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Analysis of data on the generation of waste electrical and electronic equipment

Evgeniy Grechanyuk*

Postgraduate Student
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose Str., Vinnytsia, Ukraine
https://orcid.org/0009-0008-5687-2269

Vitalii Ishchenko

PhD in Technical Sciences, Associate Professor
Vinnytsia National Technical University
21021, 95 Khmelnytske Shose Str., Vinnytsia, Ukraine
https://orcid.org/0000-0002-8464-1096

Abstract. The amount of waste electrical and electronic equipment (WEEE) is growing rapidly worldwide, outpacing the development of infrastructure for its collection and recycling. This aggravates environmental challenges and exacerbates the shortage of critical resources. The study aimed to conduct a comparative analysis of approaches to WEEE management in Ukraine, the European Union, Africa, Latin America, the United States, Australia and Brazil. The study emphasised the identification of differences in regulatory approaches, collection rates, recycling methods, and formulating recommendations for the implementation of effective practices in the Ukrainian context. The methodology included a systematic analysis of the legislative framework, statistical methods for assessing the dynamics of WEEE generation and collection, a comparative geographical analysis of national models, and a content analysis of regulatory documents. The study demonstrated that the EU has the most structured waste management model based on the principle of extended producer responsibility, but even with clear standards in place, collection rates are significantly lower than target values. In the US, WEEE management is fragmented and lacks uniform federal regulation, which makes it difficult to compile reliable statistics. Australia demonstrates the effectiveness of co-regulatory approaches, while Brazil demonstrates the unique integration of the informal sector into the official reverse logistics system. A comprehensive combination of legislative, infrastructural and behavioural dimensions of EPR management in five countries with different economic models is considered. The practical significance of the study is determined by the formulation of recommendations for Ukraine on the implementation of extended producer responsibility, the development of a monitoring system, increasing market transparency and adapting successful international instruments for the transition to a circular economy

Keywords: electronic waste; extended producer responsibility; circular economy; international management models; collection infrastructure; environmental policy

Introduction

Intensive digitisation and shorter lifespans of electrical and electronic devices have led to a sharp increase in the volume of related waste, making it one of the most challenging elements of global material circulation. Electronic waste contains high concentrations of strategically relevant metals and critical resources, but at the same time

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*Corresponding author

includes components that, in the absence of proper control, pose a serious threat to the environment and public health. Given that the scale of electrical and electronic equipment (WEEE) generation worldwide exceeds the capacity of existing collection and recycling systems to respond quickly to these changes, public policy should be based on accurate quantitative estimates, flow analysis and forecasting of the potential for material reuse within a circular economy.

During 2021-2024, the scientific community has paid significantly more attention to the dynamics of electronic waste generation and management. The latest global monitoring by WEEE shows record figures: in 2022 alone, 62 billion kg of electronic waste was generated worldwide, while the share of documented collection remains critically low (Baldé *et al.*, 2024). It is predicted that without changes to modern models, collection rates could decline to 20% by 2030, while generation rates will increase. The results of scientific research by M. Compagnoni (2022) show that improving the efficiency of waste management systems creates opportunities for significant economic benefits, in particular through the return of valuable materials to production cycles.

The issue of waste electrical and electronic equipment management is widely researched in contemporary scientific literature. S. Gulliani *et al.* (2023) conducted a critical review of existing technologies for extracting metals and valuable chemical compounds from electronic waste, noting significant potential for resource recovery when modern processing methods are used. According to D.D.S. Azizi *et al.* (2023), the material flow analysis (MFA) method is one of the leading analytical tools in the field of electronic waste management, but existing studies have significant limitations, including insufficient coverage of countries outside the OECD and limited use of dynamic models.

In a systematic review of the literature, M. Compagnoni (2022) analysed the effectiveness of the extended producer responsibility (EPR) mechanism in electronic waste management and concluded that, despite its prevalence, this tool does not always ensure that collection targets are met. According to N.M. Franz & C.L. Silva (2022), the traditional model of assessing collection relative to the volume of equipment placed on the market does not consider the unevenness of product life cycles, the accumulation of equipment in households, and the scale of informal flows. Among Ukrainian scientists, H. Yafen & T. Shevchenko (2021) significantly contributed to the study of this issue by analysing the mechanisms for promoting smart e-waste management systems in China and determining that small household electronics have the lowest return rates to collection systems. In addition, F. Mihai *et al.* (2024) investigated the characteristics of the circular economy and waste management in Eastern European countries.

In the European Union, concern regarding WEEE is reflected in the revision of the targets stipulated in Directive 2012/19/EU, as the traditional model of "collection relative to the volume of equipment placed on the market" does not cover the unevenness of life cycles, the accumulation of equipment in households and the scale of informal flows (Franz & Silva, 2022). In this regard, researchers highlight a need for a transition to more dynamic, material-specific indicators that are consistent with European aspirations for digital product passports and the recovery of critical raw materials (Kusch & Hills, 2017; Xavier *et al.*, 2021). The study aimed to conduct a comparative analysis of approaches to WEEE management in Ukraine, the European Union, the United States, Australia and Brazil, incorporating their legal framework, structural characteristics of waste, level of technological development and the effectiveness of existing collection and recycling models.

Materials and Methods

The study was conducted using a comprehensive combination of methods, which ensured a comprehensive coverage of the peculiarities of WEEE management in different regions and ensured the analytical consistency of the results obtained. Each method was selected, incorporating the specifics of the set goal and the nature of the available data. The system analysis method was used to consider national WEEE management systems as internally linked structures in which legislative requirements, infrastructure, economic incentives and behavioural factors form a common trajectory of efficiency. This method was used to track the impact of changes in one element (e.g., stricter ERP requirements) on collection rates or consumer behaviour. The relevance of the method is determined by the need to integrate diverse types of data, from legal provisions to statistical indicators, into a comprehensive picture of the system's functioning.

