Ecological Economics 216 (2024) 108031

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Is environmental regulation keeping e-waste under control? Evidence from e-waste exports in the European Union

Sónia Almeida Neves [a,b,*], António Cardoso Marques [a,b], Leonardo Batista de Sá Lopes [a]

[a] University of Beira Interior, Management and Economics Department, Rua Marquês d'Ávila e Bolama, 6201-001 Covilhã, Portugal
[b] NECE-UBI, Management and Economics Department, Rua Marquês d'Ávila e Bolama, 6201-001 Covilhã, Portugal

ARTICLE INFO

Keywords:
E-waste
Circular Economy
Recycling
European Union
Waste Shipment Regulation
Environment

ABSTRACT

Waste generated from electrical and electronic equipment, known as e-waste, is increasing worldwide. Developed countries like those in Europe produce the most significant proportion of e-waste worldwide and, therefore, rely on exporting it to other countries for waste disposal. As Europe is transiting towards a Circular Economy and tackling environmental-related problems, there has been an increase in environmental policies and regulations in this area. This paper presents empirical evidence of how European Union regulations have affected the exports of e-waste. Yearly data from 2010 to 2018 for a panel of 18 European Union countries were analysed using the PCSE (Panel-Corrected Standard Error) estimator. In order to measure environmental regulation, Environmental Tax Revenues from the manufacture of computers, electronic, and optical products were selected. The findings of this paper suggest that taxation is ineffective in reducing e-waste exports, with a tax on manufacturers actually increasing them. Also, high dependence and sub-standard e-waste collection systems increase e-waste exportation. Given that countries often depend on foreign raw materials, a sensible approach would be to invest in collection points for e-waste to take economic advantage of this waste's vital elements.

1. Introduction

The Circular Economy (CE) is an economic model that allows countries and economies to achieve sustainable growth by minimising waste generation. As of today, there is no single definition of CE. Therefore, this study adopts the definition of Kirchherr et al. (2017), p.p. 229, defining CE as "*an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes*". CE is the alternative to a linear economy where the material is converted into a product and later waste, with a beginning and end. Contrary to this concept, a CE tries to tackle the end of life by either recycling, reusing or extending the useful life of the said object, thus reducing waste generated and resources lost.

In 2015, the European Union (EU) released the first Circular Economy action plan, mapping 54 measures to be implemented, and proposing four legislations for waste, thus creating the foundation of the EU plans towards a CE (European Commission, 2015). In December 2019, the European Green Deal was presented to transition the EU's economy to a more sustainable one. Therefore, the EU aims to take advantage of CE practices, improve resource efficiency, and transit towards renewable energy. The Green Deal also aims to control climate change and biodiversity loss to achieve a carbon-neutral Europe by 2050 (European Commission, 2020a).

Waste from electrical and electronic equipment (WEEE), commonly known as electronic waste or e-waste, can be defined in numerous ways. Some of these differences result from how it is classified from country to country (Islam et al., 2016) and the lack of definition of what is actually e-waste. According to Ilankoon et al. (2018), e-waste can be described as any end-of-life piece of electric equipment. The EEE industry is rapidly changing and evolving. This progress can cause a significant rise in demand for EEE due to the increasing desire for superior equipment. As a result, e-waste generation has also risen rapidly and is now the fastest-growing waste stream (European Parliament, 2020). Most European countries manage their waste either by recycling, landfill disposal, or exporting it to other countries. Although landfill disposal has decreased substantially in the last few years, it is still tremendously hazardous to the environment and public health.

Exposure to e-waste has been shown to affect children, lead poisoning being a significant example. Repeated exposure to lead, possibly through breastfeeding, affects future generations, hindering their development, reproduction, and even neurobehavioral systems if

* Corresponding author at: University of Beira Interior, Management and Economics Department, Rua Marquês d'Ávila e Bolama, 6201-001 Covilhã, Portugal.
E-mail address: sonia.neves@ubi.pt (S.A. Neves).

https://doi.org/10.1016/j.ecolecon.2023.108031
Received 3 May 2023; Received in revised form 19 October 2023; Accepted 27 October 2023
Available online 3 November 2023

this exposure occurs without appropriate precautions (Frazzoli et al., 2010). *E*-waste export has also been a public health issue and environmental hazard to host countries. With most e-waste trading being made illegally, it has become a serious talking point. To stem the tide of exports, the EU is continuously establishing new regulations and tightening already existing waste shipment guidelines. By exporting waste, EU countries could disrupt the environment and go against EU initiatives of transition towards a CE. If CE plans are met, the increase in recycling levels could provide most of the raw materials needed for EEE production.

With the burgeoning issues derived from e-waste management, such as the rise of e-waste in Europe and the illegal exporting to less-developed world countries, EU policymakers have increased focus on environmental topics and regulations. Such regulations can contribute to enlarging the incorporation/recycling of e-waste, or instead, they can incentivise the escape and loss of e-waste. Remarkably, removing e-waste, for instance, through exports, represents a significant economic loss. In 2019 alone, the loss of precious metals and critical raw materials in e-waste amounted to 12.9 billion dollars (Forti et al., 2020). Thus, this study aims to analyse how regulation, namely the taxation of the manufacture of computers and electronic and optical products, has affected e-waste exports. In sum, the main objective of this paper is to answer the following central question: is environmental regulation keeping e-waste under control?

The EU context analysis is especially relevant given its recent pledge to be a leader in the transition to a CE. Furthermore, all EU countries follow similar environmental policies and regulations. The main contribution of this paper is to address and provide empirical evidence on e-waste management practices, which are crucial for environmental protection and a successful transition towards a CE. In detail, this paper innovates by empirically analysing the relationship between regulation and e-waste exports in the context of 18 EU countries. At this time, the literature acknowledges that more evidence is required about the effects of regulation initiatives on people's behaviour, recognizing the importance of behavioural spillovers of law and regulation for e-waste management practices (Newaz and Appolloni, 2023). This paper contributes to a deeper understanding of the effect of regulation on e-waste exports and its effect on the behaviour of e-waste exporters. According to our best knowledge, a limited number of papers empirically analyse the effect of environmental regulation on the exports of e-waste. One exception is Callao et al. (2021), who studied hazardous waste exports for disposal in Europe and found that the EU acts under the proximity and self-sufficiency principles.

Even under the limitation that the e-waste export statistics do not cover all the e-waste streams because a large proportion of end-of-life e-waste is not documented (Habib et al., 2022), the findings of this paper are crucial for policymakers to improve the efficiency of the current e-waste management practices, particularly in reducing the exports of e-waste. The issue of e-waste exports is even more relevant if one considers the exports to developing countries, as some of those countries lack recycling systems, and e-waste is usually managed in informal e-waste recycling facilities, resulting in environmental damage and potential risk to human health (Andeobu et al., 2023; Hoang et al., 2023).

The remainder of this paper is organised as follows. Section 3 describes the central literature on the field. The data and methodology used are presented in Section 4. The results are described in Section 5 and discussed in Section 6. Section 6 presents the main conclusions.

