Compliance with the EU Waste Hierarchy:
A matter of stringency, enforcement, and time

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Abstract

This paper assesses whether and to what extent income and the stringency and enforcement (S&E) of environmental regulation influence compliance with the EU Waste Hierarchy (EWH), i.e., how EU member states treat waste. The EWH prioritizes waste prevention and re-use over recycling, which is ranked above waste to energy (WtE), while incineration and landfilling are the least preferred options. Biennial panel data for the period 2010–2016 is used to create a compliance index based on the waste treatment alternatives in the EWH. The waste (excluding major mineral waste) of 26 European Union countries is examined. This study is the first of its kind to regress an EWH compliance index on income, the stringency and enforcement of environmental regulation, and other variables that are also expected to affect the relative benefits and costs of waste treatment, such as population density, heating demand, and electricity prices. The shares of landfilling, incineration, WtE, and recycling are also modeled to capture the effect of these variables in the waste treatment mix. The stringency and enforcement of environmental regulation are found to have a positive effect on compliance with the EWH, which has increased over time.

Keywords: EU waste hierarchy, waste treatment ladders, income, policy stringency, policy enforcement.

Highlights:

- A compliance index is created based on the waste treatment ladders of the EU Waste Hierarchy.
- Higher stringency and the enforcement of environmental regulation are related to less landfilling.
- Compliance with the EU Waste Hierarchy has increased over time.

1. Introduction

This paper investigates the effect of income and the stringency and enforcement (S&E) of environmental regulation on how waste is treated, in particular regarding compliance with the EU Waste Hierarchy (EWH). The EWH is a crucial part of the EU Action Plan for the Circular Economy. It establishes a hierarchy of priorities for how waste should be treated. According to the Directive 2008/98/EC on waste, hereinafter the EU Waste Framework Directive, countries should take into consideration the hierarchy illustrated in Appendix A, i.e., the EWH. Waste prevention and re-use are at the top of the hierarchy, followed by material recycling, waste to energy (WtE), with disposal methods such as incineration and landfilling listed as the last resorts. By following this directive, countries can design and implement policies to promote a shift towards the upper levels of the hierarchy.[1]

The EWH is a top-down policy guideline that EU member states must follow in line with the Waste Framework Directive. However, countries differ concerning income levels, the stringency and enforcement of environmental regulation, and other aspects, e.g., population density and heating demand. Country-specific characteristics such as these likely influence the cost-benefit structure of waste treatment options and, in turn, levels of compliance with the EWH.[2] The objective of this paper is to estimate if and how these country-specific characteristics affect the waste treatment mix of EU member states and their compliance with the EWH. To this end, an EWH compliance index was constructed and regressed on the countries' characteristics. A system of seemingly unrelated regression equations (SURE) was also estimated to show if and how the characteristics mentioned above influence the waste treatment mix, determined

[1] The focus of this paper is on the ladders of the EWH concerning waste treatment, i.e., landfilling, incineration, WtE, and recycling. Waste prevention and re-use are beyond the scope of this study.

[2] According to EU Directive 2008/98/EC (Article 4: Waste Hierarchy, numeral 4, last paragraph): "Member States shall take into account the general environmental protection principles of precaution and sustainability, technical feasibility and *economic viability*, protection of resources as well as the overall environmental, human health, economic and social impacts..." (emphasis mine).

by the shares of landfilling, incineration, WtE, and recycling. The data used in the analyses was biennial panel data for the period 2010–2016.

The literature has examined the determinants of waste treatment, mainly in the context of substituting landfilling with other waste treatment options such as incineration or recycling.[3] However, compliance with the EWH goes beyond diversion from landfilling because WtE and recycling are alternative waste treatment methods with different rankings in the EWH. To accommodate this, a composite indicator to explicitly address the question of compliance with the EWH is required.

This paper adds to the literature by constructing a waste hierarchy compliance index. This index is based on different weights assigned to the share of waste that is recycled, recovered as WtE, incinerated, and landfilled. The compliance index is then regressed on country-specific characteristics that include GDP per capita, the stringency and enforcement of environmental regulation, population density, heating demand, and electricity prices. By doing so, this paper complements recent attempts to capture compliance with the EWH in an indicator (Castillo-Giménez et al., 2019; Pires and Martinho, 2019).

