efficiency of waste management systems, and support sustainable development goals [31].

Waste-to-energy via thermochemical conversion is still underdeveloped in Latvia. Schwenk Latvija, a cement plant located near Broceni town in the western part of Latvia, is the only facility that co-incinerates specially prepared waste—RDF (Refuse-Derived Fuel) or SRF (Solid Recovered Fuel)—in the production process. The use of alternative fuels in Schwenk Latvia's cement clinker kiln, which operates at temperatures exceeding 1500 degrees Celsius, is significantly different from simple incineration plants, where waste is burned to recover energy, leaving waste and ash that require further management. In the cement clinker kiln, the ash from alternative fuels becomes a raw material, an essential component of the final product. This ensures a completely closed production process, with no residual products or waste that needs to be managed. The use of waste in the production process defines relatively high-quality requirements for the incoming waste flows, and currently around 15,000 t or around 3% of total generated residual waste in Latvia annually is delivered to Schwenk Latvia for co-incineration. In total, Schwenk Latvia uses annually around 160,000–200,000 tons of specially prepared mixture from specially processed household and industrial waste sorted, dried, shredded, and mixed in pre-defined proportions. These materials make up 98% of all the fuel used at the Schwenk Latvija cement plant.

Apart from the existing co-incineration cement plant in Schwenk Latvia, several other WtE facilities are in the planning and/or development phases.

4.3.1. Riga Region WtE Facilities

In the year 2023, 390,000 tons of waste ended up at the "Getliņi" landfill located in the Riga region, and nearly half, or 53%, of the waste, was landfilled. Based on the interviewed waste management experts' estimates, around 150,000 t of non-recyclable waste, which is currently landfilled, could be used for energy recovery. In addition, around 90,000 t of non-recyclable waste landfilled in other regions of Latvia could be used for energy production. It means that, overall, around 240,000 t of non-recyclable waste could be used annually in Latvia as a resource for energy recovery and accordingly diverted from landfills.

A private company (Vides resursu centrs Ltd.) has performed an environmental impact assessment for the construction of a new cogeneration plant for the production of heat energy and electricity, along with its associated infrastructure. The primary fuel is intended to be refuse-derived fuel (RDF), which is sorted and prepared specifically for combustion. It is planned that the cogeneration plant will also be suitable for the combustion and co-combustion of biomass (solid fuel). The RDF consumption is planned to be up to 143,000 tons per year, with the cogeneration plant producing approximately 404 GWh/a of net (delivered) heat energy and approximately 126 GWh/a of net (delivered) electricity. Within the scope of the proposed activity, the proponent does not rule out the possibility of partially or completely replacing RDF with biomass (wood chips).

In May 2024, a private energy company Gren Latvija announced the development of a modern and safe waste regeneration station in the Acone, Riga region, with the parameters as outlined in Table 2.

Table 2. Parameters of WtE facility in Acone, Riga region (under development).

Parameter	Description
Annual Regeneration Capacity	150–200 thousand tons
Energy Source	Sorted, non-recyclable non-hazardous waste; low-quality wood residues; other biomass residues
Source Location	Latvia
Thermal Power	50–70 MW
Electric Power	15–20 MW
Produced Heat Energy	~40,000 households

4.3.2. Other Regional WtE Facilities

The proposed project in the Ventspils (a city in the Western part of Latvia) region developed by a municipal company involves the construction of regeneration facilities and associated engineering communications to produce heat energy and electricity from fuel derived from waste. The nominal production capacity of the RDF recovery plant is designed for 8.5 MW, featuring a steam heat carrier at 40 bar/400 °C, and energy production metrics in cogeneration mode: 5.6 MWth of heat and 1.5 MWel of electricity. The RDF recovery plant will incinerate 15,300 tonnes of RDF annually with a calorific value of 16 MJ/kg (including 11,000 tonnes from the Ventspils waste management region and 4300 tonnes from surrounding regions). As a result of the NAIK recovery process, both heat energy and electricity will be produced.