2. Literature review

The lack of an overarching global definition of e-waste makes it challenging to track the global e-waste illegal trade network (Bakhiyi et al., 2018). Lepawsky (2015) mentions that measuring e-waste trade is a significant challenge since there is no single definition of e-waste and a lack of trade data that can differentiate new and old equipment. In fact, the literature argues that a major issue in global e-waste trade is presented as the fine line separating legal and illegal trade and how this line can easily be infringed (Efthymiou et al., 2016). As Robinson (2009) highlighted, exporting countries tend to violate treaties concerning the trade of hazardous e-waste. Furthermore, the illegal trade of e-waste tends to occur from economically and socially developed countries to countries with lower economic and social development (Efthymiou et al., 2016).

E-waste, along with other types of waste, have been exported from the EU to other countries to avoid stricter treatment requirements locally or exploit low wages abroad. It has also been shown that this illegal shipment has increased, but it is not yet clear if this growth is real or just a result of improved monitoring by the countries (European Environment Agency, 2009). Furthermore, in 2012, the expected amount of e-waste exported by EU countries was about 1.5 million tonnes, but only 200,000 t were documented. It was also found that 3.15 million tonnes of e-waste were recycled but not following the current regulation and that 4.65 million tonnes were mismanaged or illegally traded between European countries (Huisman et al., 2015).

In the last few decades, the majority of e-waste collected in the EU has been exported to Asia, specifically China and India, due to the lack of regulation and cheaper disposable facilities in these locations (Ilankoon et al., 2018). However, due to increased regulation in the exporting countries and receiving ones, a shift started concerning e-waste exports. As a result, West Africa has become one of the new areas to which countries export waste (Ilankoon et al., 2018).

Since the production of EEE is highly dependent on the use of scarce materials such as precious metals, the recovery of this commodity presents a remarkable economic opportunity (Cucchiella et al., 2015) and an obstacle to be surpassed so that the EU countries reach the goals set by The Green Deal. In 2019, Europe generated 20 Million tonnes of e-waste or 16.2 kg per capita, with an estimated value of raw materials of around 12.9 million USD (Forti et al., 2020). Although the value of e-waste is high, only a fraction of its value is extracted in recycling, which means that various precious metals are lost in the process (Chancerel et al., 2009). In fact, less than 40% of this waste was recycled, and only 20% of the total waste generated was recycled correctly (European Parliament, 2020).

The high demand for EEE has created challenges in managing the additional e-waste it creates. Furthermore, these challenges are also a consequence of manufacturers of this type of product refusing to show interest or not being forced to take responsibility for what happens to these products at the end of their useful life (Andeobu et al., 2021). For most EEE products, when they are damaged, they tend to be immediately replaced and not repaired. This problem arises from the limited technology, high labour costs, and the time-consuming task of repairing the product (Bakhiyi et al., 2018). Another relevant challenge is the current inadequate product design. The products are designed to be replaced and not repaired. They are frequently assembled in such a way that carrying out repairs is hugely time-consuming, thus not worth it at all, and in some cases, the designs can even hinder the recycling process (Pickren, 2015).

According to the UNEP (2009), the lifespan of computers ranges from five to eight years, televisions eight years, and mobile phones four years. Huang et al. (2020) showed that the average lifespan for the household appliances category is between eleven and nineteen years but that the average lifespan of products depends highly on the region. According to the author, second-hand markets could be a possible solution to increase the lifespan of some EEE. By promoting reutilization, the products are kept in the market as long as possible, reducing the generated e-waste and the need to extract primary resources to produce new equipment.

Regarding environmental legislation, policymakers can adopt several instruments, such as regulations, informative programmes, subsidies, and taxation (OECD, 2011). According to the European Environment Agency (2016), EU legislation tends to be implemented in environmental policy areas, such as energy, greenhouse gas emissions, ozone-depleting substances, waste, sustainable consumption and production, and biodiversity, among others. These legislations can either set a binding or non-binding goal. Binding goals are established by EU legislation containing goals the EU has agreed to implement. All other targets are deemed non-binding and thus are not obligatory. In the case of binding targets, the respective legislation comes with a specific time period to either achieve the set target or apply the said legislation (European Environment Agency, 2016).

Over the last few decades, countries have started to develop policies and legislation to reduce the environmental impact of products. Several of these policies are based on Extended Producer Responsibility (EPR) (Nnorom and Osibanjo, 2008), where producers are responsible for the treatment and disposal of the products they make. Although it is not a policy, policymakers can apply EPR principles to developing new legislation (Ilankoon et al., 2018). Environmental policies are instruments that can be used by policymakers so that new legislation and regulations can be established in order to tackle environmental problems.

Developed countries such as those in the EU tend to implement environmental policies such as taxation to be climate-friendly and achieve sustainable growth (Kang and Lee, 2021). Taxation is the main instrument used by policymakers because it can directly address the inability of the markets to take environmental impacts into account. Taxation increases the prices of products or activities to reflect the environmental harm they cause. This fact allows policymakers to include in the price the negative externalities of pollution, incentivizing enterprises and consumers to consider these environmental problems (OECD, 2011).

The relationship between environmental regulation and trade has already been studied in the literature (Cantore and Cheng, 2018; Jug and Mirza, 2005; Kuik et al., 2019; Tsurumi et al., 2015; Van Beers and Van Den Bergh, 1997). The findings are not consensual, possibly due to the variables selected to measure environmental regulation and the countries chosen for the study sample. For example, Jug and Mirza (2005) note that environmental expenditures are able to decrease exports of goods and services. On the other hand, Tsurumi et al. (2015) express that those proxies of environmental policy stringency, such as energy intensity and abatement costs, are shown to increase the export flow.

The findings by Rodríguez et al. (2019) show that green tax reforms can improve environmental quality. Likewise, Esen et al. (2021) argue that environmental taxes can reduce environmental problems and improve the ecological balance if they are well implemented. In the same way, Tao et al. (2021) and Safi et al. (2021) state that both environmental taxes and eco-innovation play a significant role in carbon abatement and, therefore, achieving carbon neutrality. Romano and Fumagalli (2018) presented that if governments are reluctant and not committed to adopting green policies, these can negatively impact the environment and governments. Furthermore, Callao et al. (2021) showed that the absence of landfill taxes in the receiving country does not affect Hazardous Waste Shipment for disposal, and the EU countries act under the proximity and self-sufficiency principles.

Concerning e-waste collection, it is essential to increase the collection rate since it is the largest growing waste stream and a significant environmental hazard in Europe and for host countries. Increasing collection control of e-waste is vital, but this alone will not be enough. It is also essential to improve and develop the treatment of waste. As such, recycling will need to be further developed and implemented for the EU to reduce the existing dependency on external raw materials essential for EEE production (European Commission, 2020b).

Economic growth of economies has been achieved through a significant environmental footprint. Much of this footprint is caused by using energy based on CO_2 emissions. Ghosh (2010), and Wang and Wang (2011), have already shown the bidirectional relationship between economic growth and CO_2 emissions. Following this bidirectional relationship, Kasman and Duman (2015) also found that GDP (Gross Domestic Product) can help explain and somewhat predict the CO_2 emissions of a named country. Furthermore, Kumar et al. (2017) have already stated that the higher a country's GDP, the higher the e-waste generation will be. Furthermore, Boubellouta and Kusch-Brandt (2021) also found that GDP has a positive and statistically significant effect on uncollected and mismanaged e-waste in the EU.

