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How have waste management policies impacted the flow of municipal waste? An empirical analysis of 14 European countries

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ABSTRACT

Waste management policies aim to divert waste from lower positions on the waste hierarchy such as landfill and incineration to higher positions in the hierarchy such as energy recovery and recycling. However, empirical evaluations of such policies are scarce. This study highlighted the effect of waste management policies on the amount of waste treated with landfill, incineration, energy recovery and recycling by analysing a panel dataset consisting of 14 European countries and the period 1996 to 2018. Findings from a seemingly unrelated regression model suggest that the landfill ban is associated with a decrease in landfill waste, but an increase in incineration, energy recovery and recycling waste. The landfill tax is also correlated with an increase in energy recovery waste but, in contrast, it is associated with a reduction in incineration and recycling waste. Meanwhile, the deposit refund scheme is associated with a decrease in the amount of landfill waste. Concerning the effects on total waste generated, regression results from a fixed effects model indicate that the landfill tax and the deposit refund scheme are both correlated with a reduction in the amount of waste generated. These findings contribute to the scarce academic literature evaluating waste management policies and may better inform policy makers on their longer-term implications.

1. Introduction

Landfill and incineration waste has been the prevalent form of waste management for decades and have severe consequences for the local environment such as contamination of groundwater (Chofqi et al., 2004), deterioration in agricultural soils (Akinbile, 2012), and air pollution (Weng et al., 2015). In an effort to transition away from this linear model, the European Union (EU) has promoted practices such as prevention, reuse, recycling, and recovery through the adoption of the waste management hierarchy (Gharfalkar et al., 2015) which was formally implemented by the 2008 Waste Framework Directive and sets several targets for the re-use and recycling of waste (European Commission, 2021). At least 55% of municipal waste, by weight, should be re-used or recycled by 2025. This target subsequently increases to 60% by 2030 and 65% by 2035. While the waste hierarchy is recognized as a strategy to reduce landfill and incineration, doubts remain over its ability to minimise environmental implications and reduce natural resource use, however (van Ewijk and Stegemann, 2016).

To incentivise the diversion of waste towards higher positions on the waste hierarchy (Martin and Scott, 2003), as well as other value retention options such as refurbishing, repurposing and remanufacturing, several countries have adopted waste management policies at the national level. In the context of this article, limited availability of data led to waste management policies being restricted to the landfill tax, landfill ban, incineration tax, deposit refund scheme (DRS) and WFD policies. Empirical studies into the effectiveness of these policies are scarce. To the best of our knowledge, only three national level econometric studies into waste management policies exist (Bassi and Watkins, 2012; Karousakis, 2009; Papineschi et al., 2019). A review of these studies is carried out in section 3 and none of them consider the effect of as many waste management policies among multiple treatment methods and as many countries as the present study. To address this gap, the research question, “How have waste management policies impacted the flow of municipal waste in 14 European countries?”, is investigated.

The research question is explored by adopting seemingly unrelated regressions (SUR) and fixed effects (FE) models to explore a panel

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dataset consisting of 14 European countries between 1996 and 2018. The 14 countries are Croatia, Cyprus, Denmark, Estonia, Finland, Germany, Hungary, Ireland, Malta, the Netherlands, Romania, Slovenia, Sweden, and the United Kingdom. Data for landfill tax, landfill ban, incineration tax, DRS policies and other characteristics for these countries are collected from various sources such as Eurostat, the World Bank, the OECD (Organisation for Economic Co-operation and Development) and UNESCO (United Nations Educational, Scientific and Cultural Organization).

The findings of this study contribute to the scarce academic literature on waste management policies, and better inform policy makers on the longer-term impacts of such policies. In turn, this may influence the approach of policy makers' future waste management strategies.

The rest of the study is organised as follows. Section 2 reviews the scarce prior literature on econometric studies of waste management policies. An outline of the methodology, including the model specification, data collection and descriptive statistics, can be found in section 3. The results of the econometric analysis and a discussion of its implications are presented in section 4, before concluding remarks are made in section 5.

2. Literature review

A review is conducted using the Scopus database with the search criteria: (TITLE-ABS-KEY ("landfill tax" OR "incineration tax" OR "deposit return scheme" OR "deposit refund scheme") AND TITLE-ABS-KEY (econometric OR "economic analysis" OR "panel data")). The search was conducted in April 2022 and returned 16 results.

The abstracts of the returned articles were evaluated using inclusion criteria such as whether the policy is an explanatory variable. Studies involving the use of econometric models and measuring the impact of waste management policies were scarce.

Some studies explore the role of such policies using non econometric methods (Klavenieks and Blumberga, 2017; Reggiani and Silvestri, 2018), with Reggiani and Silvestri (2018), observing a negative correlation between disposal costs and the percentage of waste at landfill or incineration. Other studies are conducted at the local authority (Panzone et al., 2021), provincial (Mazzanti et al., 2010, 2009) or regional (de Weerdt et al., 2022, 2020; Sasao, 2014) level. However, only three studies explore their role at the national level using econometric methods (Bassi and Watkins, 2012; Karousakis, 2009; Papineschi et al., 2019), to the best of the authors' knowledge.

Papineschi et al. (2019) explored the effect of interventions such as landfill taxes, landfill bans, waste targets and DRS on waste generated and the recycling rate (Papineschi et al., 2019). The period 1994 to 2017 and five countries were studied (Denmark, Finland, Iceland, Norway, and Sweden). In the fixed effects (FE) model exploring waste generation, the significant variables were packaging tax, energy recovery targets, total recovery targets, and landfill ban interventions. Whereas the FE model exploring recycling rate found landfill tax, packaging tax, total recovery targets, landfill targets, landfill ban on combustible waste and biodegradable waste, DRS for metal containers and extended producer responsibility (EPR) interventions to be statistically significant. This study, however, does not consider the implication of interventions on the amount of landfill, energy recovery and incineration waste, and considers only five countries.