Countries treat waste in different ways because the relative costs between waste treatment alternatives differ.[4] As Marin et al. (2018) accurately summarize, the empirical literature highlights the effect of income, environmental policy, and population density in diversion from landfilling in favor of alternative waste treatment methods. Income affects the relative costs of waste treatment options because of the role it plays in technological progress and social preferences towards the environment (Johansson and Kriström, 2007; Karousakis, 2009). Hereinafter, pro-environmental social preferences imply that while the marginal utility of

[3] See, e.g.: Antonioli et al. (2018); Ichinose et al. (2011); Karousakis (2009); Marin et al. (2018); Mazzanti et al. (2009a, 2009b); Mazzanti & Zoboli (2008); Nicolli et al. (2012).
[4] Tradition, habits, culture, and social norms also play a role, especially with respect to recycling behavior, which affects how waste is treated. See also: Crociata et al. (2015); Henriksson et al. (2010); Kirakozian (2016).

income decreases, the marginal utility of the environment increases. As the marginal utility of the environment increases, society favors stringent and enforceable environmental regulations.

Stringency refers to the strictness or tightness of a regulation, e.g., high environmental taxes. Enforcement refers to the mechanisms and institutions in place to enforce compliance with the regulations. Enforcement is related to the collection mechanisms for environmental taxes, for instance. Both stringency and enforcement have an impact on the effectiveness of a regulation. For example, enforcement mechanisms may be very tough due to the rule of law, but nevertheless, regulations may remain lax, e.g., low environmental taxes. Likewise, high environmental taxes may be stringent, but weak enforcement institutions will affect the overall effectiveness of the policy instrument.

If an environmental policy is in line with the Waste Framework Directive, its purpose is to affect the relative prices for waste treatment options and promote the most preferred methods in the EWH, i.e., recycling over WtE, and WtE over incineration and landfilling. Population density affects the relative costs of waste treatment options because of changes in the opportunity cost of land and the marginal costs of waste separation and collection due to economies of scale (Berglund and Söderholm, 2003; Berglund et al., 2002; Johnstone and Labonne, 2004; Nicolli et al., 2012).

As mentioned before, previous empirical studies have mainly focused on diversion from landfill, where there is evidence that income, environmental policy, and population density play a role. However, by not addressing WtE explicitly as a dependent variable, some determinants can be overlooked. This paper adds to the literature by incorporating heating demand and electricity prices as regressors in the econometric estimations. These variables may affect the competitiveness of WtE. Some WtE plants generate heat for local district heating networks. Therefore, the heating market plays an important role, and heating demand cannot be dismissed. The electricity price also affects WtE in different ways. Some

WtE plants are combined heat and power (CHP) plants, where electricity is a byproduct, while others can only supply electricity using, for example, biogas. Higher electricity prices will incentivize the production of electricity. Another reason for analyzing electricity prices is that district heating competes with other heating sources, such as heat pumps, in a broader heating market. Heat pumps require electricity to run, and higher electricity prices will, *cæteris paribus*, reduce the relative price of district heating.

The paper is structured as follows. The theoretical framework is presented in section 2. A review of the empirical literature is set out in section 3. In section 4, the data and methods are described. Results are reported in section 5. The main conclusions and discussion are summarized in section 6.

2. Theoretical framework

From an economic perspective, countries choose how to treat their waste, considering the present value of private and social costs and benefits of different alternatives (Rasmussen et al., 2005). Theoretically, this implies an optimal amount of landfilled, incinerated, WtE, and recycled waste. Brisson (1997) proposes a simple theoretical framework to obtain the optimal distribution of recycling, incineration, and landfilling. The intention of the policymaker within this framework is to minimize the Net Social Costs (NSC) of waste treatment. Considering the waste treatment methods in the EWH, the optimality condition follows the equi-marginal condition where the marginal net social cost (MNSC) is equal for all the waste treatment alternatives. See equation (1).