Another regional WtE project under development is in Jelgava (a city in the Southern part of Latvia). The developer of the project, namely, a private company, Gren Latvija, commenced the project in 2018, and, in 2023, the necessary authorizations were obtained for the co-incineration of RDF. It is planned to use up to 30,000 tons of RDF per year for energy production, mixed with wood chips up to 35%. The planned amount of produced energy is 460 GWh. In cases where the quantity of domestically produced RDF of appropriate quality is insufficient, increasing the amount of biomass (up to 205,000 tons per year) has also been considered as an alternative.

One of the main facilitators of the WtE discussion in Latvia and the business case for the WtE facilities under development–an increase in natural resource tax for waste landfilling (Figure 7). Higher landfilling taxes make it more expensive for businesses to dispose of waste in landfills and incentivize them to seek alternative waste management solutions, such as waste-to-energy facilities. Taxation changes on landfilling create a strong business model including tipping fee calculations considering that increased landfilling taxation might lead to increased tipping fees set by WtE operators. However, since most of the WtE plants have not commenced operation in Latvia and business plans thereof are not publicly available, the precise business model cannot be analyzed, and the modeling is based on assumptions.

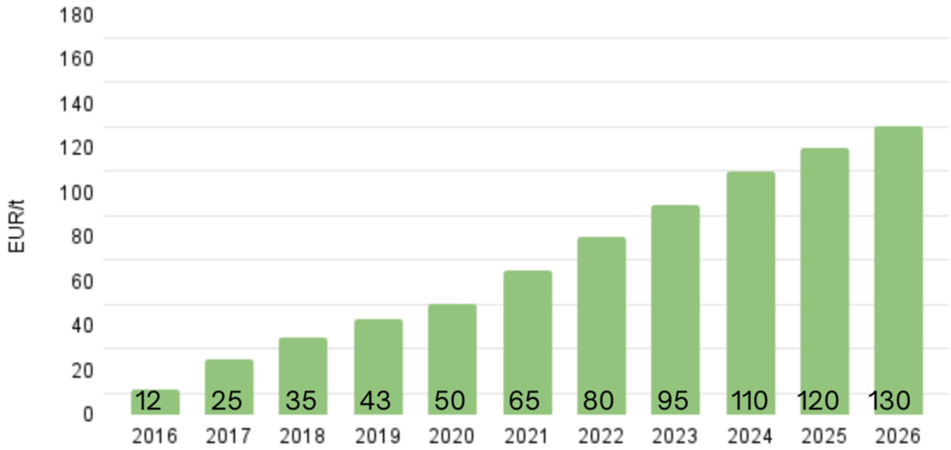

Figure 7. Natural resource tax changes in Latvia 2016–2026. Source: by authors.

5. Case of Ukraine

The problem of waste in Ukraine is particularly large and significant due to the dominance of resource-intensive and multi-waste technologies in the national economy, as well as the long-standing lack of an adequate response to these challenges. High resource use and energy and raw materials specialization of the economy, together with an outdated technological base, have led to and continue to lead to high rates of waste generation and accumulation.

Such circumstances deepen the environmental crisis and exacerbate the socio-economic situation in society, which necessitates the reform and development of the entire legal and economic system regulating the use of natural resources and waste management, taking into account domestic and international experience. The waste problem is one of the key environmental issues, especially significant from the resource perspective.

Waste generated during mining, enrichment, chemical and metallurgical processing, transportation, and storage of minerals is a secondary raw material reserve for industry, construction, and energy. Waste as a secondary raw material from end-use products, such as wastepaper, polymers, glass, worn-out tires, etc., also has significant resource potential. High levels of waste generation and low rates of recycling have resulted in significant amounts of solid waste being accumulated in Ukraine's industry and municipal sector each year. Only a small part of this waste is used as secondary material resources, while the rest ends up in landfills.

The difference between Ukraine's waste situation and that of other developed countries is the large volumes of waste generated and the lack of waste management infrastructure. At the same time, the availability of such infrastructure is an essential feature of all developed economies.