Another study examined 30 OECD countries between 1980 and 2000 (Karousakis, 2009), using four panel data models. A random effects (RE) model explored the effect of population density, GDP per capita, urbanisation and the waste legislation and policy index on municipal waste generation. However, it does not explore the role of landfill interventions. In contrast, the three other models explore the role of landfill tax using a feasible general least squares (FGLS) approach and control for GDP per capita, population density, urbanisation, and the waste legislation and policy index. One of the models considers the proportion of waste disposed in landfills as the dependent variable and finds all variables to be statistically significant, except landfill tax. The second model's dependent variable was the proportion of paper, cardboard and glass recycled, where all explanatory variables were significant at a 5% significance level besides urbanisation. The third model considers the percentage of glass recycled as the dependent variable and finds that GDP per capita, population density and the waste legislation and policy index are all statistically significant. However, landfill tax is not statistically significant. This study only considers the effect of landfill tax and does not consider other waste management policies such as landfill ban, incineration tax or deposit refund schemes. Furthermore, energy recovery and incineration treatment methods are not explored.

The effect of landfill tax on the landfill rate was explored in a study that included observations from Denmark, Finland, Netherlands, Sweden and the UK between 1995 and 2009 (Bassi and Watkins, 2012). The main model in the study used an Autoregressive Distributed Lag (ARDL) approach for each country. Controlling for landfill waste, amount of waste generated, GDP and population size, it found that one-year lags of waste landfilled and generated are significant for Sweden. Furthermore, waste generated was significant in explaining the UK's landfill rate. All remaining coefficients were not statistically significant. The study only considered the effect of the landfill tax, neglecting landfill ban, incineration tax, and DRS policies.

Literature in this field also suggests a relationship between waste and economic activity that follows the hypothesis of the so-called Environmental Kuznets Curve (EKC) which postulates a non-linear relationship between GDP per capita and waste. The hypothesis of the existence of EKC tests the presence of an inverted U-shaped curve. The EKC postulates a positive relationship between GDP per capita and waste generation at the beginning of the development process in a country until the curve reaches a turning point; after that the relationship between economic activity and waste is negative. A very recent study by Chakraborty et al. (2022) has highlighted the functional form described in literature under the hypothesis of EKC comparing a threshold model in which the relationship between GDP and waste is linear around the threshold point and the standard curvilinear EKC. Chakraborty et al. (2022) found weak evidence of the link between GDP and waste within the EKC framework across Italian provinces in the last twenty years. Even if the evidence for an EKC was weak in Chakraborty et al. (2022), it may be of interest to extend the model specification that we present in our study and include income both linearly and non-linearly as a robustness check.

The effects of waste management policies from the three studies, based on a 5% significance level, are summarised in Table 1 for waste generation, recycling, and landfill. Among the three studies, what appears to be missing is a study that investigates multiple waste management policies, while exploring more than five countries, and the four waste treatment methods: recycling, energy recovery, incineration and landfill. This study contributes to the scarce relevant literature by addressing these gaps.

3. Methodology

3.1. Model specification

Eq. (1) shows the general model specification adopted in this study:

$$\begin{aligned} Waste_{itk} = {} & \beta_{1k} landfilltax_{it} + \beta_{2k} landfillban_{it} + \beta_{3k} incinerationtax_{it} + \beta_{4k} DRS_{it} \\ & + \beta_{5k} WFD_{it} + \beta_{6k} timetrend_k + x_{itk}^{'}\gamma_k + u_{ik} + \epsilon_{itk} \end{aligned} \quad (1)$$

The subscript k represents the treatment method, i.e., recycling, energy recovery, incineration, and landfill. An identical specification is used to estimate the amount of waste generated. Subscripts i and t denote country and year, whereas the set of control variables are denoted by the vector x. Meanwhile, u_{ik} captures the effect of country specific unobserved variables and ϵ_{itk} denotes the remainder disturbance.

Table 1
Summary of policy effects from relevant literature.

Dependent variable	Study	Independent variable: Landfill tax	Independent variable: Landfill ban	Independent variable: Incineration tax	Independent variable: DRS plastic	Independent variable: DRS metal	Independent variable: DRS glass
Waste generated	Papineschi et al., 2019	No significant correlation	Positive correlation (only for combustible waste)	No significant correlation	No significant correlation	No significant correlation	No significant correlation
Waste generated	Karousakis, 2009	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Waste generated	Bassi and Watkins, 2012	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Recycling	Papineschi et al., 2019	No significant correlation	Positive correlation	No significant correlation	No significant correlation	No significant correlation	No significant correlation
Recycling	Karousakis, 2009	Positive correlation (only for paper and cardboard)	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Recycling	Bassi and Watkins, 2012	Positive correlation (only for Finland)	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Landfill	Papineschi et al., 2019	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Landfill	Karousakis, 2009	No significant correlation	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed
Landfill	Bassi and Watkins, 2012	No significant correlation	Not analysed	Not analysed	Not analysed	Not analysed	Not analysed

To account for exogenous change in the different waste treatment methods that the other variables do not control for, a linear trend or time dummies can be used. Since no intense fluctuations in the series were observed and to also save degrees of freedom it was decided to include a linear time trend instead of time dummies. This time variable could also act as a proxy for time variant effects such as technological change.

Two approaches are taken to estimate the effects of the waste management policies. Firstly, a SUR approach is adopted to account for contemporaneous correlation of the error terms among individual equations representing the four waste treatment methods (recycling, energy recovery, incineration, and landfill). The acknowledgement of the error term's contemporaneous correlation is likely to make the SUR regression more efficient than individual FE regressions for each waste treatment method. For the amount of total waste generated, a separate FE model is estimated since this variable is not a waste treatment method.

Among the policies explored in this study, the landfill and incineration taxes would be expected to make the treatment of waste with landfill and incineration methods relatively more expensive, possibly resulting in a substitution effect towards other treatment methods such as energy recovery and recycling. Similarly, the landfill ban may achieve the same substitution effect by forcefully preventing some types of waste from being disposed at landfill sites. The DRS policies, on the other hand, would be expected to encourage plastic, metal, and glass beverage containers to be redirected to recycling from the other treatment methods, as they encourage consumers to return beverage containers at specialised recycling stations to reclaim a deposit fee. The 2008 Waste Framework Directive (WFD) introduces important concepts such as the waste hierarchy, waste separation, and extended producer responsibility. Subsequently, the WFD would be expected to be associated with an increase in the amount of recycling and energy recovery waste, yet a decrease in the amount of landfill and incineration waste.