The comparative geographical method was used to identify differences and similarities between countries (the practices of the European Union, the United States, Australia, African countries, and Latin America) in terms of the regulatory framework, infrastructure organisation, level of technological development, and dynamics of WEEE flows. This identified both the structural advantages of individual regions and their characteristic problems. This method ensured the comparison of management models and the identification of the most effective practices for possible implementation in Ukraine. Statistical methods and Pearson's correlation coefficient were used to analyse quantitative indicators related to the generation, collection and processing of WEEE. The relationship between the volume of equipment placed on the market and the actual collection of its waste was analysed by constructing a linear regression. The study used dynamic series processing, calculation of intensive and relative indicators, as well as analysis of the relationship between the main variables of WEEE volumes on the market and the mass of officially collected waste. This ensured a transition from descriptive characteristics to quantitative conclusions and comparisons, which significantly increased the reliability and accuracy of the analytical part.

Synthesis was applied at the final stage of the research to combine the conclusions obtained using all previous methods. It was used to form a consistent model of the state of WEEE management in selected countries, identify general trends, characteristic problems and features of individual regions. The synthesis formulated balanced recommendations on adapting international experience to Ukrainian conditions. The study used data from the following groups of sources: international monitoring reports; peer-reviewed scientific publications presented in the international databases Scopus and Web of Science; official statistics from government and industry institutions. Their combined interpretation provided a broad view of the global context of WEEE management and enabled accurate cross-country comparisons. Content analysis and secondary processing of documents were the main tools used when working with regulatory acts, reports of international organisations, scientific publications and official statistics (Directive of the European Parliament and of the Council No. 2012/19/EU, 2012; Draft Law of Ukraine No. 2350, 2019; Hlavatska, 2021; Update of WEEE…, 2021; International Trade Administration, 2022; Baldé *et al.*, 2024; Clean Up Australia, 2024; Regulation of the European Parliament and of the Council No. 2024/1252, 2024; Eurostat, n.d.). This approach identified key legislative provisions and assessed performance indicators that shape the modern discourse in the field of WEEE management. In the context of the scale of the problem and the fragmentation of information, the decision to forego primary data collection in favour of a thorough analysis of authoritative sources ensured the high quality and validity of the results obtained.

Results and Discussion

The waste electrical and electronic equipment management system in the European Union was formed based on Directive of the European Parliament and of the Council No. 2012/19/EU (2012), which became a key regulation aimed at minimising environmental risks and implementing circularity principles. Its emergence was a response to the continuous growth of WEEE flows and the need to create mechanisms capable of ensuring control over the entire product life cycle. The Directive is based on the EPR approach, which places financial and organisational obligations for the collection, treatment and disposal of waste on electronic equipment manufacturers, rather than on municipalities or end users. As noted in several studies, this model forms the basis of EU policy on WEEE management and serves as a key prerequisite for the development of an economically efficient and sustainable collection infrastructure (Xavier *et al.*, 2021; Compagnoni, 2022; Zoka & Korez Vide, 2025).

The directive obliges Member States to establish national registers of EEE manufacturers and importers, to ensure that equipment can be returned free of charge at the end of the service term, and to prevent it from entering unsorted municipal waste. The "one-for-zero" and "one-for-one" principles, whereby retailers accept old equipment regardless of whether new equipment is purchased or sold, have become one of the key practices in EU countries (Kusch & Hills, 2017). The system of minimum targets is substantial: from 2019, EU countries must ensure a collection rate equivalent to 65% of the average weight of equipment placed on the market in the previous three years.

Despite the existence of a single regulatory framework, implementation varies significantly between countries (Grandhi *et al.*, 2024). Germany and Sweden demonstrate consistently high results, which are associated with the early introduction of EPR and a developed waste management infrastructure (Update of WEEE..., 2021). At the same time, publications note that a significant portion of WEEE still bypasses official collection channels, ending up in "grey" streams caused by exports, informal dismantling, or long-term storage in households (Serpe *et al.*, 2025). The data show contradictory dynamics: although the total volume of waste collected is growing in absolute terms, its share relative to the volume of EEE placed on the market is showing a downward trend (Directive of the European Parliament and of the Council No. 2012/19/EU, 2012). In 2022, the collection rate was only 40.06%, which is significantly below the regulatory benchmark. At the same time, the volume of EEE introduced into circulation has almost doubled compared to 2011, putting additional pressure on the collection and recycling system. Below is a summary of the dynamics for 2011-2022 (Table 1).

Table 1. Dynamics of EEE generation and collection in the EU (2011-2022)

Year	Volume of EEE on the market (million tonnes)	Collected WEEE (million tonnes)	Level of WEEE collection (%)
2011	7.65	3.04	37.44
2012	7.63	2.97	38.58
2013	7.76	2.97	38.38
2014	7.00	2.96	38.58
2015	8.04	3.23	41.54
2016	8.51	3.49	44.20
2017	9.07	3.76	46.12
2018	10.29	3.99	46.76
2019	11.21	4.52	48.61
2020	12.40	4.72	46.30
2021	13.74	5.06	44.76
2022	14.44	4.99	40.06

Source: compiled by the authors based on Eurostat (n.d.)

To quantitatively confirm the relationship between the main variables, a correlation analysis of data for the period 2011-2022 was performed. The results of the analysis are presented in Table 2.

Table 2. Results of correlation analysis of WEEE management indicators in the EU

Variable pair	Pearson's correlation coefficient (*r*)	Significance (*p*)	Interpretation
EEE POM – Absolute volume of WEEE collection	0.94	<0.001	Strong positive correlation
EEE POM – Relative collection rate (%)	-0.21	>0.05	Weak negative correlation (statistically insignificant)
Year – EEE POM	0.98	<0.001	Strong positive correlation
Year – Absolute volume of WEEE collection	0.91	<0.001	Strong positive correlation

Note: EEE POM – electrical and electronic equipment placed on the market
Source: calculated by the authors based on Eurostat (n.d.)

The results obtained indicate a strong positive correlation ($r = 0.94$; $p < 0.001$) between the volume of electrical and electronic equipment placed on the market (EEE POM) and the absolute volume of waste collected. This means that as the number of products on the market increases, so does the absolute volume of WEEE collected. At the same time, the correlation between EEE POM volumes and the relative collection rate (in percent) is weak negative ($r = -0.21$) and statistically insignificant ($p > 0.05$). This confirms that the growth rate of the electronics market significantly outpaces the development of collection infrastructure, as a result of which the relative collection rate does not grow proportionally and has even shown a downward trend (Chu *et al.*, 2024). In addition, a linear regression analysis was performed to determine the dependence of the absolute volume of WEEE collection on the volume of EEE POM. The resulting regression equation is as follows:

$$Y = 0.31X + 0.77\ (R^2 = 0.89), \quad (1)$$

where Y – volume of collected WEEE (million tonnes); X – EEE POM volume (million tonnes); determination coefficient $R^2 = 0.89$, indicating that 89% of the variation in collection volumes is explained by changes in production volumes on the market. A regression coefficient of 0.31 means that an increase in EEE POM by 1 million tonnes is accompanied by an increase in absolute collection of only 0.31 million tonnes, which quantitatively confirms the insufficient adaptability of existing collection systems to the growing volumes of electronic products.