Ukraine currently has only one energy recovery plant, the Energia plant, which provides heat and hot water to high-rise buildings in Kyiv. By 2018, it was planned to almost double the amount of household waste utilization by thermal means in Ukraine compared to 2016, including through the construction of two new incinerators, as set out in the National Waste Management Strategy for Ukraine until 2030 [9] and the concept of legislative changes to create conditions for energy recovery of household waste in Ukraine. Energy recovery of household waste is the next step after its sorting and allows not only the effective use of the remaining waste that cannot be further processed but also the generation of electricity and heat as close to its consumers as possible. Thus, the Energia plant processes about two hundred and fifty thousand tonnes of household waste, which is about 2.5% of the total waste volume. The plant produces 200 thousand gcal of heat energy per year, which replaces up to 30 million cubic meters of gas (Figure 8).

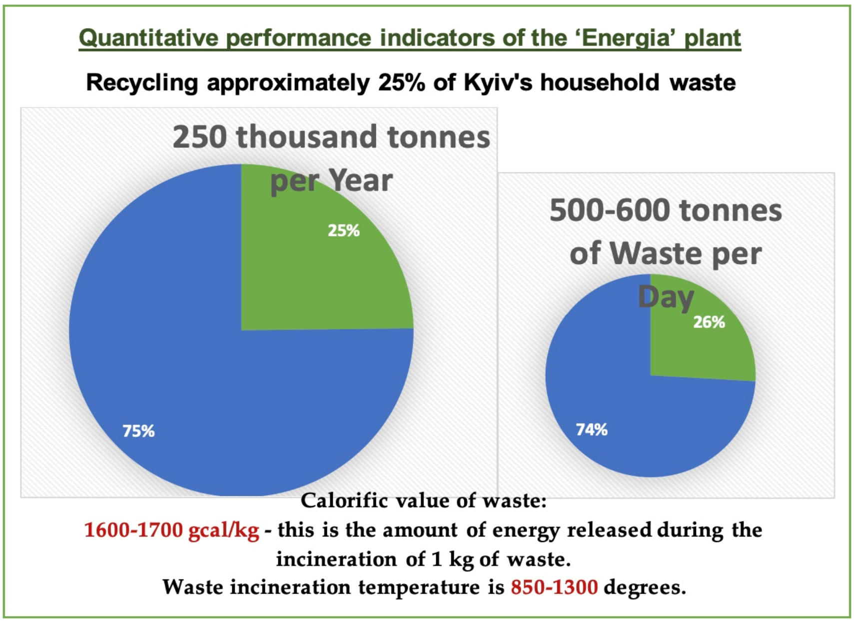

Figure 8. Waste-to-energy parameters of the 'Energia' plant (Ukraine). Source: by authors.

For comparison with Latvia, previously mention in Table 2, in Table 3 shown Parameters of WtE facility in Energia, Kiyv region.

Table 3. Parameters of WtE facility in Energia, Kiyv region. Source: by authors.

Parameter	Description
Annual Regeneration Capacity	250 thousand tons
Energy Source	municipal solid waste
Source Location	Ukraine
Thermal Power	50–70 MW
Electric Power	15–20 MW
Produced Heat Energy	~60,000 households

Waste is transported to the waste treatment plant in accordance with existing regulations by transportation companies. The carrier unloads the waste at the plant, where it is deposited for about a week and saturated with gases; the waste is fed into a boiler where it is incinerated, and the heat generated during incineration heats water, which is used for heating and hot water supply to apartments. The slag (ash) generated after incineration is taken to a landfill for disposal or used for road construction.

The incineration temperature at the plant is 850–1300 degrees. At this temperature, most harmful substances are neutralized, and the unpleasant smell disappears. Electrostatic precipitators are installed to collect dust and harmful substances from the flue gases. In 2020, the last stage of the flue gas cleaning system modernization began, which will bring emission standards in line with European Union standards. Today, the plant's emissions are half the amount allowed by Ukrainian law (Figure 9). The Energia plant's emissions account for 0.2% of total emissions in Kyiv.