The waste management policies may also impact the amount of waste generated. However, the effect of some policies such as the landfill tax and incineration tax can be difficult to establish because it is unclear how the taxes, which usually apply directly to waste collection companies, are forwarded to individuals and households that generate the waste. This decision is often taken at a municipal or regional level (Reichenbach, 2008), with the possibility of volume based, weight based or flat fee pricing (Hage and Söderholm, 2008). Nevertheless, since national level data is used in this study, it might be reasonable to assume that at least a few municipalities or regions in each country where the taxes are adopted might forward the taxes to individuals and households, such that at an aggregate level, some kind of cost-forwarding behaviour is still realised. In this case, the expected sign of the tax coefficients would be negative, since the generation of waste would become more expensive and therefore discouraged.

The expected relationship between the DRS policies and the amount of waste generated is also unclear. From one perspective, it can be argued that the DRS policies offer a sense of reassurance to individuals and households that beverage containers would be recycled through the schemes if deposited at a beverage container collection station. Consequently, this may inadvertently encourage further consumption of such beverages and contribute to an increase in waste generation. On the other hand, it could be argued that, for example, the DRS fee that is added to the ordinary price of applicable beverages would make the beverage more expensive and reduce demand, subsequently reducing the amount of waste generated. The WFD, on the other hand, would be expected to be associated with a decrease in the amount of waste generated, as it introduces the waste hierarchy which prioritises waste reduction above all other waste treatment activities. Similarly, the landfill ban is also expected to be associated with a decrease in the amount of waste generated, due to one less waste treatment option being available for some types of waste.

3.2. Data

The definition of waste in this dataset is that of municipal solid waste (MSW), which is defined as household or similar waste, such as paper, plastic, food, glass, metal and textiles (Eurostat, 2021a). MSW does not include waste from agriculture and industry. However, waste from offices, commerce and public institutions are included if they resemble household waste.

The dataset used for this study is compiled from several sources, including Eurostat, the World Bank, and the OECD. Data availability restricted the period explored in this study to 1996 to 2018 and the following 14 European countries: Croatia, Cyprus, Denmark, Estonia, Finland, Germany, Hungary, Ireland, Malta, the Netherlands, Romania, Slovenia, Sweden, and the United Kingdom. A limitation of our dataset was the scarcity or complete lack of official available data for some European countries. In addition, for some other countries, data on landfill taxes, landfill ban and incineration taxes do not exist because these taxes have not been implemented or come into force yet (CEWEP, 2020). We have used three different official databases to include as many countries for as many years as possible. We have compiled a reasonably full and homogenous panel dataset for 14 European countries that gives us the possibility to perform an econometric analysis.

As far as we know, this is the first and longest panel dataset for landfill taxes, landfill bans and incineration taxes that has been constructed at country level for Europe.

The control variables were motivated by relevant literature which found, for example, urbanisation (Intharathirat et al., 2015; Khajuria et al., 2010; Mian et al., 2017; Wang and Nie, 2001), population density (Intharathirat et al., 2015; Mazzanti et al., 2009; Nicolli and Mazzanti, 2013; Rinaldi et al., 2013; Romano and Molinos-Senante, 2020), GDP (Duan et al., 2020; Khajuria et al., 2010; Mian et al., 2017; Minelgaitė and Liobikienė, 2019; Wang and Nie, 2001) and education (Halkos and Petrou, 2019; Sidique et al., 2010) to be cited as contributory factors in determining the amount of waste generated, or the amount of waste disposed of at different treatment methods.

The following variables exist in the dataset:

Amount of landfill waste. Amount of waste disposed of at landfill sites, measured in millions of tonnes. Obtained from Eurostat (Eurostat, 2021b).

Amount of incineration waste. Amount of waste disposed of at incineration sites, measured in millions of tonnes. Obtained from Eurostat (Eurostat, 2021b). It should be noted that this only includes waste that is incinerated without any energy recovery.

Amount of energy recovery waste. Amount of waste disposed of at energy recovery sites, measured in millions of tonnes. Obtained from Eurostat (Eurostat, 2021b).

Amount of recycling waste. Amount of waste recycled, measured in millions of tonnes. Obtained from Eurostat (Eurostat, 2021b).

Total waste generated. Amount of total waste generated, measured in millions of tonnes. Obtained from Eurostat (Eurostat, 2021b). This value is equal to the sum of the landfill waste, incineration waste, energy recovery waste and recycling waste.

Landfill tax. The value of the landfill tax levy in EUR per tonne. Where necessary, local currencies are converted to EUR using the corresponding EUROSTAT exchange rates for each year (Eurostat, 2021c). The tax is not adjusted for purchasing power parity. Before 1999, European Currency Unit (ECU) rates published by the European Commission are used. Data are obtained from several sources such as the Confederation of European Waste to Energy Plants (CEWEP, 2020), and national policy documents (Finnish Environment Institute, 2020). Some countries such as the United Kingdom adopt multiple tiers for the landfill tax. In these cases, the tier that applies to most municipal waste is used. For the countries included in this study, the tax is implemented at a national level, with no regional heterogenity.

Landfill ban. The landfill ban was implemented differently in each country. For example, the ban has applied to recycling and combustible waste in Denmark, untreated municipal waste in Estonia, and organic waste in Finland. For simplicity, a binary variable was created to indicate whether a landfill ban was in place for each country for at least one waste treatment method: recyclable, combustible, untreated or organic waste. Data are obtained from the CEWEP (CEWEP, 2020). The landfill ban is adopted at a national level, with no regional heterogeneity for the countries investigated in this study. However, for the United Kingdom, it should be noted that the landfill ban has only been implemented by Scotland in 2014 and Northern Ireland in 2015. Since these countries represent only 11% of the United Kingdom's population, and since England and Wales did not implement a landfill ban, a value of 0 was assigned. The ban was implemented at a national level in all other countries included in this study.