To quantitatively confirm the relationship between the volume of electrical and electronic equipment placed on the market (EEE POM) and the level of waste collection, a correlation analysis of data for the period 2011-2022 was performed. The Pearson correlation coefficient between EEE POM volumes and absolute waste collection volumes is $r = 0.94$ ($p < 0.001$), indicating a strong positive relationship. At the same time, the correlation between EEE POM volumes and the relative collection rate (in percent) is weak and negative ($r = -0.23$), confirming the growing gap between the rate of new product introduction and the capacity of the collection system.

The results of the study show that most European Union countries are taking consistent steps towards improving WEEE management systems. At the same time, the growth rate of new electronics entering the market significantly outpaces the development of the relevant infrastructure and the effectiveness of take-back mechanisms. A range of studies emphasise that even well-structured approaches, such as the European model, face challenges such as the existence of illegal or hidden flows, weak motivation among end consumers to participate in return systems, and the widespread use of small household appliances with particularly low return rates (Yafen & Shevchenko, 2021; Liu *et al.*, 2023). The figure below illustrates one of the most pressing challenges for the EU: the imbalance between the speed at which new equipment appears on the market and the speed at which old devices are returned to the collection and recycling system (Fig. 1).

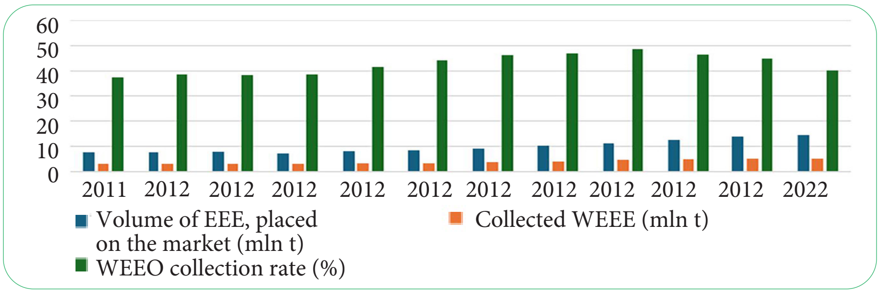

Figure 1. Dynamics of WEEE generation and collection in the EU (2011-2022)
Source: compiled by the authors based on Eurostat (n.d.)

Eurostat data (n.d.) shows rapid growth in the amount of electrical and electronic equipment entering the European Union market each year. Since 2015, this figure has increased by approximately 80% from 18 to 28 kg per capita. In contrast, the volume of officially collected WEEE during this period increased by only 54.7%, indicating a widening gap between the generation and actual return of products to the recycling system. This disproportion confirms that, despite the existence of European legislation and a formally developed infrastructure, the "take-make-waste" model continues to prevail. The reasons lie in the high dynamics of technological renewal, the growth in consumption of consumer electronics, limited repair options and the gradual reduction in product life cycles, trends that are noted in contemporary studies of the circular economy (Liu *et al.*, 2023).

Behavioural barriers are a substantial factor hindering the achievement of collection targets. A survey conducted in EU countries as part of the Global E-waste Monitor showed that a significant proportion of small electrical appliances and accessories are stored in households for years. Almost 13% of respondents admitted that they keep old phones, headphones, remote controls or chargers due to "emotional attachment", while the rest of the respondents stated they did not know where to properly dispose of such equipment. As a result, millions of electronic devices remain outside official collection streams, and valuable materials, including metals and critical raw materials, are effectively removed from economic circulation. According to Global E-waste Monitor estimates, this represents a loss of resources worth approximately 62 billion USD annually (Baldé et al., 2024).

The situation in Ukraine differs significantly in terms of scale, but the nature of the problem is similar. According to estimates by L. Hlavatska (2021), approximately 28,000 tonnes of WEEE are generated in the country annually. However, this figure is approximate, as Ukraine does not have a comprehensive system for monitoring and state accounting of electronic waste generation, especially in the household sector, where a significant portion of devices are retained by consumers or end up in mixed waste. The lack of reliable data creates a false impression of the scale of the problem and complicates the formation of effective state policy. Based on available estimates, a generalised component composition of WEEE in Ukraine has been formed (Table 3-4), which confirms the significant share of valuable metals, but also indicates significant volumes of hazardous components.

Table 3. Distribution of waste electrical and electronic equipment in Ukraine by category (2019)

Waste category	Approximate volume (thousand tonnes)	Share of total volume (%)
Technological devices	16.506	58.5
Batteries	5.934	21.0
Home and office appliances	3.637	12.9
Electronic components	1.196	4.2
Fluorescent lamps	0.564	2.0
Total	**~28.225**	**100**

Source: compiled by the authors based on L. Hlavatska (2021)

Table 4. Average material composition of waste electrical and electronic equipment in Ukraine

Material	Share by mass (%)	Note
Plastic	30.0	Cases, insulation
Copper	20.0	Wires, coils, printed circuit boards
Metal	8.0	Frames, mounts
Tin	4.0	Solder
Nickel	2.0	Batteries, coatings
Aluminium	2.0	Radiators, cases
Lead	2.0	Batteries, solder
Zink	1.0	Coatings
Silver	0.2	Contacts
Gold	0.1	Contacts, printed circuits
Other materials (glass, ceramics, etc.)	30.7	-
Total	**100**	-

Note: certain categories of WEEE (batteries, fluorescent lamps) contain hazardous substances such as lead, cadmium, mercury and arsenic, which require special handling conditions

Source: compiled by the authors based on L. Hlavatska (2021)

The state of WEEE management infrastructure in Ukraine remains fragmented. Although more than 1,500 companies are operating in the field of waste management in the country, only a small proportion of them have licences for WEEE collection and disposal operations. Of the 128 companies capable of accepting certain types of hazardous electronic waste, only 22 have the appropriate permits for its treatment, and only four are operating. This means that most electronic waste is either mixed with household waste or ends up in the informal sector, where it is dismantled without environmental control. Illegal imports of electronic waste from EU countries create an additional burden. According to the Global E-waste Monitor, it accounts for 14-18% of all WEEE generated in Ukraine (Baldé *et al.*, 2024). This situation makes Ukraine one of the destination countries for cross-border waste shipments, which is a serious problem in a global context. Weak control and the lack of specialised infrastructure contribute to the formation of a "shadow" market, which highlights the difference between formal obligations and actual practices.