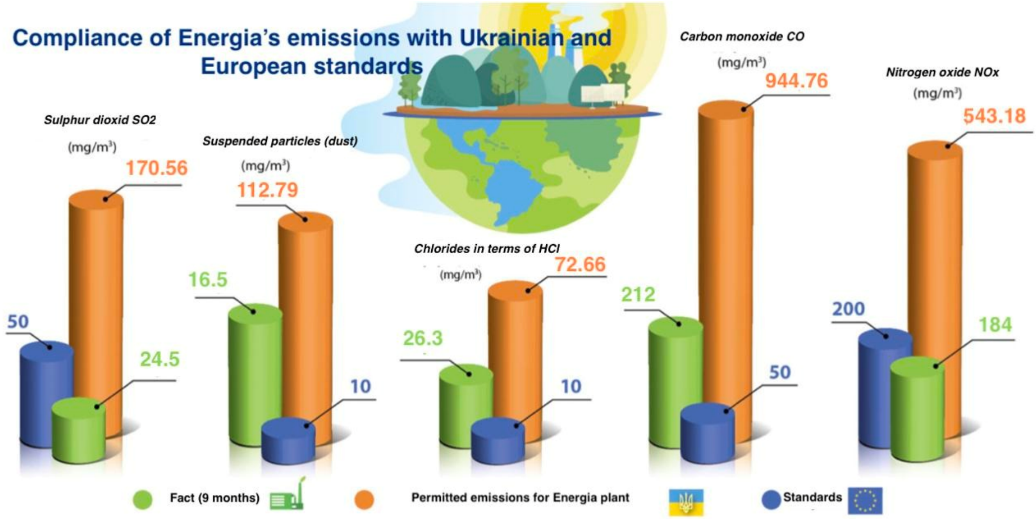

Figure 9. Infographics of Energia plant emissions and relevant Ukrainian and European standards. Source: [39].

The environmental standards of the incinerator in Ukraine are met by installing electrostatic precipitators that collect dust and harmful substances from the flue gases. The flue gas cleaning system is currently being modernized to bring emissions in line with European Union standards, and the plant's emissions are already half the level required by Ukrainian legislation. The modernization of the flue gas cleaning system involves the introduction of the latest technologies that will significantly increase the efficiency of removing harmful substances such as dioxins, furans, and heavy metals. These changes will enable the plant to meet the most stringent environmental standards of the European Union, which will help reduce its negative environmental impact. At the same time, efforts to improve the emissions monitoring and control system will allow us to quickly detect any deviations and respond to them in a timely manner, providing additional protection for the ecosystem and human health [40–42].

It should be noted that waste generation in Ukraine averages 250–300 kg per person per year and is on the rise. At the same time, state accounting and statistics of household waste in Ukraine have significant shortcomings. Statistical reporting and regulations on household waste management use both volume and weight categories. Conversion of one unit to another leads to significant errors in assessments, forecasts, etc.

The dominant method of household waste management is still its removal and disposal at landfills and dumpsites. In 2016, only 5.8 percent of the household waste generated was recycled, including 2.71 percent (1.3 million cubic meters) disposed of (incinerated), 3.09 percent (1.53 million cubic meters) sent to other waste processing facilities, and about 0.003 percent (2000 cubic meters) composted. The remainder (about 94 percent) is disposed of at landfills and dumpsites, of which there were 5470 in Ukraine as of 2016, of which 305 (5.6 percent) were overloaded and 1646 (30 percent) did not meet environmental safety standards [43,44].

Under the current waste management system, the main operators are carriers that transport waste from households, institutions, and organizations to landfills or dumps. Disposal of unsorted waste is a costly method that is financed through tariffs for households. This tariff is supposed to cover the costs of maintaining container sites, transporting waste to landfills, and disposing of it. However, such a system does not bring economic benefits, and the tariff will inevitably increase every year as the amount of waste increases. The costly recycling technologies are financed through tariffs and budget subsidies, making the system economically inefficient.

Carriers participating in this system are not engaged in solid waste disposal and do not profit from this process, which makes them disinterested in introducing the latest technologies and integrated waste management systems. The result is a system that only provides for the disposal of solid waste to landfills that do not meet landfill standards, which only postpones the solution to the problem and does not bring any economic benefits. The issue of creating a waste management system should take into account key principles, such as the choice of a waste collection and disposal area, the choice of modern processing technologies to obtain secondary products, the creation of an administration system, and the formation of tariff policy, ensuring the interests of investors and communities.