$$MNSC_{Landfill} = MNSC_{Incineration} = MNSC_{WtE} = MNSC_{Recycling} \qquad \text{Eq. (1)}$$

However, there remains the challenge of deriving benefit and cost functions for each option. A full valuation of the private and social costs and benefits is not always achievable. Instead, one can think that country characteristics, such as the ones evaluated in this paper, directly or indirectly affect the benefits and costs of treating waste. See equation (2).

$$NSC(W_i) = Costs_i\big(W_i(CC)\big) - Benefits_i\big(W_i(CC)\big) \qquad \text{Eq. (2)}$$

Where i represents each of the waste treatment methods in the EWH and CC is a set of country characteristics that affect the cost and benefits structure of the system, i.e., the relative costs. The model above serves as a theoretical basis for this paper because the marginal net social costs of each of the alternatives that define the equi-marginal optimality condition are intrinsically affected by a set of country-specific characteristics, CC. Since the waste treatment options are substitutes, changes in their relative costs and benefits will also affect compliance with the EWH.

As in Brisson (1997), the equi-marginal principle between waste treatment alternatives is the basis of other theoretical contributions such as those mady by Highfill and McAsey (2001), Conrad (1999), Huhtala (1997), Goddard (1995), and Pearce and Turner (1993). Highfill and McAsey (2001) have modeled the optimal level of consumption or waste treatment (either recycling or landfilling) of a representative municipality when income is growing. They have shown that wealthier municipalities are more likely to favor recycling over landfilling because the marginal value of landfilling is higher in less wealthy municipalities, i.e., the marginal cost of landfilling is higher in wealthier municipalities. Conrad (1999) has modeled the role of policy in the relative costs of waste treatment alternatives from a firm's perspective. He compares the impact of taxing virgin materials versus taxing waste disposal in the relative costs of recycling and demonstrates that taxes on virgin materials are more effective on promoting recycling than taxes on waste disposal. The reason for this is that the value of recycled material increases as virgin materials become more expensive with the tax. Lokrantz (2019) has used a computable general equilibrium (CGE) framework to show the effect of taxes and technological shifts in the EWH. Her simulations suggest that taxes that comply with the EWH may reduce waste generation.

The models of Highfill and McAsey (2001), Conrad (1999), and Lokrantz (2019) demonstrate that country-specific characteristics such as income, taxes, and landfill space affect the relative benefits and costs of waste treatment options, and, therefore, societal optimal choices. In this paper, income, the stringency and enforcement of environmental regulation, and population density are some of the country characteristics that are expected to affect how to treat waste and compliance with the EWH.

3. Review of the empirical literature

Income and waste treatment

Waste treatment methods such as recycling and WtE require more advanced technology and infrastructure to be cost-effective than traditional waste disposal methods such as landfilling or incineration. Wealthier countries may be more likely to afford the development of WtE and recycling infrastructure, and the relative value of the environment increases with income due to the decreasing marginal utility of income (Johnstone and Labonne, 2004; Karousakis, 2009).

Empirical research that examines the relationship between income and waste treatment commonly refers to the Environmental Kuznets Curve (EKC). These studies often find a negative (Karousakis, 2009; Mazzanti et al., 2009a, 2009b) or inverted U shape relationship between income and landfilling (Ichinose et al, 2011; Mazzanti and Zoboli, 2008; Nicolli et al., 2012). The geographic scope varies among these studies: Mazzanti and Zoboli (2008) and Nicolli et al. (2012) use EU data; Karousakis (2009) uses data from the Organisation for Economic Co-operation and Development (OECD); Ichinose et al. (2011) use municipal-level data for Japan; and Mazzanti et al. (2009a, 2009b) use provincial-level data for Italy.

Huhtala (1999) has found a positive relationship between income and incineration, and Mazzanti and Zoboli (2008) have found a U shape relationship. Marin et al. (2018) have found no statistically significant relationships between income and waste treatment in the EU; however, recycling and incineration patents explain changes in the share of recycling and incineration (including WtE). In Marin et al. (2018), income and technological progress captured by the patent variables can be correlated.