3. Data and methodology

This study used annual data from 2010 to 2018 and a sample of 18 countries from the European Union, namely Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Latvia, Lithuania, Luxembourg, the Netherlands, Poland, Slovakia, Slovenia, Spain, and Sweden. These countries were selected based on the criteria of data availability. Table 1 contains the description, source, and descriptive statistics of the variables used in this study.

The dependent variable in this study is related to the exports of e-waste. Therefore, data for exports of e-waste both inside and outside of the EU were obtained from UN COMTRADE using HS 2002 code 854810[1] in US dollars. For consistency, the variable was converted to Euro (2015) prices using the GDP deflator (base = 2015) and exchange rates obtained from Eurostat and OECD databases, respectively. It is important to highlight that this variable does not ensure that all the major e-waste categories have been taken into account (Petridis et al., 2020) because it measures only one category of e-waste (Kahhat and Williams, 2012), which is primary cells, batteries, and electric accumulators. Notwithstanding, the adequacy of this variable for the study at hand is noticeable for three main reasons. Firstly, this variable overcomes the lack of data on the e-waste trade (Petridis et al., 2020). Second, this variable provides the primary information on the behaviour of exports of e-waste by the countries despite its lack of capability to capture all the e-waste categories. Third, the literature supports the suitability of this variable use (Lepawsky, 2015; Lepawsky and McNabb, 2010; Petridis et al., 2020), and it allows the use of data from a single database, avoiding the inconsistency of using national databases.

Given that the main objective of this paper was to analyse the impact of regulation on e-waste management, specifically on e-waste exports, Environmental Tax Revenue from the manufacture of computers, electronic, and optical products was included as the explanatory variable as a proxy for environmental regulation. This variable measures the total environmental revenue taxes from the manufacture of computers, electronic and optical products in a million euros, later converted to euro (2015) prices per capita (*ETEpc*). Since environmental taxes are a significant part of the environmental regulation stringency index for energy (OECD, 2016), the value of the environmental taxes was used as an environmental regulation proxy.

The ratio between Gross Domestic Product and CO_2 Emissions (CO_2dep), the Recycling rate of e-waste (*REC*), WEEE collected (*Wcoll*), Gross Domestic Product per capita (*GDPpc*), Domestic credit to the private sector (*DCPS*), and Material Import Dependency (*MID*) were also used as explanatory variables. CO_2dep was used due to its ability to measure how dependent on pollution the country is in terms of economic growth (Ma et al., 2019; Wen and Dai, 2020). This variable was constructed by dividing GDP (Euro, 2015 prices) by CO_2 Emissions obtained from the WDI (World Development Indicators Database). The recycling rate of e-waste was included to quantify the treatment of e-waste since it is one of the main processes EU regulations have to incentivise and tackle waste issues. Recycling is expected to reduce the level of e-waste exports.

Closing the loop is one of many initiatives from the EU created to address the dependency on materials from outside its borders. The dependency of Europe on external material is noticeable; the region has a

[1] 854,810 - waste and scrap of primary cells, primary batteries, and electric accumulators; spent primary cells, spent primary batteries, and spent electric accumulators

Table 1
Variables used in this study and descriptive statistics.

Variable	Description/ Measurement	Data Source	Obs	Mean	Std. Dev.	Min	Max
LEXPew	Export of *E*-waste (total), (Euro, 2015 prices)	UN Comtrade	162	15.0291	2.4113	6.9304	18.7901
LETEpc	Environmental taxes revenues per capita, (Euro (2015 prices)	WDI	162	−0.7433	1.4319	−4.0712	2.3876
LCO₂dep	GDP per Co2 Emissions, (Euro (2015 prices)/kg)	Eurostat/WDI	162	1.3652	0.5266	0.1707	2.6030
LREC	Recycling rate of e-waste (% of total e-waste collected)	Eurostat	162	3.5773	0.2975	2.6741	4.2121
LWcoll	WEEE collected, (Kg)	Eurostat	162	17.9736	1.3905	15.2692	20.5644
LMID	Material Import Dependency (% of direct material inputs)	Eurostat	162	3.6478	0.3975	2.7408	4.5207
LDCPS	Domestic credit to private sector, (%GDP)	Eurostat	162	4.3311	0.4363	3.4777	5.2629
LGDPpc	Gross Domestic product per capita (2015 prices)	Eurostat/WDI	162	10.1994	0.6279	9.1883	11.4892

Note: All variables were converted to their respective natural logarithms.

high material import dependency (Giljum et al., 2015). In the case of metal ores, only 13% of the required metal ores are acquired within the EU (Giljum et al., 2016). Many of these critical raw materials are essential for the manufacture of electronic equipment, and as such, the Commission aims to encourage recovery to reduce EU dependency on imported critical raw materials (European Commission, 2015). For that reason, Material Import Dependency was included as an explanatory variable.

Although variables like Gross Domestic Product per CO_2 Emissions, the Recycling rate of e-waste, and Material Import Dependency (*MID*) cannot measure environmental regulation as a whole, these could represent the effects of specific directives and regulations. For example, CO_2*dep* can somewhat measure regulations regarding the transition to cleaner energy and the EU commitment to reaching carbon neutrality in 2050, with plans like the LIFE Clean Energy transition sub-programme. The recycling rate could quantify the adoption of directives such as the Batteries and Accumulators regulation and the WEEE regulation regarding the EU's commitment to increasing the recycling level to reduce its need for virgin material. Further increase in recycling will also decrease dependency on importing certain materials to manufacture EEE.

WEEE collected was selected to measure the amount of waste collected in the EU. This variable was later converted from kilogram per capita to kilograms. A higher level of e-waste collection is expected to result in a higher level of e-waste export. GDP per capita (2015 prices) was used as an economic growth proxy, following the studies of Kang and Lee (2021), De Pascale et al. (2021), and Tamazian et al. (2009). Furthermore, it aims to capture the macroeconomic dimension of the countries. GDP per capita was constructed using GDP (Euro, prices 2015) and total population, obtained respectively from Eurostat and the WDI. Kumar et al. (2017) have already stated that the higher a country's GDP, the higher the generation of e-waste, but an effect on waste exportation needs to be established.

Regarding *DCPS*, it intends to capture the effects of economic development and ascertain if it impacts the environment, as suggested by Esen et al. (2021) and Shahbaz et al. (2013). According to Tamazian et al. (2009), financial and economic development can decrease both environmental degradation and CO_2 emissions. This variable was also used by Boubellouta and Kusch-Brandt (2021), who found that the DCPS increases the uncollected e-waste. *E*-waste causes environmental damage, even when it is exported. Therefore, it is expected that DCPS could reduce the exportation of e-waste.