In general, the waste management system in Ukraine is characterized by the following trends:

(a) Accumulation of waste in both the industrial and domestic sectors, which has a negative impact on the environment and human health;
(b) Improper utilization and disposal of hazardous waste;
(c) Disposal of household waste without taking into account possible hazardous consequences;
(d) Inadequate use of waste as a secondary raw material due to imperfect organizational and economic principles of its involvement in production;
(e) Inefficiency of the economic instruments implemented in the field of waste management.

Significant volumes of waste accumulated in Ukraine and the lack of effective measures aimed at preventing its generation, recycling, neutralization, and disposal deepen the environmental crisis and become a hindrance to the development of the national economy.

This situation necessitates the creation and proper functioning of a nationwide system of waste prevention, collection, recycling and utilization, neutralization, and environmentally safe disposal. This should be an urgent task even in the context of the relatively limited economic capacity of both the state and major waste generators. Thus, the only possible way to resolve the situation is to create a comprehensive waste management system.

6. Discussion

Ukraine has made significant progress in waste-to-energy, with important steps being taken both in the legislative field and in the development of technologies. These efforts are already beginning to bear results: the share of waste used as secondary raw materials is increasing, the amount of waste going to landfills is decreasing, and greenhouse gas emissions are decreasing. Continuing this work will allow Ukraine not only to improve energy efficiency but also to make a significant contribution to environmental protection and sustainable economic development and to balance the ecological and economic system.

However, there are still issues to be resolved: Ukraine currently prefers landfilling solid waste to recycling it into heat and power, due to the low prices for landfilling. To make this industry more interesting for investment, the first step is to provide incentives from the government. Industries that require the use of expensive technologies usually develop only under certain economic conditions.

Therefore, to ensure energy efficiency and energy conservation, it is proposed to introduce changes that would make waste disposal the least economically viable option, stimulate the attraction of private capital to energy recovery, establish an effective system of waste management administration at the municipal level, and expand the powers of local governments.

7. Conclusions

Undoubtedly, achieving the SDGs requires collective action from countries, businesses, and individuals, with waste management playing a significant role due to the massive amounts of waste generated globally every year. The existing data indicate that the EU has implemented policies and directives to promote sustainable development, resource efficiency, and a transition towards a circular economy, with member states like Latvia making substantial progress in improving waste management systems. It is worth considering that waste-to-energy approaches can provide alternative energy sources with reduced carbon footprints, but they must be carefully implemented with appropriate technologies and controls to minimize emissions and environmental risks. Similar ideas are expressed in this research paper [30,45,46]; the authors of this research paper [46,47] present comparable concepts, highlighting that waste-to-energy technologies can play a crucial role in reducing carbon emissions from energy systems and promoting a sustainable circular economy. However, they emphasize that this potential can only be fully realized when these technologies are implemented alongside suitable emission control measures and a holistic approach to waste management.

The statistical data analysis leads to the conclusion that the continuous growth in production and consumption driven by population increase leads to negative environmental consequences like resource depletion and pollution, creating contradictions between human needs, economic activities, and natural ecological systems. To achieve sustainability, there is a need to develop and implement effective science-based practical mechanisms for balanced environmental management by forming balanced ecological and economic systems at the regional and industrial complex levels. The proposed model by the authors represents the ecological–economic system as a combination of jointly functioning ecological and economic subsystems, where the economic subsystem utilizes resources from the environmental subsystem and generates waste that impacts the environment, highlighting the need to balance the anthropogenic load with the self-healing potential of natural systems. To achieve a balanced and sustainable EES, waste management mechanisms need to be developed, focusing on reducing waste production, controlled waste disposal (landfilling), waste-to-energy conversion, and recycling, as statistics show an increase in solid waste generation is an integral part of economic growth. The conclusions are in line with previous studies highlighting that, in response to the growing waste problem, global efforts from scientists, foundations, and companies have led to innovative technologies and strategies addressing various waste sources, incorporating both technological and sociological approaches, leveraging digital platforms for awareness, and aligning with sustainable development goals and circular economy principles [48]. Moreover, global solid waste management faces diverse challenges across regions, requiring improved waste hierarchy and circular economy compliance, enhanced stakeholder participation to address inefficiencies, promote sustainability, and support UN Sustainable Development Goals [49].