Incineration tax. The value of the incineration tax in EUR per tonne. Eurostat's exchange rates for each year are used to convert local currencies (Eurostat, 2021c). Data is obtained mainly from the CEWEP (2019). The tax is not adjusted for purchasing power parity. The tax is implemented at a national level, with no regional heterogeneity, for the countries explored in this study.

DRS. A binary variable where 1 signifies that a deposit refund scheme was in force for either plastic, aluminium or glass beverage containers, and 0 otherwise. Data are obtained primarily from grey documents and supplemented from news articles. (BCRS Malta, 2022; CM Consulting and Reloop, 2016; Cyprus Mail, 2021; Defra, 2021; Ireland Department of the Environment, 2021; Reloop Platform, 2020; Schoenherr Rechtsanwälte, 2021; Slovenia Times, 2022). The policy is adopted at a national level, with no regional heterogeneity.

WFD. A binary value where 1 indicates that the Waste Framework Directive was transposed into and active in the national law of a country, and 0 otherwise. The data for this variable is obtained from a report from the European Commission, authored by Tsiarta et al. (2015). Within the report, some countries transpose the Waste Framework Directive into multiple national level laws. The implementation of the last of these laws is interpreted to be the moment that the directive has been fully transposed nationally, signalling the year that the variable takes a value of 1 in the dataset.

GDP per capita. GDP divided by population size at the middle of each year. It is expressed in thousands of constant 2010 US dollars to adjust for inflation. It is obtained from the World Bank (2021a), where GDP is calculated as the sum of gross value added by domestic producers, and product taxes. Subsidies not accounted for in the value of products are deducted, but no deductions are made for the condition of fabricated assets and natural resources.

Urban population. The number of people living in urban areas divided by the total population, as defined by national statistical offices. Expressed as a percentage and obtained from the World Bank (The World Bank, 2021b).

Enrolment in tertiary education. Proportion of the population that is registered in tertiary education programmes i.e. for a bachelor degree and higher, or equivalent. Obtained from UNESCO, (The United Nations Educational, Scientific and Cultural Organization), (UNESCO, 2021).

Population density. Population size at the middle of the year divided by the area of land in square kilometres. Expressed as number of people per square kilometre of land area and obtained from the World Bank (The World Bank, 2021c). Population size includes all residents, regardless of their citizenship or legal status, except for refugees that have not permanently settled with the country. Land area excludes inland water bodies (even major rivers and lakes), exclusive economic zones, and national claims to continental shelf.

Share of population aged 15–64. The proportion of the total population that falls within the age range 15 to 64, frequently used to measure the size of the economically active population. Expressed as a percentage and sourced from The World Bank (2021d).

Population size. Estimations of the number of residents in the middle of each year in millions, ignoring legal position or citizenship status. This variable is obtained from the World Bank (2022).

The data on the amount of waste at different treatment methods from Eurostat may not be perfectly consistent across countries, because of importation, exportation and dehydration, for instance (Eurostat 2021b). Furthermore, the data contains a proportion of missing values: 2% in energy recovery, 2% in incineration waste, 4% in landfill waste and 2% in waste generated. According to Eurostat, this is due to no proper data sources being available at the time. Some missing values were discovered from other sources (Barro and Lee, 2013; Finnish Environment Institute, 2020).

Most of the remaining missing values can be handled with simple imputation methods such as averages of adjacent observations. In the case of Croatia, the values for the amount of landfill waste are missing for the first 10 years, 1996–2005. However, data for the other waste treatment methods and the total waste generated are available so the missing values for the landfill waste variable are calculated by subtracting the amount of waste at incineration, energy recovery and recycling from the amount of waste generated, producing an estimate for the amount of landfill waste. This therefore represents a balanced panel dataset.

Besides Croatia, Cyprus, Germany, Malta and Romania, all remaining countries investigated in this study adopted the landfill tax. The level of the tax and the period that it was implemented in are displayed in Fig. 1. There is a substantial amount of variability, with Denmark and Sweden adopting the tax prior to the turn of the century, which contrasts with Hungary's adoption of the tax in 2012 and the Netherlands in 2014 following the abolishment of the Netherland's first implementation of the tax in 2012. The levels of the tax also vary considerably, with Hungary, the Netherlands and Slovakia restricting the tax to no more than 20 EUR per tonne. Whereas the United Kingdom's landfill tax reached almost 115 EUR per tonne in 2015, accounting for exchange rate fluctuations.

The incineration tax, on the other hand, was only adopted by Denmark, the Netherlands, and Sweden. As shown in Fig. 2, Denmark and the Netherlands adopted the tax for almost the entire period explored in this study, whereas Sweden only implemented the tax between 2006 and 2010. When the incineration tax was adopted, Denmark and Sweden charged around 40 EUR per tonne, whereas the Netherlands increased the tax several times during the first phase of its implementation before 2012, where it reached over 110 EUR per tonne. In the second phase of its implementation from 2014 onwards, the tax was charged at a reduced level of around 13 EUR per tonne.

Fig. 3 visualises the year that DRS, landfill ban and WFD policies were adopted in each country. A reasonable amount of variation can be observed in the year that policies are adopted. The earliest policy adopted is the DRS by Sweden in 1984. Meanwhile, the most recent policy adopted was the landfill ban by Croatia in 2017.

The expectation that an increase in the landfill tax would divert waste away from landfill appears to be somewhat supported by the scatterplot in Fig. 4, which indicates a negative correlation between the two variables in 2018 among the countries explored in this study.

Table 2 outlines the summary statistics of the variables included in the dataset. The first line of statistics relates to the overall variation, the second line to the between variation and the third line the within variation. The dependent variables, landfill, incineration, energy recovery, recycling, and total waste generated, have means of 2.78 million, 0.85 million, 1.3 million, 3.58 million and 8.64 million tonnes, respectively. Landfill tax has an average value of 15.91 EUR and varies from 0 EUR to 113.80 EUR. Meanwhile, incineration tax has an average value of 7.29 EUR and varies from 0 EUR to 108.13 EUR.