The preliminary analyses of the variables included (i) a Variance Inflation Factors test (VIFs), (ii) Correlation matrix values, (iii) a Cross-sectional Dependence test (CD-test), and (iv) a Panel unit root test. The VIF test and the correlation matrix values were used to analyse the multicollinearity and the correlation between the presented variables, respectively. As shown in Table 2, both VIF and correlation matrix values do not raise concern, implying that neither correlation nor multicollinearity compromises the robustness of the estimations.

The cross-sectional dependence in the variables was evaluated by employing the CD-test proposed by Pesaran (2004). The result of this test is essential because if a variable indicates the presence of cross-sectional dependence, traditional unit root tests are unreliable. Thus, the second-generation unit root tests must be performed.

The null hypothesis of the CD-test indicates that there is cross-sectional independence. The results presented in Table 3 indicate that the null hypothesis was rejected for the majority of the variables, except *LETEpc* and *LDCPS*. As the CD-test fails to reject the null hypothesis for *LETEpc* and *LDCPS*, the first-generation test proposed by (Maddala and Wu, 1999) and the second-generation test CIPS proposed by (Pesaran, 2007) were conducted. The second generation CIPS test was carried out

Table 3
Cross-sectional dependence test and second-generation unit root test.

Variable	CD-test	CIPS		Maddala and Wu	
		Without Trend	Trend	Without Trend	Trend
LEXPew	6.82***	−1.806**	−1.819**		
LETEpc	−0.92	−0.617	−0.691	45.403	85.714***
LCO₂dep	31.59***	−2.250**	−1.488*		
LREC	16.76***	−1.941**	0.751		
Lwcoll	17.97***	−1.495*	−1.452*		
LMID	34.08***	−2.000**	0.252		
LDCPS	−1.00	−0.693	0.469	65.287***	25.233
LGDPpc	5.04***	−2.254**	0.602		

Notes: ***, ** and * denotes statistical significance at 1%, 5% and 10% levels of significance, respectively.

Table 2
Correlation matrix values and variance inflation factors (VIF).

	LEXPew	*LETEpc*	*LCO₂dep*	*LREC*	*Lwcoll*	*LMID*	*LDCPS*	*LGDPpc*
LEXPew	1.0000							
LETEpc	0.3398	1.0000						
LCO₂dep	0.3490	03734	1.0000					
LREC	0.0274	0.2760	0.3757	1.0000				
Lwcoll	0.3453	0.3930	0.2117	0.1181	1.0000			
LMID	0.1225	0.0183	0.2497	0.0185	−0.2058	1.0000		
LDCPS	0.2081	0.3222	0.6587	0.0000	0.3287	0.1465	1.0000	
LGDPpc	0.1843	0.6148	0.7828	0.2942	0.1721	0.4901	0.6386	1.0000
VIF		2.64	3.81	1.42	1.41	1.99	2.57	7.58
Mean VIF		3.06						

for the variables that showed cross-sectional dependence under the null hypothesis of the variables being I(1). The result of this test is displayed in Table 3. Although the tests do not prove the stationarity of the variables in level unequivocally, it is important to consider that when the time spam under analysis is small, the unit root test may not be robust (Karlsson and Löthgren, 2000).

In order to know if there were no omitted variables that could result in biased results in the model, the Ramsey (1969) regression specification-error test (RESET) was conducted after a simple Ordinary Least Squared estimation (OLS). The null hypothesis of the RESET test is that the model has no omitted variables. Table 4 presents the result of the Ramsey Reset test, where one can see that it is failing to reject the null hypothesis. Accordingly, the test does not identify evidence of the existence of omitted variables.

Remembering that the main objective of this paper is to analyse the impact of environmental regulation on the exports of e-waste, one model was estimated. The functional form of the model is described in Eq. (1).

$$lEXPew_{it} = \beta_0 + \beta_1 lETEpc_{it} + \beta_2 lva_{it} + \beta_3 lREC_{it} + \beta_4 lWcoll_{it} + \beta_5 lMID_{it} + \beta_6 lDCPS_{it} + \beta_7 lGDPpc_{it} + \mu_{it} \tag{1}$$

where i denotes de countries and t the time. β_0 denotes the intercept, β_i denotes the coefficients of the parameters, and μ_{it} represents the error term.

The Hausman (1978) test was employed to test the presence of fixed effects or random effects in the model, following the Eq. (1) specification. The null hypothesis predicts that the random effects model is appropriate. Table 4 shows that the null hypothesis was not rejected at the significance level of 5%; therefore, there are no statistical significant evidence supporting the use of fixed-effects model. Aware that the Hausman test could produce biased results in small samples, the robust Hausman test was also performed. The null hypothesis of this test could not be rejected, which reinforces the findings of the traditional Hausman test (Kaiser, 2015). As robust Hausman test is failing to reject the null hypothesis, the random effects model could be appropriate.

Given that the Hausman test does not support the adequacy of fixed effects, the suitability of random effects should be tested against a simple OLS regression. Accordingly, the Breusch and Pagan (1980) Lagrangian multiplier test for random effects was carried out. The results in Table 4 show that the null hypothesis cannot be rejected, supporting that a simple OLS regression is not appropriate.

In order to use an adequate estimator for the data features, a set of specification tests was performed. These features include the evaluation of cross-sectional dependence, first-order serial correlation, and heteroskedasticity. In this sense, the Pesaran (2004) test for cross-sectional dependence was carried out under the null hypothesis of cross-sectional independence. The Wooldridge (2002) test for serial correlation was performed to evaluate the existence of first-order serial correlation. It follows the procedure of Drukker (2003) and its null hypothesis predicts the there is no serial correlation in the specification.

To assess the existence of heteroskedasticity, two tests were performed after a single OLS, namely the Breusch and Pagan (1979) Lagrange multiplier test for heteroskedasticity and the Breusch and Pagan (1979) and Cook and Weisberg (1983) test for heteroskedasticity. Both tests were performed under the null hypothesis of homoscedasticity.

The results of the specification tests are displayed in Table 5. The null hypotheses of all the realised tests were rejected; therefore, there is evidence of the existence of cross-sectional dependence, first-order serial correlation, and heteroskedasticity, which may be considered for choosing the appropriate estimator.

The estimators PCSE (Panel-Corrected Standard Error) and FGLS (Feasible Generalized Least Squared) could have been adequate for this study due to their ability to deal with the presence of cross-sectional dependence, heteroskedasticity, and first-order serial correlation. However, given that the panel data presented has a small-time dimension (T) compared to the cross-sectional dimension (N) and as the FGLS estimator is mainly used with panels where T > N, the PCSE estimator was used since it is suitable for panel data with T < N (Hoechle, 2007).

4. Results

The model was estimated using the PCSE estimator as in Table 6. Different options were used in the PCSE estimation to ensure the stability of the findings. The PCSE without any robust option (PCSE) is robust to first-order serial correlation (AR1), robust to heteroskedasticity (HET), and robust to both first-order serial correlation and heteroskedasticity (AR1/HET) (see Table 6). Additionally, the significance of the squared residuals was evaluated to secure the specification of the estimations. These were not significant in all four estimations, indicating that no omitted variables in the model could bias the results.