In the context of reforms, one of the key areas is the introduction of EPR. Draft Law of Ukraine No. 2350 (2019) proposes to lay the foundations for a system that will provide for the financial and organisational participation of producers in the collection, processing and disposal of electronic waste (Table 5). It is expected that the introduction of EPR will not only align Ukrainian legislation with EU standards, but also stimulate changes in product design, increase its repairability and create conditions for the circular use of materials.

The integration of the RBB principle in Ukraine is viewed as one of the key steps on the path from a linear approach to resource management to a circular economy. In a situation where a significant portion of electronic waste is disposed of as general household waste or processed in the informal sector, the creation of a transparent, regulated system for WEEE management is critical. This approach will minimise environmental threats and facilitate the return of strategically relevant materials to production cycles.

Table 5. Comparison of key aspects of WEEE management systems in the EU and Ukraine

Characteristic	European Union	Ukraine (draft law)
Legal framework	Directive 2012/19/EU	Law of Ukraine "On Waste Management", draft Law "On WEEE"
Key principle	ERP	ERP
Goals	Prevention, reuse, recycling, and collection of 65% of EEE POM	Environmental safety, recycling of secondary raw materials, and introduction of RBB
Manufacturer responsibility	Financial and organisational responsibility for collection, processing and disposal	Financial responsibility, organisation of collection and recycling
Methods of fulfilling obligations	Individually or collectively (through producer responsibility organisations)	Individually or collectively (through ERP organisations)
Infrastructure	Developed, but with problems in achieving target indicators	Primitive, with low levels of licensing and control

Source: compiled by the authors based on Directive of the European Parliament and of the Council No. 2012/19/EU (2012) and Draft Law of Ukraine No. 2350 (2019)

European partner countries are substantial in supporting reforms aimed at modernising and developing the national waste management system. International technical assistance projects, in particular EU initiatives aimed at harmonising Ukrainian waste management legislation with the requirements of the European acquis, form the basis for the integration of modern approaches to WEEE management. Alongside regulatory support, investment programmes implemented with the participation of the European Investment Bank are significant. EIB financing is aimed at developing municipal infrastructure, including the modernisation or reclamation of waste disposal sites, which is critical in the context of the transition to a circular economy and overcoming the financial constraints characteristic of the Ukrainian waste management sector (Pan *et al.*, 2022; Baldé *et al.*, 2024).

The introduction of the EPR mechanism creates the basis for the development of a new economic direction, which covers enterprises specialising in the collection, sorting and processing of electronic waste. The practice of EU countries shows that such models stimulate the inflow of private capital and contribute to the modernisation of processing infrastructure (Xavier *et al.*, 2021; Compagnoni, 2022). In the Ukrainian context, this instrument can be strategic not only in increasing the collection rate of WEEE, but also in revitalising the industrial sector, creating new jobs, reducing dependence on imports of critical raw materials and deepening economic integration with the European Union.

At the same time, an analysis of electronic waste collection practices in the United States reveals significant discrepancies in statistical data, which can be explained by different reporting sources. The lack of a unified national accounting system means that different organisations use internal methods to estimate the volume of WEEE generated. Publications cite different figures for annual electronic waste generation: from 6.9 million tonnes to 9.9 million tonnes, which characterises the United States as one of the largest producers of electronic waste in the world. A similar situation is observed regarding the recycling rate, which ranges from 15.4% to 25%. This discrepancy in statistical data reflects a systemic problem: the lack of a comprehensive federal regulatory approach to WEEE accounting and management.

Due to the lack of uniform national standards, the United States operates a decentralised management model, within which each state adopts its own regulations on electronic waste. There are 25 states and the District of Columbia with separate laws in this area, most of which are based on the RBA approach, with the exception of the models used in

Utah and California. At the same time, the scope of state legislation varies significantly: some programmes apply exclusively to households, while others cover schools, commercial establishments or small businesses. The diversity of regulatory requirements creates a significant administrative burden on manufacturers and hinders the development of a coordinated recycling infrastructure (Liu *et al.*, 2023).

One of the most significant problems is the export of electronic waste to countries with less stringent environmental standards. Since the United States has not ratified the Basel Convention, it remains possible to legally export WEEE to countries where it is processed using primitive technologies that pose an increased risk to the health of workers and the environment. A systematic review of the risks of informal e-waste recycling in Africa and a review by P. Kumar *et al.* (2024) on the toxicological aspects of e-waste document the use of decomposition and metal extraction methods such as acid leaching and open burning, which are accompanied by emissions of lead, cadmium and mercury. These processes cause significant socio-environmental losses and highlight the need for the development of a comprehensive federal policy on WEEE management.

Australia also has high per capita e-waste generation rates. According to analytical estimates, the average amount of e-waste generated is 20-22 kg per person per year, while the global average is around 7 kg (Baldé *et al.*, 2024). In 2019, approximately 511,000 tonnes of electronic waste were generated, and this figure is projected to grow to 657,000 tonnes by 2030. A significant proportion of the value of materials in Australian WEEE remains unused: in 2019 alone, resources with an estimated value of 430 million USD were disposed of in landfills, which could have been returned to the production cycle (Xavier *et al.*, 2021).