4. Results and discussion

For the dependent variables corresponding to the four waste treatment methods, a SUR approach is adopted to account for contemporaneous correlation of the error terms in the individual equations. The procedure for obtaining results using the SUR approach firstly involves developing separate FE models for each of the four waste treatment methods. Then, variables with a p-value greater than 0.4 are removed to obtain unique equations for each waste treatment method. The SUR model is then estimated, and the results are displayed in Table 3. The blank cells in Table 3 indicate the variables that were removed during the SUR estimation procedure.

The landfill tax, as established in section 3, would be expected to redirect waste from landfill to the other waste treatment methods. There is some support for this effect from the SUR estimations, which indicate that a 1 EUR increase per tonne in the landfill tax is associated with, on average and keeping other factors fixed, a 0.019 million tonne increase in energy recovery waste. However, the SUR results also suggest a contradiction of the anticipated redirection of waste from landfill, as the landfill tax is associated with a decrease in incineration and recycling waste.

The negative sign of the recycling coefficient is at odds with the findings from Papineschi et al. (2019), where no statistically significant relationship could be found with the landfill tax. However, both Bassi and Watkins (2012) and Karousakis (2009) find no statistically significant relationship between landfill tax and landfill waste, which is consistent with the findings of this study, where the landfill tax was removed during the SUR estimation procedure as it had a p-value of 0.551 in the single-equation FE regression that preceded SUR estimation.

The landfill ban, which is more stringent than the landfill tax, would also be expected to redirect waste from landfill to the other waste treatment methods. The results from the SUR model do find evidence of this pattern, suggesting that the presence of the ban is associated with, on average and keeping other factors constant, a 2.919 million tonne decrease in landfill waste, a 0.933 million tonne increase in incineration waste, a 0.943 million tonne increase in energy recovery waste and a

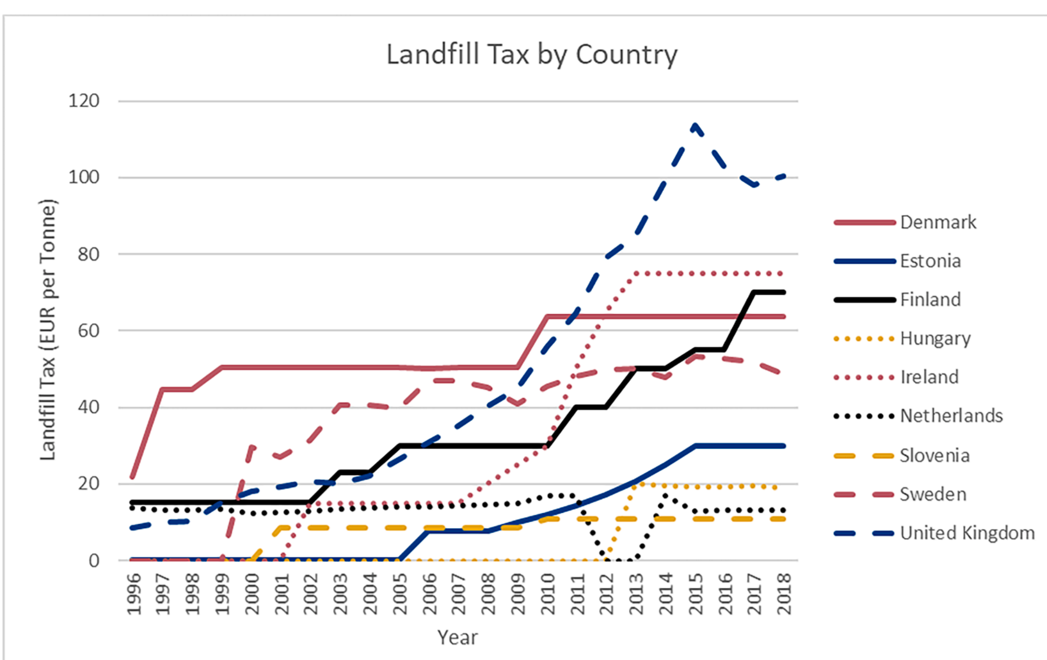

Fig. 1. The timing and value of landfill tax adopted by each country.

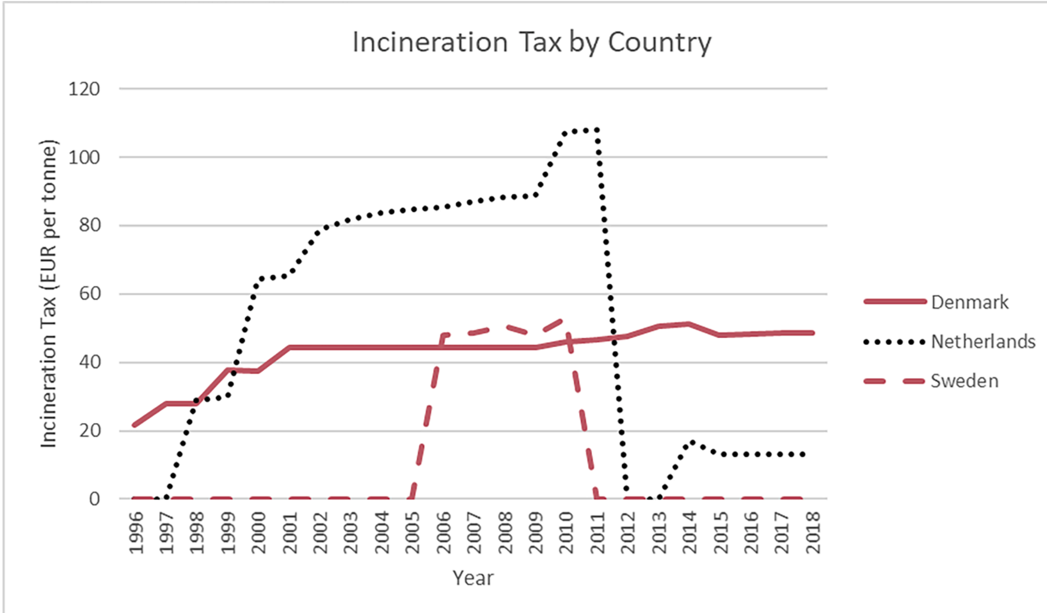

Fig. 2. The timing and value of incineration tax adopted by each country.