Firstly, regarding the variables that presented similar levels of significance for all the estimations, *LCO₂dep* can be seen to have a strong positive effect on the exporting of e-waste, which means that countries whose economies are highly dependent on CO_2 emissions tend to export more e-waste. Secondly, for the variable *Lwcoll*, it can be said that the more e-waste collection there is, the higher the export of e-waste.

In terms of material import dependency, it can be stated that it has a positive effect on the export of e-waste, meaning that in the countries studied, the higher the dependency of a country on imported material, the higher the exportation of e-waste. The high dependency of EU countries on importing vital materials to produce electric and electronic equipment could explain this positive effect of LMID on e-waste exports. Lastly, the *LGDPpc* has a negative and statistically significant effect on e-waste export.

Although *LETEpc* appears to be significant in all the estimations, in PCSE(AR1) and PCSE(AR1/HET), the variable is only significant at the 10% and 5% significance levels, respectively. Nevertheless, it is shown that environmental taxes from the manufacture of computers, electronic, and optical products increase the exports of e-waste. This finding deserves particular attention in the Discussion Section.

When the recycling rate of e-waste is considered, it is found that this could reduce the amount of e-waste exported, which is not surprising and could signal the robustness of the results. Lastly, a country's financial and economic development (*LDCPS*) did not show a significant effect in any of the PCSE estimations; therefore, it does not impact the export of e-waste.

Table 4
Preliminary tests.

	Model
Breusch and Pagan LM test for random effects	250.55***
Ramsey Reset test	1.24
Hausman test	13.67*
Robust Hausman test	1.64

Notes: *** and * denotes statistical significance at 1% and 10% levels of significance, respectively.

Table 5
Specification tests.

	Statistics
Pesaran's test	4.632***
Wooldridge test	4.519**
Breusch-Pagan LM	52.312***
Breusch-Pagan/Cook-Weisberg	26.100***

Notes: ***, ** and * denotes statistical significance at 1%, 5% and 10% levels of significance, respectively.

Table 6
Estimated model.

	PCSE	PCSE(AR1)	PCSE(HET)	PCSE(AR1/HET)
LETEpc	1.1564***	0.4422*	1.1564***	0.4422**
LCO_2dep	4.2772***	3.1447***	4.2772***	3.1447***
LREC	−1.6109***	−0.4904	−1.6109***	−0.4904
Lwcoll	0.3735***	0.5278***	0.3735***	0.5278***
LMID	3.0863***	2.0005***	3.0863***	2.0005***
LDCPS	−0.0879	0.1652	−0.0879	0.1652
LGDPpc	−4.5578***	−2.9305***	−4.5578***	−2.9305***
Constant	44.7076***	25.2325***	44.7076***	25.2325***
R^2	0.4684	0.7589	0.4684	0.7589

Notes: ***, ** and * denotes statistical significance at 1%, 5% and 10% levels of significance, respectively. PCSE represents the estimation without any robust option; PCSE(AR1) represents the estimation robust to first-order serial correlation; PCSE(HET) represents the estimation robust to heteroskedasticity; PCSE (AR1/HET) represents the estimation robust to first-order serial correlation and heteroskedasticity; R^2 means R-squared.

5. Discussion

Increasing production and dependency on EEE creates more e-waste, increasing legal and illegal e-waste export to other countries. To deal with this, the EU has implemented measures to control e-waste trade. This paper aims to understand the impact of environmental regulation on the management of e-waste, particularly its export, considering 18 EU countries. Is regulation contributing to more remarkable reincorporation/recycling, or, on the contrary, does it encourage the escape and loss of e-waste? When analysing the question, there is an evident lack of data on the matter (Lepawsky, 2015; Luther, 2010; Petridis et al., 2020; Shamim, 2015). This lack of data can be explained by the majority of the e-waste trade being conducted illegally.

Focusing on the main findings of this paper, environmental regulation apparently contributes to the loss of precious materials found in e-waste because stricter environmental regulations lead to increased e-waste exportation. This finding proves that taxation on the manufacture of computers, electronic, and optical products is ineffective in reducing e-waste export. Instead, producers of EEE should be further incentivised by governments to take responsibility for a product's whole life. Ideally, this process should start in the design and production process. A product's environmental footprint can be reduced by extending its lifespan and ensuring that the design and assembly of the product are accomplished to facilitate the recycling process (Petridis et al., 2020; The Lancet, 2013). As stated by Pickren (2015), many current product designs are far from ideal – the finished products are not designed to be repaired – and in some cases, they can even hinder the recycling process. Furthermore, as proposed by Lancet (2013), producers of EEE should be responsible for the end-of-life recycling process. Consumers should ideally return products to manufacturers at their end-of-life. The collection and recycling process should be either done by the producers or supervised in case of resorting to third parties. Additionally, policymakers should raise consumers' awareness regarding the need to manage e-waste and dispose of it properly.

The findings of this paper demonstrate that richer countries are responsible for lower levels of e-waste export, given that economic growth reduces e-waste exports. As Mazzarano (2022) pointed out, GDP per capita enlarges the in-use stock of EEE and, consequently, as highlighted by Kumar et al. (2017), GDP enlarges e-waste generation. Accordingly, it could indicate that, although economic growth causes a possible increase in e-waste generation, economic development can also allow the countries to invest in internal recycling facilities. Economic growth could also make countries more committed to environmental protection and allow them to employ strict regulations to reduce the exports of e-waste. This finding could be explained by the country sample of the study that only includes EU countries (developed countries), in contrast to most e-waste trade studies (Abalansa et al., 2021; Lepawsky, 2015; Petridis et al., 2020). EU policymakers could finance those EU countries with more modest GDP growth so that these countries can invest in waste management and treatment, further preventing e-waste export.

Evidence in the literature shows that receiving countries are not prepared and equipped to properly deal with imported e-waste (Luther, 2010). As such, it is essential to develop the required infrastructure in host countries to deal with e-waste soundly, minimising human health risks and environmental damage (Abalansa et al., 2021; Petridis et al., 2020; The Lancet, 2013). Policies would also be required to ensure the safety of workers and that the recycling process is done under the stated regulation (Abalansa et al., 2021; Ilankoon et al., 2018; Petridis et al., 2020; The Lancet, 2013). Furthermore, Lancet (2013) supports that this legislation would have to enter into force locally, nationally, and globally. As a result, the first step would be recognizing the problem at hand and tackling it at all levels and worldwide. Legislations should also be established to guarantee that the developed countries assist the receiving sub-developed ones to protect them from the environmental damage of e-waste importation. Exporting countries should be accountable for e-waste management in receiving countries and penalized if mismanagement occurs.

As expected, e-waste collection is a significant positive predictor of the exports of e-waste. To avoid unnecessary export, the EU should increase the number of recycling centres focused on large e-waste materials, such as household appliances and small EEE, such as smartphones. Populations need easy access to collection systems, and policymakers should significantly increase the supply of e-waste collection points. Currently, e-waste recycling is not as easy to practice as plastic or paper recycling. By developing an efficient and easy-to-access collection system, citizens will be incentivised to partake, thus upping the collection level. Simultaneously, the existence of suitable e-waste collection points and the importance of not putting e-waste in traditional municipal waste collection points must be advertised close to the population. Media campaigns or sensitising actions could be an effective way of increasing consumers' awareness and their willingness to recycle e-waste.