The significant volumes of electronic waste generated in Australia are one of the factors stimulating national discussions on the need to transition to circular approaches to resource management. According to the Global E-waste Monitor, Australia is among the countries with the highest per capita e-waste generation, significantly exceeding the global average. This is influenced by the high frequency of electronics upgrades and the rapid obsolescence of technology. Despite this, a significant portion of valuable materials, particularly metals and plastics, are still not being returned to the production cycle, resulting in both economic losses and environmental risks (Xavier *et al.*, 2021; Liu *et al.*, 2023; Baldé *et al.*, 2024). EPR, widely implemented in EU countries, is considered in international reviews to be an effective tool for financing WEEE collection and recycling systems. The use of EPR involves manufacturers in managing the entire product life cycle and has demonstrated its ability to ensure steady growth in the collection of electronics and the return of secondary raw materials to production (Azizi *et al.*, 2023).

At the same time, fragmentation of regulation and the lack of mechanisms that integrate all categories of electronic waste into a single system remain key challenges in Australia. Policies focused on individual product groups do not provide comprehensive coverage of WEEE, making it difficult to achieve high material recovery rates (Liu *et al.*, 2023). As a result, a significant amount of resources end up in the informal sector or in landfills, hindering the implementation of the circular model. Brazil, which is the leader in e-waste generation in South America, also faces similar institutional constraints. The steady growth in e-waste volumes is linked to the spread of short-term use models for electronic devices and frequent replacement of equipment (Souza, 2020). Despite the presence of ERP elements in national legislation, their implementation remains limited, and most waste is processed outside formalised systems (Xavier *et al.*, 2021).

A distinctive feature of Latin America is the active role of the informal sector in the collection and dismantling of electronics. According to research, a significant portion of WEEE is handled by individual collectors or small businesses without compliance with technological and environmental standards (Issah *et al.*, 2022). This not only poses a threat to the health of people working with toxic substances but also reduces the efficiency of returning valuable components to production chains. However, as R.G. Souza (2020) highlighted, this sector is substantially linked to the actual extraction of metals, so effective policy should not exclude it, but rather gradually formalise its participation.

The challenges identified in Australia and Latin American countries demonstrate a common trend: WEEE management systems are unable to keep pace with the rate of technological renewal and growth in consumption. Studies show that even with formal infrastructure in place, a significant portion of waste ends up in mixed streams or is not registered at all (Liu *et al.*, 2023; Baldé *et al.*, 2024). This confirms the need for a comprehensive approach that combines strengthening the role of WEEE, developing infrastructure, information campaigns, and economic incentives for formalised resource recovery. A comparison of statistical estimates for the United States, Australia, and Brazil reveals notable differences, which are mainly due to the specifics of the regulatory environment. Australia and Brazil have national data collection systems in place, ensuring a more consistent WEEE accounting. However, rapid device upgrades and the availability of consumer electronics continue to place a burden on management systems, as confirmed by recent analytical materials (Xavier *et al.*, 2021; Liu *et al.*, 2023).

The situation in the United States is different. Due to the lack of a central federal accounting system and regulatory approach, data on the generation and processing of electronic waste is compiled by different institutions using different methodologies, which leads to significant discrepancies in the indicators. This complicates the construction of a unified national profile of WEEE flows and makes it impossible to assess the effectiveness of regulatory measures in a consistent manner (Kumar & Dixit, 2018; Baldé *et al.*, 2024). Overall, the comparison shows that the differences between countries are due not only to the scale of waste generation, but also to how statistics are collected and what tools are used to describe flows. Australia and Brazil provide more comprehensive data sets through national policies, while in the United States, the fragmentation of the regulatory framework creates structural gaps in accounting.

The analysis is based on a comparison of official statistics, international reports and scientific sources that reveal the peculiarities of the functioning of waste electrical and electronic equipment (WEEE) management systems in the European Union countries, as well as in Ukraine, the United States, Australia and Brazil. The summary data presented below provide an overview of the scale of electronic waste generation, the level of collection and the main institutional factors that influence the effectiveness of the relevant systems. According to Eurostat (n.d.), between 2011 and 2022, EU countries saw a steady increase in the volume of electrical and electronic equipment entering the market (EEE POM) (Fig. 2). While in 2011 this figure was 7.65 million tonnes, by 2022 it had increased to 14.44 million tonnes. The volumes of waste collected also showed growth, but lagged significantly behind the rate of increase in production. In 2022, only 4.99 million tonnes of WEEE were collected, which is 40.06% less than the 65% target set by Directive of the European Parliament and of the Council No. 2012/19/EU (2012).

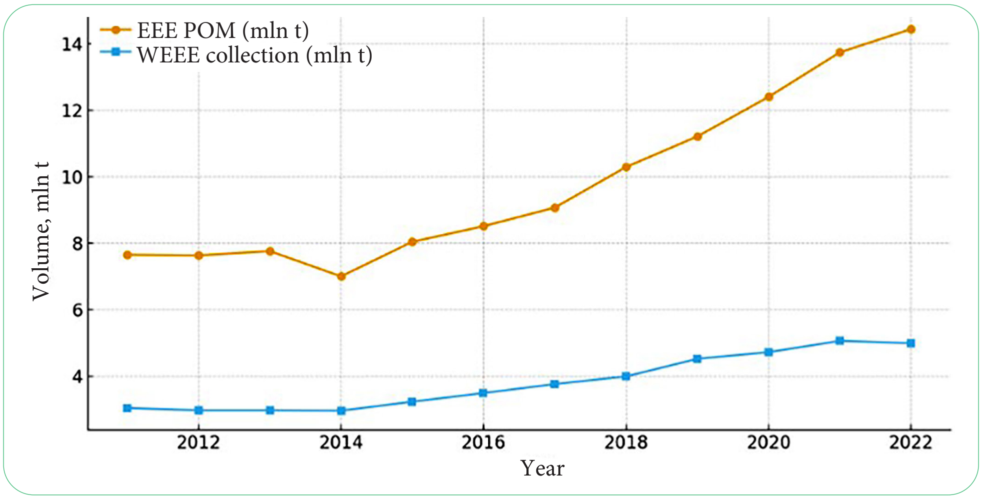

Figure 2. Generation and collection of WEEE in the EU (2011-2022)
Source: compiled by the authors based on Eurostat (n.d.)

The collection rate is presented separately as a percentage of the weight of electronic equipment placed on the market. From 2011 to 2019, this indicator showed an upward trend, reaching a maximum of 48.61%. However, after 2020, it began to decline, reaching 40.06% in 2022 (Fig. 3).