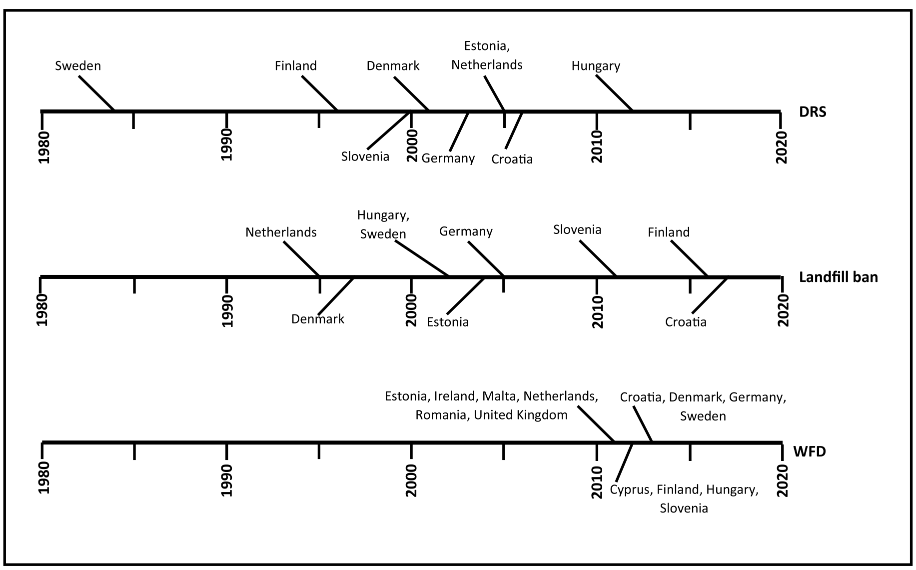

Fig. 3. Timeline of each country's implementation of the DRS, landfill ban and WFD.

2.024 million tonne increase in recycling waste. The positive sign of the recycling coefficient is also consistent with the findings from Papineschi et al. (2019).

The incineration tax is removed from the SUR model, as it had p-values greater than 0.4 in the single-equation FE regressions that preceded SUR estimation. Meanwhile, although the WFD is included in the SUR model, it is not observed to demonstrate a statistically significant correlation with the amount of waste at any of the waste treatment methods. Perhaps this could be due to insufficient variability in the variable, as the WFD was successfully transposed into national law by the end of 2012 by all member states besides Slovakia and Croatia (Tsiarta et al., 2015).

The DRS would be expected to divert waste from landfill, incineration, and energy recovery to recycling. Our results suggest some support of this effect, where the presence of the policy is associated with a 0.838 million tonne decrease in landfill waste, on average and holding other factors constant. The coefficients of the other waste treatment methods are not observed to be statistically significant in relation to the DRS policy.

Among the control variables, GDP per capita has a statistically significant negative correlation with the amount of landfill waste, yet a statistically significant positive association with the amount of incineration and recycling waste. GDP per capita can represent several factors, such as individual consumption and income, and would be expected to increase the amount of waste at each treatment method. The positive coefficients of incineration and recycling waste are, therefore, consistent with expectations, although the negative coefficient of landfill waste contradicts them.

The share of the population in urban areas is statistically significant at a 10% level and positively correlated with the amount of landfill waste, which matches expectations. Meanwhile, the proportion of the population aged 15 to 64 is statistically significant in determining the amount of energy recovery waste, where it was observed to have a negative correlation. This age group is representative of the

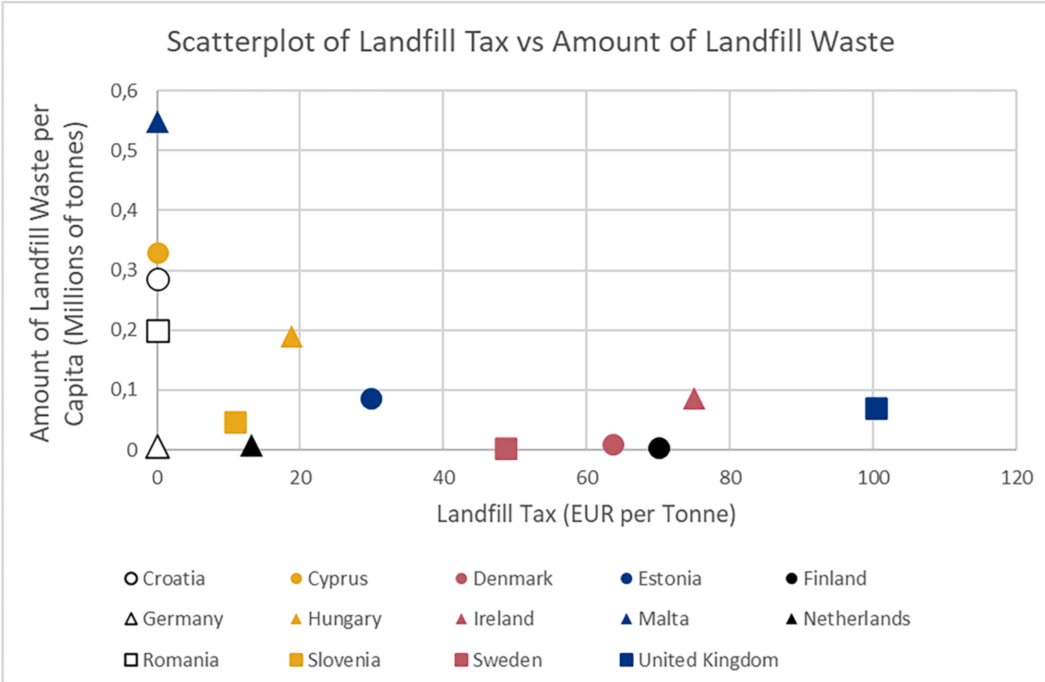

Fig. 4. Scatterplot of Landfill Tax vs the Amount of Landfill Waste Per Capita in 2018.

Table 2
Descriptive statistics.