The literature shows that the relationship between income and recycling can be positive or negative. Technological progress and pro-environmental preferences, due to the decreasing marginal utility of income, may explain a positive relationship between income and recycling. However, recycling may be more labor-intensive than other waste treatment methods, and countries with higher incomes have higher labor costs (Berglund and Söderholm, 2003; Berglund et al., 2002). From the household perspective, as income increases, the opportunity cost of the time and effort needed for recycling increases too (Huhtala, 1999). The net effect of the relationship between income and recycling remains an empirical question, as noted by Berglund and Söderholm (2003) and Berglund et al. (2002). Huhtala (1999) has found a negative relationship between income and recycling in Finnish households, while Karousakis (2009) has found a positive relationship between income and the recycling of municipal solid waste (MSW) in OECD countries. Berglund and Söderholm (2003) and Berglund et al. (2002) have shown a positive relationship between income and paper recovery in more than 80 countries worldwide.

Stringency and enforcement of environmental policy in waste treatment

Waste policies can increase compliance with the EWH because they affect the relative costs and benefits of waste treatment to promote some options over others. EU membership entails the implementation of directives into national legislation. Therefore, it is reasonable to assume that environmental policies are in line with the EWH in the Waste Framework Directive. Countries are free to choose different policy instruments to affect the marginal costs of waste treatment, so that recycling becomes cheaper than WtE, and WtE becomes cheaper than incineration and landfilling. Examples of these policies are: landfill and incineration taxes (or regulatory bans); technology standards that directly increase the marginal cost of landfilling or incinerating; disposal fees, or curbside recycling programs that reduce the relative costs of sorting waste; or capital grants for WtE and recycling infrastructure (Kinnaman, 2009; Werner, 2017).

While data on income and population density is generally comparable between countries and is available from official statistics, studies differ in terms of how they model environmental policy. Local studies such as Antonioli et al. (2018) and Mazzanti et al. (2009a, 2009b) in Italy, Ichinose et al. (2011) in Japan, or Dijkgraaf and Gradus (2017) in the Netherlands, account for local instruments such as landfill taxes, waste tariffs, or sorting systems. Conversely, studies analyzing many countries, such as Marin et al. (2018), Mazzanti and Zoboli (2008) and Nicolli et al. (2012) in the EU, and Karousakis (2009) in the OECD countries, use environmental policy indexes to reflect the implementation of environmental policy. The policy indexes used in many studies with data from EU members use weights based on the countries' level of implementation or the impact of the policies compiled by the European Environment Information and Observation Network (EIONET). Similarly, Karousakis (2009), who studied OECD countries, used the European Environment Agency's waste legislation and policy index, which assigns scores based on the level of implementation of different instruments.

Results of these studies confirm a negative relationship between environmental policy and landfilling (Antonioli et al., 2018; Ichinose et al., 2011; Karousakis, 2009; Mazzanti et al., 2009a, 2009b;[5] Mazzanti and Zoboli, 2008; Nicolli et al., 2012), and a positive relationship between environmental policy and alternative waste treatment methods (Antonioli et al., 2018; Dijkgraaf and Gradus, 2017; Marin et al., 2018; Mazzanti and Zoboli, 2008). Karousakis (2009) has found a

[5] In this case, waste management tariffs were a more effective policy driver for landfill diversion compared with landfill taxes, which do not show a statistically significant relationship, probably due to the low level of enforcement (Mazzanti et al., 2009a, 2009b).

negative relationship between environmental policy and recycling in the OECD countries. The author argues that this unexpected result may be due to the time-invariant nature of the environmental policy index used to measure policy enforcement.

The stringency and enforcement of environmental policies and regulations are a result of social preferences towards the environment. Therefore, the S&E indicator used in the present paper reflects these preferences and not the effect of the implementation of specific waste policies as used in the previous literature.

Population density and waste treatment

If the amount of land is scarce, and population density is high, the opportunity cost of landfilling is high, so alternative waste treatment methods become more competitive. In contrast, if land is abundant and population density is low, waste disposal becomes cheaper because of the higher transportation and logistical costs of collecting waste for WtE or recycling. However, it is important to note that waste disposal can be either landfilling or incineration without energy recovery. Therefore, even though higher population density in urbanized areas may help to reduce the costs of collection and sorting for recycling, these benefits must offset the net costs of incineration. Incineration partially addresses the space issue characteristic of landfills. Another aspect to take into consideration is that incineration may cause local pollution and discomfort in highly populated areas. However, technological solutions such as tall flue-gas stacks can address this inconvenience.