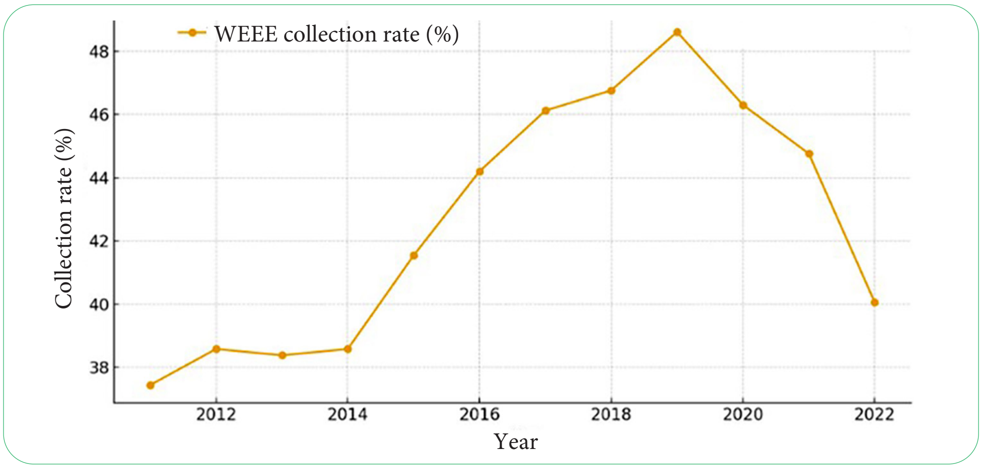

Figure 3. Dynamics of the level of WEEEE collection in the EU, 2011-2022
Source: compiled by the authors based on Eurostat (n.d.)

According to estimates by L. Hlavatska (2021), approximately 28,000 tonnes of WEEE are generated annually in Ukraine. At the same time, official statistics do not cover a significant part of the household sector, which leads to significant discrepancies between actual and documented volumes. The market has limited infrastructure: of the 128 enterprises capable of accepting hazardous waste, only 22 are licensed to process WEEE, and only 4 are operational. A major problem is the illegal import of electronic waste from EU countries, which, according to The Global E-waste Monitor, accounts for 14-18% of the total volume of WEEE generated in Ukraine. This further complicates the already inadequate infrastructure (Baldé *et al.*, 2024).

The United States is one of the world's largest producers of electronic waste. However, official data show significant differences depending on the methodology of the source. In 2021, the country generated 6.9-9.9 million tonnes of e-waste. The recycling rate fluctuates between 15.4 and 25%, which does not correspond to the scale of WEEE generation. A fragmented management system, with 25 states having their own e-waste laws, results in a lack of uniform national standards for collection and accounting. This complicates the creation of a reliable database and hinders the development of national infrastructure. Australia has one of the highest rates of e-waste generation per capita, at 20-22 kg per year (Clean Up Australia, 2024). In 2019, the total volume was 511,000 tonnes, and by 2030, it is expected to grow to 657,000 tonnes. The basis of the national collection system is the National Television and Computer Recycling Scheme (NTCRS), which aims to increase the collection rate to 80% and the material recovery rate to 90% by 2027. However, the scheme covers only certain product categories, which results in a significant portion of the WEEE stream remaining outside the formal system.

Brazil generates 2.1-2.4 million tonnes of electronic waste annually, which is 10.2 kg per capita (International Trade Administration, 2022; Vargas *et al.*, 2024). The recycling rate remains low at less than 3%. The National Solid Waste Policy (PNRS) sets a recycling target of 17% by 2025 and introduces reverse logistics for electronics. A significant element of the PNRS is the integration of informal collectors ("catadores") into the formal system, but uneven infrastructure development and low consumer participation remain key constraints. A comparison of per capita e-waste generation shows significant differences between the countries considered. Australia has the highest rate (over 20 kg/person), Brazil – approximately 10.2 kg, and the United States – approximately 7 kg (Fig. 4).

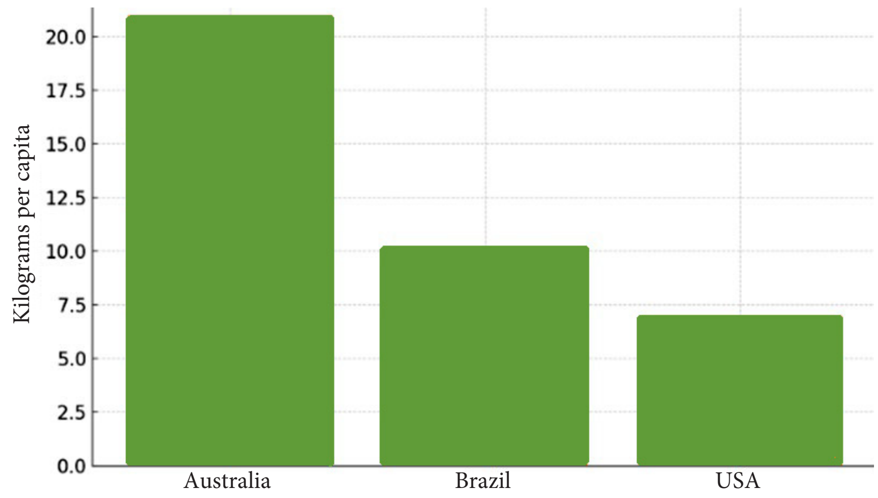

Figure 4. Comparison of e-waste generation per capita (Australia, Brazil, United States)
Source: compiled by the authors based on International Trade Administration (2022), C.P. Baldé *et al.* (2024)

A comparison of approaches to waste electrical and electronic equipment management in different countries covered by the study shows that the volume of electronic waste generation is on a steady upward trend. At the same time, existing institutional and infrastructural mechanisms are unable to keep pace with technological progress. According to analytical reports by international organisations, the scale of WEEE generation exceeds the capacity of official collection and recycling, which creates systemic pressure on resource turnover and the functioning of secondary raw material markets (Baldé *et al.*, 2024). Similar trends are also observed in individual regional analyses: researchers cite the short service life of electronic goods and the lack of a systematic approach to eco-design as key reasons for the increase in waste generation (Liu *et al.*, 2023; Kumar *et al.*, 2024).