Some consumers tend to dispose of EEE within their lifecycle not because they are damaged, unsuitable, or malfunctioning but because of improved technological options in the market. Also, producers often push updates to force consumers to purchase the products latest version. Incentives should be put forward to prolong the lifespan of EEE through, for instance, the creation of second-hand markets and incentives to consumers not to relinquish the products but to extend their use as much as possible. At the same time, policymakers could incentivise the collection of products that are perfectly functioning and could be, for instance, donated to charitable institutions or less wealthy countries.

The findings support that high carbon dioxide emissions are linked to increased e-waste export. Countries with high emissions from elevated economic growth may be less environmentally responsible and export more e-waste. Further measures must be taken in the EU, as exporting e-waste means losing vital raw materials, materials essential in the supply chains in producing batteries for electric vehicles, for example. To deepen the circularization in EU countries, e-waste recycling is essential and can be achieved by incentivizing the recycling industry, funding research for new recycling technologies, and implementing policies such as the Batteries and Accumulators regulation and the WEEE regulation. These policies will push and encourage e-waste recycling, contributing to achieving a viable path for sustained raw materials within Europe. As Forti et al. (2020) demonstrated, the quantity of precious metals within e-waste already presents a viable economic opportunity if well pursued. Lastly, further monitorisation of the existing WSR is crucial due to the constantly evolving global e-waste trade network.

6. Conclusions

Regulation is crucial for improving the management of e-waste and a critical way to avoid the loss of precious materials found in it. Therefore, the impact of environmental regulation on the export of e-waste from the EU was analysed for 18 EU countries from 2010 to 2018. In order to measure environmental regulation, the total environmental taxes from the manufacture of computers, electronic, and optical products per capita were used. Empirically, various tests were conducted to ensure the robustness of the results and the appropriateness of the estimator used. The data features made the use of the PCSE estimator appropriate.

The main findings suggest that environmental regulation drives the export of e-waste. On the other hand, recycling e-waste reduces the volume of e-waste exported. It implies that policymakers should invest in recycling facilities. At the same time, consumer incentives should be pursued to encourage proper e-waste disposal. Also, deploying collection points with easier access for the population is crucial. This paper also points out that economic growth hampers the export of e-waste. It could indicate that economic growth is crucial to managing e-waste properly and avoiding the transfer of the e-waste to other countries. Policymaking could be focused on creating and improving local recycling facilities for e-waste, contributing to reducing e-waste exports.

If it is necessary to send e-waste to another part of the world to be treated and recycled, then safeguarding the environment and protecting workers' health in the recipient country must be paramount. More affluent countries should urge host countries to develop structurally and policy-wise so that these countries are better suited to deal with imported waste. Secondly, exporting countries should improve both the quality of e-waste they send abroad and its design, as these factors are crucial in terms of lifespan and the ease of recycling when the product is at the end of its life. Thirdly, EU policymakers should increase the collection points for e-waste, enabling citizens to partake. Further regulation should also be pursued to reduce the current persistence of high CO_2 emissions in EU economies. As for recycling, the government must continue to implement policies that advocate its use while providing the necessary measures for its development. Lastly, the current WSR should be kept up to date to control the export of e-waste.

The presented study has three main limitations. Firstly, it could be stated that there is a lack of data about e-waste exports, which makes it challenging to analyse the topic at hand comprehensively. An improvement in the data availability containing data in a broader spectrum of types of e-waste would allow further analysis and studies on the matter. In this paper, the e-waste exports variable does not ensure that all the major e-waste categories have been considered, and therefore, the conclusion could change if the e-waste exports measured all the e-waste categories. The second limitation was the brief time span of the study due to a lack of available data, which is a common issue when secondary databases are used for current topics that require balanced panel data. Besides this recognised limitation, all the appropriate steps and tests were conducted to guarantee the robustness of the results. The third limitation of this study is that, it does not include all the relevant information to study the e-waste export phenomena, given that illegal exports of e-waste are not encompassed.

Future lines of research are suggested, namely: (i) apply a similar approach to a different geographical area with developed countries but with different characteristics and (ii) provide an analysis of the environmental effects of imported e-waste on host nations, which could aid policymakers in regulating e-waste trade more effectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The financial support of the NECE-UBI, Portugal, Research Unit in Business Science and Economics, Portugal, sponsored by the Portuguese Foundation for the Development of Science and Technology, project UIDB/04630/2020, is gratefully acknowledged.

References

Abalansa, S., El Mahrad, B., Icely, J., Newton, A., 2021. Electronic waste, an environmental problem exported to developing countries: The GOOD, the BAD and the UGLY. Sustain. 13, 5302. https://doi.org/10.3390/SU13095302.

Andeobu, L., Wibowo, S., Grandhi, S., 2021. An assessment of e-waste generation and environmental management of selected countries in Africa, Europe and North America: a systematic review. Sci. Total Environ. 792, 148078 https://doi.org/10.1016/j.scitotenv.2021.148078.

Andeobu, L., Wibowo, S., Grandhi, S., 2023. Environmental and health consequences of E-Waste dumping and recycling carried out by selected countries in Asia and Latin America. Sustainability 15, 10405. https://doi.org/10.3390/su151310405.

Bakhiyi, B., Gravel, S., Ceballos, D., Flynn, M.A., Zayed, J., 2018. Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges. Environ. Int. 110, 173–192. https://doi.org/10.1016/J.ENVINT.2017.10.021.

Boubellouta, B., Kusch-Brandt, S., 2021. Relationship between economic growth and mismanaged e-waste: panel data evidence from 27 EU countries analyzed under the Kuznets curve hypothesis. Waste Manag. 120, 85–97. https://doi.org/10.1016/j.wasman.2020.11.032.

Breusch, T.S., Pagan, A.R., 1979. A simple test for heteroscedasticity and random coefficient variation. Econometrica. https://doi.org/10.2307/1911963.

Breusch, T.S., Pagan, A.R., 1980. The lagrange multiplier test and its applications to model specification in econometrics. Rev. Econ. Stud. https://doi.org/10.2307/2297111.

Callao, C., Latorre, M.P., Martinez-Núñez, M., 2021. Understanding hazardous waste exports for disposal in Europe: a contribution to sustainable development. Sustain. 13 https://doi.org/10.3390/SU13168905.

Cantore, N., Cheng, C.F.C., 2018. International trade of environmental goods in gravity models. J. Environ. Manag. 223, 1047–1060. https://doi.org/10.1016/J.JENVMAN.2018.05.036.

Chancerel, P., Meskers, C.E.M., Hagelüken, C., Rotter, V.S., 2009. Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment. J. Ind. Ecol. 13, 791–810. https://doi.org/10.1111/J.1530-9290.2009.00171.X.