Previous empirical evidence confirms a negative relationship between population density and landfilling (Antonioli et al., 2018; Ichinose et al., 2011; Karousakis, 2009; Mazzanti et al., 2009a, 2009b; Mazzanti and Zoboli, 2008; Nicolli et al., 2012) and a positive relationship between population density and incineration (Antonioli et al., 2018; Mazzanti and Zoboli, 2008). Mazzanti and Zoboli (2008) have found a negative relationship between population density and recycling, mainly driven by a substitution effect from incineration, where a positive relationship with population density was confirmed. Berglund and Söderholm (2003), Berglund et al. (2002), and Karousakis (2009) have found a positive relationship between population density and recycling, probably driven by reduced costs for collection and sorting for recycling in countries with higher population density. The study by Antonioli et al. (2018) did not find a statistically significant relationship between population density and recycling, but the relationships of population density with landfilling and incineration were significant, as stated before. Marin et al. (2018) did not find a statistically significant relationship between population density and any of the analyzed waste treatment methods. The authors argue that their findings may be driven by how population density can play a role in waste generation, but not in treatment choices. However, as noted previously, other studies have found evidence of the effect of population density on waste treatment.

Considering the arguments presented in this and the previous section, Table 1 collates some initial hypotheses about the relationships between country characteristics (independent variables) and compliance with the EWH and its waste treatment ladders (dependent variables).

Table 1: Summary of hypotheses

Dependent Variables Independent Variables	Compliance Index	Share of Landfilling	Share of Incineration	Share of WtE	Share of Recycling
GDP per capita	+	(-		+)	±
Environmental regulation (S&E)	+	(-			+)
Population density	±	(-		+)	±
Heating degree days	±			+	
Electricity price	±			+	

4. Data and methods

This paper relies on data from Eurostat and the World Economic Forum (WEF). The analyzed country characteristics and waste treatment data were obtained from Eurostat's open-access databases. The environmental regulation stringency and enforcement indicators were obtained from the WEF. The dataset was a balanced panel for 26 EU member states with biennial observations for the period 2010–2016.[6] This timeframe was convenient as the Waste Framework Directive dates back to 2008.

The waste category in this study is classified as non-hazardous and includes total waste (excluding major mineral waste).[7] Excluding major mineral waste increases the degree of comparability of countries. Countries with different characteristics treat waste heterogeneously. For example, countries such as the Netherlands, Denmark, Belgium, or Sweden landfill less than 10% of their total waste, while more than 60% is landfilled in countries like Romania, Cyprus, Bulgaria, and Greece. The frontrunners in WtE are Finland, Sweden, and Denmark, who recover nearly half of their waste in the form of energy. For comparison, Cyprus, the UK, Italy, Bulgaria, Croatia, or Greece recover less than 5% in the form of WtE. See Figure 1.

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[6] Luxembourg and Malta were excluded from the EU28 dataset, given their outlier characteristics. EU28 countries include Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, and the United Kingdom.

[7] In the remainder of this paper, total waste will be used to refer to total waste (excluding major mineral waste) unless stated otherwise. For further details on the classification and definition of this waste category and its treatment, see chapter 2 in Eurostat (2013).