The example of European Union countries shows a combination of a developed legislative framework with a range of structural challenges in policy implementation. Although the EPR principle is consistently applied and the collection infrastructure covers a significant part of the population, the actual achievement of WEEE treatment targets remains below the regulatory requirements. This is due, in particular, to the fact that some of the waste accumulates in the household sector, while the rest is diverted into illegal streams. Therefore, the effectiveness of EPR models in the European context is largely determined not only by regulatory policy, but also by consumer behaviour, the level of access to repair services and the quality of state control over the market.

The situation in Ukraine is characterised by a structural imbalance between the volumes generated and the capacity to process them. National data indicate approximately 28,000 tonnes of WEEE annually, but the actual volumes may be significantly higher due to the lack of systematic accounting. Limited infrastructure remains a key challenge: only a small proportion of existing enterprises have valid processing permits, leading to the dominance of mixed waste and the informal sector. Another barrier is the influx of illegal flows from the EU, which exacerbates the imbalance between the state's environmental obligations and its actual capabilities.

The experience of the United States shows that the fragmentation of the regulatory framework creates a systemic problem of reliability and comparability of statistical data. In contrast to the EU or Australia, where national accounting frameworks are in place, in the US, indicators are compiled by different agencies using different methods, leading to discrepancies in estimates of WEEE and recycling volumes (Kumar *et al.*, 2024). This approach complicates comparisons of trends and the development of long-term strategies.

Australia and Brazil, despite their different levels of economic development, demonstrate a significant impact of consumption patterns on the scale of e-waste generation. Australia is characterised by high per capita e-waste generation and the existence of national accounting and regulatory schemes (Liu *et al.*, 2023), while in Brazil, national policy focuses on developing reverse logistics and integrating the informal sector into waste management. However, even within a legally defined system, the actual recycling rate remains low, indicating a need to expand information campaigns and develop collection infrastructure.

A common conclusion for all countries analysed is the need to transition from quantity-oriented assessment models to systems capable of incorporating qualitative aspects of circularity, such as repairability, reusability, and preservation of material value. Academic reviews (Liu *et al.*, 2023; Mihai *et al.*, 2024) emphasise the need to introduce dynamic material flow analysis models focused on forecasting stocks and identifying priority fractions. For Ukraine, it is necessary to combine regulatory innovations with the development of applied mechanisms for creating a national EEE accounting system, strengthening control over cross-border flows, institutional support for the formal recycling sector, and stimulating eco-design. This will harmonise national policy with international practices and gradually transition to a functional circular economy model.

The results of the study can be used to conduct a comparative analysis with the conclusions of other researchers working in the field of waste electrical and electronic equipment management. The methodological approach to WEEE analysis is undergoing significant changes. Material flow analysis (MFA) is considered one of the leading analytical tools in this field, but existing reviews highlight a range of limitations, including a lack of research on countries outside the OECD and insufficient use of dynamic models and uncertainty accounting methods (Azizi *et al.*, 2023). The demand for more flexible approaches has led to the emergence of combined forecasting models that combine principal component analysis methods with neural network algorithms. Such solutions improve the reproduction of consumer behaviour patterns, which are a determining factor in the formation of WEEE flows (Guo & Zhong, 2021).

At the national level, the problem of e-waste management is complicated by both low recycling rates and the complex structure of the waste streams themselves. Studies show that small household electronics have the lowest return rates to collection systems, despite their significant share in the total volume of WEEE (Yafen & Shevchenko, 2021). At the same time, electronic waste is considered a valuable source of critically important raw materials. EU documents, including Regulation of the European Parliament and of the Council No. 2024/1252 (2024), emphasise the need to reduce the loss of such materials (Souza, 2020; Kumar *et al.*, 2024).

The observed decline in the relative level of WEEE collection in EU countries from 48.61% (2019) to 40.06% (2022), despite the growth in absolute volumes, is consistent with the conclusions of M. Compagnoni (2022), who stated in a systematic literature review that the ERP mechanism does not always ensure the achievement of targets. At the same time, the study supplements these conclusions with quantitative verification: a correlation analysis revealed a weak negative relationship ($r = -0.23$) between the volumes of products placed on the market and the relative collection rate, indicating a systemic inability of the infrastructure to adapt to the growth rate of electronics consumption. M. Compagnoni (2022) did not provide similar quantitative estimates, focusing mainly on qualitative policy analysis.

The results of a study by K. Liu *et al.* (2023), which emphasised the need to transition to dynamic material-specific indicators in a global review of electronic waste recycling, are confirmed by the analysis. Traditional collection indicators for EEE POM proved to be insufficiently sensitive to the actual effectiveness of management systems. However, in contrast to a study by K. Liu *et al.* (2023), which considered the problem mainly from a technological point of view, the presented study emphasised regulatory and institutional factors as determinants of effectiveness. Regarding methodological approaches, D.D.S. Azizi *et al.* (2023) highlighted in their content analysis of material flow analysis (MFA) applications the insufficient coverage of countries outside the OECD and the limited use of dynamic models. The presented study partially fills this gap by including Brazil and Ukraine in the analysis, but confirms the conclusion of D.D.S. Azizi *et al.* (2023) regarding the absence of dynamic models in the national monitoring systems of most of the countries studied.

The identified problem of illegal imports of electronic waste to Ukraine at a level of 14-18% expands on the conclusions of a study by F. Mihai *et al.* (2024) on waste management in Eastern European countries. The study noted common regional challenges but did not emphasise cross-border flows as a separate barrier to effective policy. Thus, the study complements the regional analysis with a specific quantitative measure of the problem. The results of the analysis of the situation in the United States are consistent with the findings of P. Kumar *et al.* (2024), emphasising the fragmentation of the regulatory system as a key obstacle. At the same time, the presented study adds a comparative dimension: the discrepancy in estimates of WEEE generation, ranging from 6.9 to 9.9 million tonnes, demonstrates the scale of statistical uncertainty, which significantly complicates international comparisons and prevents a correct assessment of the effectiveness of individual states' policies.