Cook, R.D., Weisberg, S., 1983. Diagnostics for heteroscedasticity in regression. Biometrika. https://doi.org/10.1093/biomet/70.1.1.

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sust. Energ. Rev. 51, 263–272. https://doi.org/10.1016/J.RSER.2015.06.010.

De Pascale, G., Fiore, M., Contò, F., 2021. Short and long run environmental tax buoyancy in EU-28: a panel study. Int. Econ. 168, 1–9. https://doi.org/10.1016/J.INTECO.2021.07.005.

Drukker, D.M., 2003. Testing for serial correlation in linear panel-data models. Stata J. Promot. Commun. Stat. Stata 3, 168–177. https://doi.org/10.1177/1536867x0300300206.

Efthymiou, L., Mavragani, A., Tsagarakis, K.P., 2016. Quantifying the effect of macroeconomic and social factors on illegal E-Waste trade. Int. J. Environ. Res. Public Health 13, 789. https://doi.org/10.3390/IJERPH13080789.

Esen, Ö., Yıldırım, D.Ç., Yıldırım, S., 2021. Pollute less or tax more? Asymmetries in the EU environmental taxes – Ecological balance nexus. Environ. Impact Assess. Rev. 91, 106662 https://doi.org/10.1016/J.EIAR.2021.106662.

European Commission, 2015. First circular economy action plan [WWW Document]. Off. J. Eur. Union. URL https://environment.ec.europa.eu/topics/circular-economy/first-circular-economy-action-plan_en (accessed 4.16.22).

European Commission, 2020a. A European Green Deal [WWW Document]. Publ. Off.. URL https://data.europa.eu/doi/10.2775/19001 (accessed 5.2.22).

European Commission, 2020b. Circular economy action plan. Europ. Union. https://doi.org/10.2775/855540.

European Environment Agency, 2009. Waste without borders in the EU? Transboundary shipments of waste. In: EEA Rep. No 1/2009 20.

European Environment Agency, 2016. Environmental taxation and EU environmental policies. In: EEA Rep. No 17/2016 92.

European Parliament, 2020. E-waste in the EU: facts and figures (infographic) [WWW Document]. URL. https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93325/e-waste-in-the-eu-facts-and-figures-infographic (accessed 5.20.22).

Forti, V., Baldé, C.P., Kuehr, R., Bel, G., 2020. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, United Nations University/United Nations Institute for Training and Research, International Telecommunication Union, and International Solid Waste Association.

Frazzoli, C., Orisakwe, O.E., Dragone, R., Mantovani, A., 2010. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. Environ. Impact Assess. Rev. 30, 388–399. https://doi.org/10.1016/J.EIAR.2009.12.004.

Ghosh, S., 2010. Examining carbon emissions economic growth nexus for India: a multivariate cointegration approach. Energy Policy 38, 3008–3014. https://doi.org/10.1016/J.ENPOL.2010.01.040.

Giljum, S., Bruckner, M., Martinez, A., 2015. Material footprint assessment in a global input-output framework. J. Ind. Ecol. 19, 792–804. https://doi.org/10.1111/jiec.12214.

Giljum, S., Wieland, H., Lutter, S., Bruckner, M., Wood, R., Tukker, A., Stadler, K., 2016. Identifying priority areas for European resource policies: a MRIO-based material footprint assessment. J. Econ. Struct. 5 https://doi.org/10.1186/s40008-016-0048-5.

Habib, H., Wagner, M., Baldé, C.P., Martínez, L.H., Huisman, J., Dewulf, J., 2022. What gets measured gets managed – does it? Uncovering the waste electrical and electronic equipment flows in the European Union. Resour. Conserv. Recycl. 181 https://doi.org/10.1016/j.resconrec.2022.106222.

Hausman, J.A., 1978. Specification tests in econometrics. Appl. Econ. 38, 112–134. https://doi.org/10.2307/1913827.

Hoang, A.Q., Tue, N.M., Tu, M.B., Suzuki, G., Matsukami, H., Tuyen, L.H., Viet, P.H., Kunisue, T., Sakai, S., Ichi Takahashi, S., 2023. A review on management practices, environmental impacts, and human exposure risks related to electrical and electronic waste in Vietnam: findings from case studies in informal e-waste recycling areas. Environ. Geochem. Health 45, 2705–2728. https://doi.org/10.1007/s10653-022-01408-4.

Hoechle, D., 2007. Robust standard errors for panel regressions with cross-sectional dependence, 7, 281–312. https://doi.org/10.1177/1536867X0700700301.

Huang, H., Tong, X., Cai, Y., Tian, H., 2020. Gap between discarding and recycling: estimate lifespan of electronic products by survey in formal recycling plants in China. Resour. Conserv. Recycl. 156, 104700 https://doi.org/10.1016/J.RESCONREC.2020.104700.

Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hintsa, J., Luda di Cortemiglia, V., Leroy, P., Vermeersch, E., Mohanty, S., van den Brink, S., Ghenciu, B., Dimitrova, D., Nash, E., Shryane, T., Wieting, M., Kehoe, J., Baldé, C.P., Magalini, F., Zanasi, A., Ruini, F., Bonzio, A., 2015. Countering WEEE Illegal Trade (CWIT) Summary Report, Market Assessment, Legal Analysis, Crime Analysis and Recommendations Roadmap. https://doi.org/10.13140/RG.2.1.4864.2328.

Ilankoon, I.M.S.K., Ghorbani, Y., Chong, M.N., Herath, G., Moyo, T., Petersen, J., 2018. E-waste in the international context – A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery. Waste Manag. 82, 258–275. https://doi.org/10.1016/J.WASMAN.2018.10.018.

Islam, M.T., Abdullah, A.B., Shahir, S.A., Kalam, M.A., Masjuki, H.H., Shumon, R., Rashid, M.H., 2016. A public survey on knowledge, awareness, attitude and willingness to pay for WEEE management: case study in Bangladesh. J. Clean. Prod. 137, 728–740. https://doi.org/10.1016/J.JCLEPRO.2016.07.111.

Jug, J., Mirza, D., 2005. Environmental regulations in gravity equations: evidence from Europe. World Econ. 28, 1591–1615. https://doi.org/10.1111/J.1467-9701.2005.00748.X.

Kahhat, R., Williams, E., 2012. Materials flow analysis of e-waste: domestic flows and exports of used computers from the United States. Resources. Conserv. Recycl. Resour. Conserv. Recycl. 67, 67–74. https://doi.org/10.1016/J.RESCONREC.2012.07.008.

Kaiser, B., 2015. RHAUSMAN: Stata module to perform robust Hausman specification test. Software component provided by Boston College Department of Economics, Number: S457909, https://ideas.repec.org/c/boc/bocode/s457909.html.

Kang, S.J., Lee, S., 2021. Impacts of environmental policies on global green trade. Sustain. 13, 1517. https://doi.org/10.3390/SU13031517.

Karlsson, S., Löthgren, M., 2000. On the power and interpretation of panel unit root tests. Econ. Lett. 66, 249–255. https://doi.org/10.1016/S0165-1765(99)00237-2.