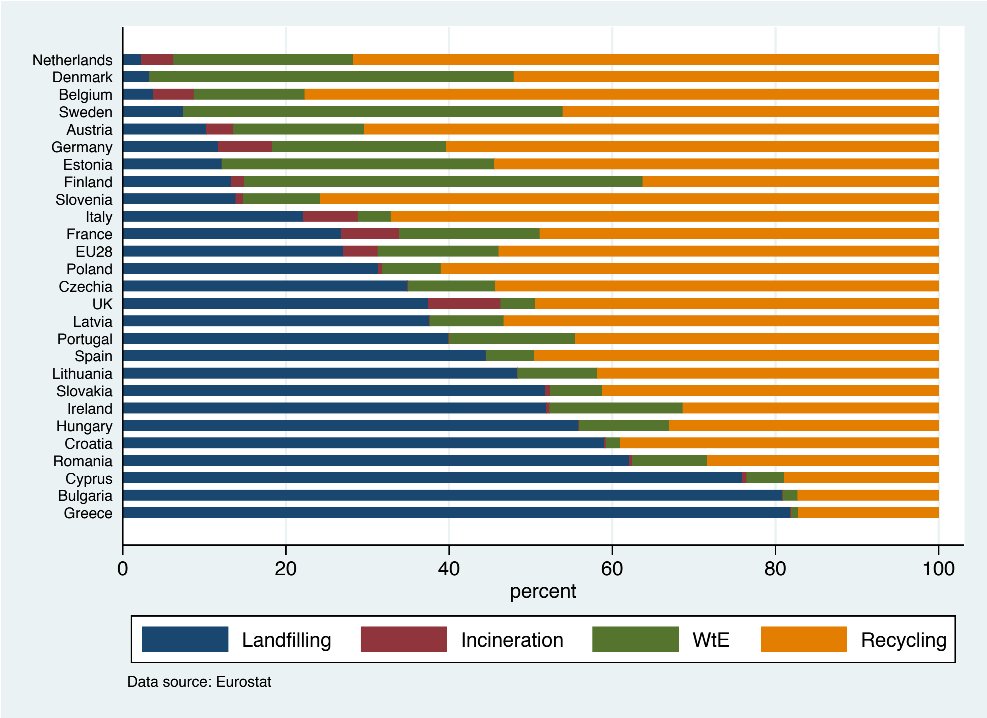

Figure 1: Treatment of total waste by country (2010–2016)

One of the key features of this paper is the construction of a waste hierarchy compliance index based on the shares of landfilling, incineration, WtE, recycling, and specific weighting coefficients to reflect the hierarchies in the EWH.[8] See equation (3).

$$CI = W_D(L + I) + W_E(E) + W_R(R) \qquad \text{Eq. (3)}$$

Where:

CI = Compliance index

L = Landfilled waste (tons) / Total treated waste (tons)

I = Incinerated waste (tons) / Total treated waste (tons)

E = WtE (tons) / Total treated waste (tons)

R = Recycled waste (tons) / Total treated waste (tons)

W_D = Weighting coefficient for waste disposal

W_E = Weighting coefficient for WtE

W_R = Weighting coefficient for recycling

[8] For the sake of simplicity, the waste generation component has been omitted from the construction of this index, which is limited to the waste treatment alternatives of landfilling, incineration, WtE, and recycling, which are substitutable.

An underlying assumption is that all waste is treated in one of four alternative ways. Therefore, total treated waste is the sum of landfilling, incineration, WtE, and recycling. The weighting coefficients were exogenously assigned based on the hierarchical order of the waste hierarchy, and different scenarios were considered in a sensitivity analysis. First, landfilling and incineration were considered as disposal operations with $W_D = 1$, followed by WtE with $W_E = 2$ and recycling with $W_R = 3$. In this baseline scenario, the maximum possible value of CI is 3 in the event that 100% of waste is recycled. However, this scenario undertakes a linear reward (Δ= 1) between disposal, WtE, and recycling. Non-linear scenarios include:

- Pro-recycling scenario, where material recycling is rewarded with a higher relative weight, keeping the same weights for waste disposal and WtE as in the baseline scenario. In this scenario, $W_D = 1;\ W_E = 2;\ W_R = 4$.
- Anti-landfill scenario, where landfilling is punished disproportionally compared to WtE and recycling. In this scenario, $W_D = 1;\ W_E = 3;\ W_R = 4$.
- Combined exponential scenario, where the relative weights for landfilling and WtE are the same as in the previous anti-landfill scenario, but recycling is rewarded more than proportionally. In this scenario, $W_D = 1;\ W_E = 3;\ W_R = 6$.