While European countries have been global leaders in promoting sustainable development and working towards the SDGs, it is important to acknowledge their challenges. Despite considerable progress across many of the 17 SDGs, total compliance with the ambitious 2030 Agenda remains a significant challenge, highlighting the need for further action and commitment. The latest statistics highlight that among the nations that scored average or above average were Latvia and Ukraine. Both have made notable strides, while each country demonstrates relative strengths and weaknesses across the various goals. The uneven progress underscores the need for further action to drive considerable improvements and meet the ambitious targets.

The EU recognizes WtE incineration as a crucial technology that can aid the transition to a circular economy by providing a sustainable solution for non-recyclable waste while generating energy and reducing greenhouse gas emissions. These conclusions support previously expressed ideas by [50,51]. Despite concerns and debates surrounding WtE, it is considered indispensable for sustainable waste management, at least until the full implementation of circular economy regulations leads to a significant reduction in non-recyclable waste volumes after 2030.

The analysis of the situation in Latvia allows the authors to claim that Latvia is at risk of not meeting the EU's target of landfilling no more than 10% of generated household waste by 2035, as, currently, 52% of household waste (around 456,000 tones) is still being landfilled. The national waste and energy plans endorse WtE as a viable solution to reduce landfilling and recover energy from non-recyclable waste. While biochemical WtE conversion through anaerobic digestion and biogas production is relatively well-established in Latvia, with over 40 biogas stations operating, thermochemical WtE conversion through incineration is still underdeveloped. The only existing facility is a cement plant co-incinerating around 15,000 tons of RDF annually. Several new WtE facilities, primarily for the thermochemical conversion of RDF and non-recyclable waste into heat and electricity, are in the planning and development phases across different regions of Latvia, such as Riga, Ventspils, and Jelgava. These projects aim to divert significant waste from landfills and contribute to energy production.

Through the examination of the situation in Ukraine, the authors can state that the country faces a significant waste crisis due to high waste generation rates, lack of proper waste management infrastructure, and dominance of outdated resource-intensive technologies, resulting in the accumulation of large volumes of solid waste, with only a small portion being recycled or used for energy recovery. The modernization of the existing waste processing plant creates additional energy capacity but does not currently solve the problem of waste processing in its entirety and does not have the effect that is possible with a comprehensive solution to this issue at the national level. The majority of solid waste is disposed of in landfills, the share of recycling does not exceed 5%, and the average tariff for solid waste disposal is EUR 2 per ton. The current situation in Ukraine is that, unfortunately, MSW energy is used in limited volumes and only 10 landfills collect biogas for electricity production and sell it to the grid at a "green" tariff. Waste incineration is an expensive option that requires significant investment and a fairly high utilization tariff, and the price of the generated heat and electricity is quite high. Therefore, in Ukraine's context, it is first and foremost necessary to implement measures to reduce the amount of waste generated (prevention) and to process it for reuse (recycling). These are the priority areas according to the European Waste Directive 2008/98/EC. Addressing the waste situation in Ukraine necessitates the creation of a comprehensive nationwide waste management system that focuses on waste prevention, collection, recycling, utilization, neutralization, and environmentally safe disposal, which has become an urgent task despite limited economic capacity. The experience of the European Union in sorting and recycling household waste demonstrates the importance of effective waste management to reduce the negative impact on the environment and conserve resources.

The EU countries are actively implementing separate waste collection systems, which are currently very underdeveloped in Ukraine, and the developed infrastructure of EU processing facilities allows for efficient conversion of collected waste into energy. At the same time, strict legislation in the EU aimed at preventing the use of harmful materials and a system of incentives to encourage society to switch to environmentally friendly materials, reduce waste sorting, and play an important role in shaping sustainable policies. This integrated approach allows EU countries to achieve high rates of waste recycling, reducing the negative impact on the environment and promoting sustainable development, which provides an opportunity for scientists, economists, and policymakers in Ukraine and Latvia to develop an effective national strategy for integrated waste to energy in terms of economic, environmental, and social components.

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