Variable	Mean	Std. Dev	Min	Max
Amount of landfill waste	2.78	5.53	0.02	27.95
		4.83	0.19	18.22
		2.98	−10.83	17.24
Amount of incineration waste	0.85	2.59	0	13.78
		2.43	0	9.04
		1.10	−7.71	5.58
Amount of energy recovery waste	1.3	2.52	0	15.95
		1.87	0	5.64
		1.77	−4.28	11.61
Amount of recycling waste	3.58	7.82	0	34.96
		7.95	0.02	29.75
		1.52	−4.01	8.78
Amount of waste generated	8.64	14.14	0.16	53.97
		14.62	0.24	50.48
		0.89	4.59	12.13
Landfill tax	15.91	23.01	0.00	113.80
		18.28	0.00	52.05
		14.77	−28.45	85.35
Incineration tax	7.29	20.02	0.00	108.13
		16.56	0.00	49.50
		12.06	−42.21	65.92
GDP per capita	31.72	16.69	4.77	76.66
		16.68	7.53	57.89
		4.39	12.53	57.55
Proportion of population in urban areas	72.42	13.25	50.65	94.61
		13.58	52.16	93.45
		1.98	62.44	80.29
Proportion of population aged 15–64	66.98	1.80	62.13	70.75
		1.44	64.30	69.14
		1.15	63.21	68.88
Proportion of population enrolled in tertiary education	3.72	1.11	1.02	5.87
		0.89	2.26	5.43
		0.69	1.54	5.99
Population density	216.24	322.78	16.82	1514.47
		333.56	17.45	1293.01
		23.47	110.43	437.70
Total population	16.04	23.83	0.38	82.91
		24.68	0.41	81.96
		0.82	12.51	20.81

Table 3
Results from the SUR model displaying the coefficients, with p-values in parentheses. ***, ** and * indicate significance at a 1%, 5% and 10% level respectively.

	Landfill	Incineration	Energy recovery	Recycling
Landfill ban $_{t-1}$	−2.919 *** (0.000)	0.933 *** (0.000)	0.943 *** (0.000)	2.024 *** (0.000)
Landfill tax$_{t-1}$		−0.031 *** (0.000)	0.019 *** (0.000)	−0.064 *** (0.000)
DRS$_{t-1}$	−0.838 *** (0.008)			
WFD$_{t-1}$	0.554 (0.447)	−0.394 (0.251)	0.133 (0.683)	−0.372 (0.501)
GDP per capita	−0.060 *** (0.000)	0.047 *** (0.000)	0.010 (0.182)	0.114 *** (0.000)
Share of population in urban areas	0.054 * (0.029)	−0.016 (0.161)		−0.030 (0.131)
Share of population aged 15–64	−0.061 (0.581)	0.075 (0.235)	−0.150 ** (0.018)	
Enrolment in tertiary education	0.993 *** (0.000)	−0.219 * (0.051)	−0.058 (0.584)	−0.414 ** (0.029)
Population density	−0.001 (0.165)	0.000 (0.347)	0.001 * (0.070)	0.001 (0.232)
Total population	0.155 *** (0.000)	0.072 *** (0.000)	0.063 *** (0.000)	0.282 *** (0.000)
Time	−0.177 *** (0.001)	−0.004 (0.875)	0.047 ** (0.042)	0.122 *** (0.003)
Constant	355.787 *** (0.001)	3.124 (0.949)	−85.390 * (0.062)	−246.243 *** (0.003)
RMSE	3.691299	1.632955	1.542213	2.770515
Chi^2 statistic	430.44	479.48	558.23	2289.94
P	0.0000	0.0000	0.0000	0.0000

economically active population, where income, and therefore, consumption, are likely to be higher. Subsequently, one would anticipate that this group would have a positive effect on the amount of waste at each treatment method. In that context, the negative effect on the amount of energy recovery waste is unusual. However, other underlying factors could also be relevant here that might justify the negative effect. For instance, perhaps due to being economically active, this age group has less time to dedicate towards activities such as waste separation, instead finding landfill and incineration more convenient waste treatment destinations.

The proportion of the population enrolled in tertiary education is included in the model as an indication of the education level of the wider population. The expectation is that, as a population's education increases, the population's awareness of the implications of waste management practices also increases, resulting in parts of the population adapting their behaviour to dispose of waste using recycling or energy recovery treatment methods, for example, as opposed to landfill and incineration. The SUR results only partly support this effect, where education is negatively correlated with the amount of incineration. However, the positive correlation with landfill waste and the negative correlation with recycling waste would oppose the anticipated effect. Perhaps this is because the proportion of the population currently enrolled in tertiary education is not an effective indicator of the overall population's awareness of sustainable waste management practices.

Population density, where high density represents high opportunity costs in relation to land value, can be expected to be associated with a landfill diversion effect (Mazzanti et al., 2009). The increase in energy recovery in the SUR results appears to be consistent with this expectation where the results estimate that, on average and keeping other factors fixed, a 1% increase in population density is associated with a 0.001 million tonne increase in the amount of energy recovery waste.

The size of the population, on the other hand, would be expected to be associated with an increase in waste at all treatment methods, and this effect is confirmed in the results. Meanwhile, the time trend suggests that it is negatively correlated with the amount of landfill waste, yet positively correlated with the amount of recycling and energy recovery waste. This means that the amount of landfill waste decreases over time, and this decrease is not attributed to the other variables in the model. In contrast, the amount of recycling and energy recovery waste increase over time, regardless of the other variables in the model.

Initial results from the FE model exploring the impact of factors on the amount of waste generated are used to exclude variables with a p-value greater than 0.4, since the inclusion of these variables only inflate the standard errors and inaccuracy of the model. The results from the refined FE model, following the exclusion of irrelevant variables, are presented in Table 4.

The results indicate that landfill tax, incineration tax, and DRS policies are all highly significant among the policy variables. More precisely, on average and keeping other factors fixed, a 1 EUR increase per tonne in the landfill tax is associated with a 0.009 million tonne decrease in the amount of waste generated. Meanwhile, a 1 EUR increase per tonne in the incineration tax is associated with, on average, a 0.01 million tonne increase in the amount of waste generated, assuming other factors are held fixed. The equivalent coefficient for the DRS suggests that its presence is correlated with a 0.404 million tonne decrease in the amount of waste generated.