Of particular scientific interest is a comparison of the results with the study by R.G. Souza (2020) on the role of the informal sector in Brazil. The study described the participation of catadores in the reverse logistics system as a unique feature of the Brazilian model. The study confirms this conclusion, while noting that the low overall recycling rate (<3%) indicates the limited effectiveness of integrating the informal sector without the parallel development of formal infrastructure. This raises a substantial point for discussion: is the formalisation of the informal sector a sufficient condition for building an effective WEEE management system? The findings of L.H. Xavier *et al.* (2021) on the concept of urban metal mining as a promising direction for the circular economy are only partially confirmed in the current study. Although the potential for recovering valuable materials is undeniable, the analysis shows that realising this potential requires first addressing basic infrastructure issues, especially in transition economies such as Ukraine.

In contrast to a study by N.M. Franz & C.L. Silva (2022), which viewed e-waste primarily as a global production challenge, presented a study focusing on behavioural barriers. In particular, the study determined that a significant proportion of small electrical appliances are kept in households due to "emotional attachment", a factor that is not sufficiently considered in traditional management models and requires separate research in the field of consumer behaviour. Research by I. Issah *et al.* (2022) on the risks of informal recycling in Africa demonstrates problems similar to those identified in this study in the context of WEEE exports from developed countries. This confirms the global nature of the problem and the need for international policy coordination that goes beyond national regulatory systems.

In summary, the study confirms most of the conclusions of previous scientific works on challenges in the field of e-waste management, while supplementing them with quantitative assessments and comparative analysis between countries with different regulatory models. A key finding is that none of the models studied – neither the powerful European EPR system, nor the decentralised American approach, nor the co-regulatory models of Australia, nor the integrative Brazilian experience – provides an adequate response to the growth rate of e-waste. For Ukraine, this means the need to develop a comprehensive approach that takes into account both international experience and national specifics, in particular, the role of the informal sector, the problem of cross-border flows, and limited financial resources for infrastructure development. Promising areas for further research include analysing consumer behaviour factors, modelling material flow dynamics, and assessing the economic effectiveness of various EPR policy instruments in the Ukrainian context.

Conclusions

The study provided a comprehensive analysis of the characteristics of electrical and electronic equipment waste management in the EU, Ukraine, the United States, Australia, and Brazil. Official reports from international institutions, scientific sources, and national regulatory acts were used for the analysis. The results demonstrated that, despite the existence of regulatory frameworks and infrastructure development, none of the models studied currently provides a level of recycling that corresponds to the rapid growth in electronics consumption.

In European Union countries, despite a strong legal framework and the implementation of the EPR principle, there has been a decline in the collection of electronic waste, indicating a gap between targets and actual results. The situation in Ukraine is characterised by a lack of infrastructure and the significant influence of the informal sector, which significantly limits the coverage of waste by official channels in the context of growing shadow imports. In the United States, the lack of a unified regulatory approach and the fragmentation of the regulatory system lead to serious statistical discrepancies, which make it difficult to form a complete picture. Meanwhile, in Australia and Brazil, despite the existence of national systems and standardised accounting methods, there are difficulties associated with high per capita waste generation and limited consumer participation in return systems.

The uniqueness of the study is determined by the comparative analysis of regulatory approaches, infrastructure characteristics and statistical data in different countries within a single methodological framework. This identified common problems: weak use of material flow methods in planning, insufficient effectiveness of existing EPR instruments, underdeveloped monitoring systems, and a lack of incentives for reuse and repair of electronic equipment. The practical value of the study is determined by the identification of areas for improvement in the Ukrainian model of electronic waste management, incorporating international experience and the principles of the circular economy: in particular, the introduction of differentiated environmental rates, strengthening control over the movement of waste across borders, developing infrastructure for reverse logistics, and introducing new economic instruments to support product reuse.

Further research should emphasise modelling of waste flows using dynamic material flow analysis, studying the impact of the shadow sector on statistics, analysing consumer behaviour, and testing new approaches to implementing the EPR principle. Promising solutions include the introduction of digital product passports, environmentally oriented tax mechanisms, and repair incentive programmes. This will form the basis for the transition to a circular model of e-waste management and a reduction in the loss of strategically significant materials.

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Аналіз даних по утворенню відходів електричного та електронного обладнання

Євгеній Гречанюк

Аспірант
Вінницький національний технічний університет
21021, вул. Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0009-0008-5687-2269

Віталій Іщенко

Кандидат технічних наук, доцент
Вінницький національний технічний університет
21021, вул. Хмельницьке шосе, 95, м. Вінниця, Україна
https://orcid.org/0000-0002-8464-1096

Анотація. У світі спостерігається стрімке зростання обсягів відходів електричного та електронного обладнання (ВЕЕО), яке випереджає темпи розвитку інфраструктури для їх збирання й переробки. Це загострює екологічні виклики та поглиблює дефіцит критичних ресурсів. Метою дослідження було здійснення порівняльного аналізу підходів до управління відходами електричного та електронного обладнання в Україні, країнах Європейського Союзу, Африки, Латинської Америки, США, Австралії та Бразилії. Основна увага зосереджена на виявленні відмінностей у регуляторних підходах, показниках збору, методах переробки, а також на формуванні рекомендацій щодо впровадження ефективних практик в українських умовах. Методологія охоплювала системний аналіз законодавчих рамок, статистичні методи для оцінки динаміки обсягів утворення та збору ВЕЕО, порівняльно-географічний аналіз національних моделей та контент-аналіз нормативних документів. Дослідження показало, що ЄС має найбільш структуровану модель управління відходами, засновану на принципі розширеної відповідальності виробника, однак навіть за наявності чітких нормативів рівень збору суттєво нижчий за цільові значення. У США управління ВЕЕО характеризується фрагментованістю та відсутністю єдиного федерального регулювання, що ускладнює формування достовірної статистики. Австралія демонструє ефективність ко-регуляторних підходів, а Бразилія – унікальну інтеграцію неформального сектору до офіційної системи зворотної логістики. Розглянуто комплексне поєднання законодавчого, інфраструктурного та поведінкового вимірів управління ВЕЕО в п’яти країнах із різними економічними моделями. Практичне значення полягає у формуванні рекомендацій для України щодо імплементації розширеної відповідальності виробника розвитку системи моніторингу, підвищення прозорості ринку та адаптації успішних міжнародних інструментів для переходу до циркулярної економіки

Ключові слова: електронні відходи; розширена відповідальність виробника; циркулярна економіка; міжнародні моделі управління; інфраструктура збору; екологічна політика