Kasman, A., Duman, Y.S., 2015. CO2 emissions, economic growth, energy consumption, trade and urbanization in new EU member and candidate countries: a panel data analysis. Econ. Model. 44, 97–103. https://doi.org/10.1016/j.econmod.2014.10.022.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Kuik, O., Branger, F., Quirion, P., 2019. Competitive advantage in the renewable energy industry: evidence from a gravity model. Renew. Energy 131, 472–481. https://doi.org/10.1016/J.RENENE.2018.07.046.

Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42. https://doi.org/10.1016/J.RESCONREC.2017.01.018.

Lepawsky, J., 2015. The changing geography of global trade in electronic discards: time to rethink the e-waste problem. Geogr. J. 181, 147–159. https://doi.org/10.1111/GEOJ.12077.

Lepawsky, J., McNabb, C., 2010. Mapping international flows of electronic waste. Can. Geogr. / Le Géographe Can. 54, 177–195. https://doi.org/10.1111/J.1541-0064.2009.00279.X.

Luther, L., 2010. Managing Electronic Waste: Issues with Exporting E-Waste. CRS Report for Congress.

Ma, S., Dai, J., Wen, H., 2019. The influence of trade openness on the level of human capital in China: on the basis of environmental regulation. J. Clean. Prod. 225, 340–349. https://doi.org/10.1016/J.JCLEPRO.2019.03.238.

Maddala, G.S., Wu, S., 1999. A comparative study of unit root tests with panel data and a new simple test. Oxf. Bull. Econ. Stat. 61, 631–652. https://doi.org/10.1111/1468-0084.0610s1631.

Mazzarano, M., 2022. Material governance and circularity policies: How waste policies and innovation affect household appliances ' accumulation. Ecol. Econ. 200, 107538 https://doi.org/10.1016/j.ecolecon.2022.107538.

Newaz, M.S., Appolloni, A., 2023. Evolution of behavioral research on E-waste management: conceptual frameworks and future research directions. Bus. Strateg. Environ. 2030, 1–27. https://doi.org/10.1002/bse.3503.

Nnorom, I.C., Osibanjo, O., 2008. Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries. Resour. Conserv. Recycl. 52, 843–858. https://doi.org/10.1016/J.RESCONREC.2008.01.004.

OECD, 2011. Environmental Taxation A Guide for Policy Makers [WWW Document]. URL. https://www.oecd.org/env/tools-evaluation/48164926.pdf (accessed 1.5.22).

OECD, 2016. How stringent are environmental policies? Policy Perspectives [WWW Document]. URL. https://www.oecd.org/environment/how-stringent-are-environmental-policies.htm (accessed 2.2.22).

Pesaran, M.H., 2004. General Diagnostic Tests for Cross Section Dependence in Panels.

Pesaran, M.H., 2007. A simple panel unit root test in the presence of cross-section dependence. J. Appl. Econ. 22, 265–312. https://doi.org/10.1002/JAE.951.

Petridis, N.E., Petridis, K., Stiakakis, E., 2020. Global e-waste trade network analysis. Resour. Conserv. Recycl. 158, 104742 https://doi.org/10.1016/J.RESCONREC.2020.104742.

Pickren, G., 2015. Making connections between global production networks for used goods and the realm of production: a case study on e-waste governance. Glob. Networks 15, 403–423. https://doi.org/10.1111/GLOB.12071.

Ramsey, J.B., 1969. Tests for specification errors in classical linear least-squares regression analysis. J. R. Stat. Soc. Ser. B 31, 350–371.

Robinson, B.H., 2009. E-waste: an assessment of global production and environmental impacts. Sci. Total Environ. 408, 183–191. https://doi.org/10.1016/J.SCITOTENV.2009.09.044.

Rodríguez, M., Robaina, M., Teotónio, C., 2019. Sectoral effects of a green tax reform in Portugal. Renew. Sust. Energ. Rev. 104, 408–418. https://doi.org/10.1016/J.RSER.2019.01.016.

Romano, T., Fumagalli, E., 2018. Greening the power generation sector: Understanding the role of uncertainty. Renew. Sust. Energ. Rev. 91, 272–286. https://doi.org/10.1016/J.RSER.2018.03.098.

Safi, A., Chen, Y., Wahab, S., Zheng, L., Rjoub, H., 2021. Does environmental taxes achieve the carbon neutrality target of G7 economies? Evaluating the importance of environmental R&D. J. Environ. Manag. 293, 112908 https://doi.org/10.1016/J.JENVMAN.2021.112908.

Shahbaz, M., Kumar Tiwari, A., Nasir, M., 2013. The effects of financial development, economic growth, coal consumption and trade openness on CO2emissions in South Africa. Energy Policy 61, 1452–1459. https://doi.org/10.1016/j.enpol.2013.07.006.

Shamim, A., 2015. E-Waste trading impact on public health and ecosystem services in developing countries. Int. J. Waste Resour. https://doi.org/10.4172/2252-5211.1000188.

Tamazian, A., Chousa, J.P., Vadlamannati, K.C., 2009. Does higher economic and financial development lead to environmental degradation: evidence from BRIC countries. Energy Policy 37, 246–253. https://doi.org/10.1016/J.ENPOL.2008.08.025.

Tao, R., Umar, M., Naseer, A., Razi, U., 2021. The dynamic effect of eco-innovation and environmental taxes on carbon neutrality target in emerging seven (E7) economies. J. Environ. Manag. 299, 113525 https://doi.org/10.1016/J.JENVMAN.2021.113525.

The Lancet, 2013. Electronic waste—time to take stock. Lancet 381, 2223. https://doi.org/10.1016/S0140-6736(13)61465-8.

Tsurumi, T., Managi, S., Hibiki, A., 2015. Do environmental regulations increase bilateral trade flows? B.E. J. Econ. Anal. Policy 15, 1549–1577. https://doi.org/10.1515/BEJEAP-2014-0164/PDF.

UNEP, 2009. Sustainable innovation and technology transfer: industrial sector studies: critical metals for future sustainable technologies and their recycling potential, UNEP, DTIE, Sustainable Consumption and Production Branch. In: UNEP, DTIE, Sustainable Consumption and Production Branch, Paris, 2009 https://doi.org/http://digitallibrary.un.org/record/785327.

Van Beers, C., Van Den Bergh, J.C.J.M., 1997. An empirical multi-country analysis of the impact of environmental regulations on foreign trade flows. Kyklos 50, 29–46. https://doi.org/10.1111/1467-6435.00002.

Wang, Kuan-Min, Wang, K.-M., 2011. The relationship between carbon dioxide emissions and economic growth: quantile panel-type analysis. Qual. Quant. 47, 1337–1366. https://doi.org/10.1007/S11135-011-9594-Y.

Wen, H., Dai, J., 2020. Trade openness, environmental regulation, and human capital in China: based on ARDL cointegration and Granger causality analysis. Environ. Sci. Pollut. Res. 27, 1789–1799. https://doi.org/10.1007/S11356-019-06808-1/TABLES/6.

Wooldridge, J.M., 2002. Econometric Analysis of Cross Section and Panel Data. MIT Press.