Table 4
Variables impacting the amount of waste generated.

Variable	Coefficient	Standard error	P-value
Landfill tax_{t-1}	−0.009 **	0.005	0.042
Incineration tax_{t-1}	0.010 **	0.004	0.015
DRS_{t-1}	−0.404 **	0.179	0.025
GDP per capita	0.077 ***	0.019	0.000
Proportion of population in tertiary education	0.296 ***	0.092	0.001
Time trend	−0.0519 ***	0.015	0.000
Constant	109.584 ***	28.966	0.000
AIC = 799.9223; BIC = 826.3441; R2 within = 0.1433			

The expected sign of the tax policies is unclear, as highlighted in section 3. The complication arises due to municipal or regional differences in how the tax is forwarded to individuals and households. However, we reasoned that at least some cost-forwarding could take place at an aggregated level in countries where the taxes are adopted, so the tax coefficients could be expected to be negative. The negative coefficient of the landfill tax therefore matches expectations. However, the positive coefficient of the incineration tax, on the other hand, contradicts expectations. Fig. 2 in section 3.2 indicates that the data for the incineration tax may suffer from a case of insufficient variability, as the tax is only implemented in Denmark, the Netherlands and Sweden, among the 14 countries explored in this study. This suggests that the coefficient for the incineration tax may not be reliable.

Re-estimating the model without the incineration tax does not significantly change the results, demonstrating that the other coefficients in the model remain robust. For the DRS variable, a negative sign is observed, although as explained in section 3, a positive or negative sign could have been expected.

Among the control variables, GDP per capita is highly significant. The results suggest that, on average and keeping other factors constant, a 1000 US dollar (constant 2010) increase in GDP per capita is associated with a 0.077 million tonne increase in the amount of waste generated. This result seems intuitive since GDP per capita is often used to represent consumption, and an increase in consumption would result in an increase in the amount of waste generated.

The coefficient for the final control variable, the proportion of the population enrolled in tertiary education, does not have the expected sign, despite being statistically significant. In general, one would expect that a more educated population is increasingly aware of the consequences of consumption, reducing its waste generation. However, the results suggest that, on average and holding other factors fixed, a 1% increase in the proportion of the population enrolled in tertiary education is correlated with a 0.296 million tonne increase in the amount of waste generated. Again, this could be due to the variable not representing an efficient indicator of the wider population's knowledge of waste management practices. The time trend, meanwhile, indicates that the amount of waste generated decreases with time due to reasons such as technical innovation.

A limitation of the findings in both the SUR and FE regression models is that the quality of the data from Eurostat may be inconsistent. For instance, the definition of municipal waste can vary, with some countries only including waste from households, in contrast with other countries where waste from offices is also included (EEA, 2016; Eunomia Research & Consulting, 2017). Other data issues include significant margins of error in packaging waste data, inadequate data capture processes, and the missing whereabouts of more than 25% of all end-of-life vehicles (Eunomia Research & Consulting, 2017).

For each model presented in this study, several alternative specifications are compared and validated for robustness, such as different extents of lags for the policy variables to acknowledge the possibility that the effects of policies may take a short while to be realised, normalisation of the dependent variables for alternative ways to account for the size of the population, the exploration of various interactions among the policy variables, and the removal of control variables in a stepwise manner to determine if any significant changes to other coefficients ensued. The results from each of these alternative specifications did not differ greatly, demonstrating that the results in each of the models presented are reasonably robust. The models presented in this study are selected based on accuracy measures such as R^2, Akaike Information Criteria and Bayesian Information Criteria.

5. Conclusions

This study explored the implications of landfill tax, landfill ban, incineration tax, and Deposit Refund Scheme (DRS) policies on the amount of waste generated and the amount of waste treated with landfill, incineration, energy recovery and recycling, in 14 European countries over a period of 23 years (1996 to 2018). Two econometric models were developed to evaluate the panel dataset. Firstly, the seemingly unrelated regressions model presented some mixed results. The landfill ban was related to a decrease in landfill waste, and an increase in incineration, energy recovery and recycling waste, which are consistent with expectations. Furthermore, the landfill tax was associated with an increase in energy recovery waste too. However, the landfill tax was correlated with a decrease in recycling waste, which contradict the anticipated findings. The DRS policy also demonstrated favourable behaviour with its negative association with the amount of landfill waste. Meanwhile, the fixed effects model suggested that the landfill tax and the DRS policies were associated with a negative effect on the amount of waste generated.

This study contributes to the scarce literature on the implications of waste management policies in relation to the amount of waste generated and the amount of waste treated with landfill, incineration, energy recovery and recycling. Furthermore, the adoption of a SUR model represents a unique approach in academic literature for analysing the effects of waste management policies.

A limitation of the study is that there are relatively few, only 14, countries in the panel. Furthermore, by using results from a fixed effects model, a disadvantage is that the between variation in the data are not accounted for. In addition, although the data used in the present study are aggregated at the national level, it would have been preferable to use disaggregated data, if available.

Besides the variables included in this study, several other factors could also be relevant. The importance of individual attitudes, values, and personality traits (Guerin et al., 2001; Lee and Paik, 2011; Strydom, 2018; van den Bergh, 2008), altruism (Yokoo et al., 2018), as well as political interest and alignment (Seacat and Boileau, 2018; van den Bergh, 2008) have been recognised in some academic literature. Meanwhile, other studies highlight social capital and social norms (Czajkowski et al., 2019; Strydom, 2018), local crime levels (D'Amato et al., 2015), distance to waste collection points (Czajkowski et al., 2014; Strydom, 2018), and past recycling behaviour (Goldenhar and Connell, 2005; Guerin et al., 2001; Seacat and Boileau, 2018) as considerable factors. If data for these variables becomes available in the future, they may represent interesting areas of future research. Future research may also explore the effects the involvement of other policies in the waste management or wider environmental domain, or the adoption of different methodologies.

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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.

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