Figure 2 shows a comparison of the countries' compliance index for the anti-landfill scenario. Belgium and the Netherlands are the frontrunners in the figure with the highest CI, while Greece, Bulgaria, and Cyprus have the lowest CI.

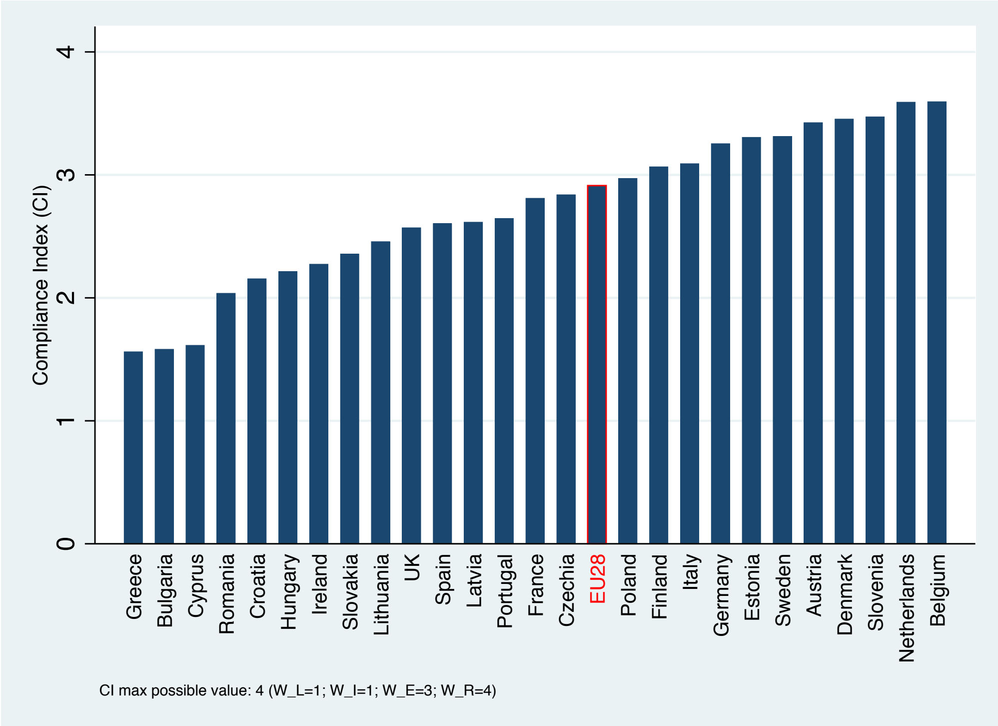

Figure 2: Waste hierarchy compliance index (CI) by country

Pires and Martinho (2019) have proposed a waste hierarchy index similar to the one proposed in this paper but with different weighting coefficients for the waste treatment alternatives. They use a weighting coefficient of 1 for waste treatment options that contribute to the circularity of materials, and -1 for alternatives against the circular economy. This index aims to capture circularity. However, as the authors state, "the energy recovered by incineration can only be used once, which limits the circularity of materials in the economy." Therefore, computing this index requires either knowledge of which fraction of WtE contributes to the circular economy or assumptions about these fractions. Alternatively, they propose a streamlined index where recycling has a weighting coefficient of 1 and incineration and landfilling have -1. The downside of this version of the index in the context of the EWH is that it weights WtE in the same way as waste disposal (incineration and landfilling). However, WtE has a higher priority in the EWH, listed between recycling and waste disposal.

Castillo-Giménez et al. (2019) have used another index. They use data envelopment and multi-criteria analysis to assign weights to different waste treatment options and to generate a composite performance index. Their results show that the best performers were Denmark, Austria, and Germany, and the worst performers were most of the Eastern European countries. However, this performance index does not necessarily reflect compliance with the EWH, although they can be correlated. One reason may be that the weights are endogenously determined by how much waste per capita a country treats in a certain way, compared to other countries. The resulting weights used by Castillo-Giménez et al. (2019) to build their performance index were landfill (0.048), incineration including WtE (0.407), recycling (0.103), and composting and digestion (0.442). In this scenario, material recycling has a lower weight than incineration, while recycling has a higher priority in the EWH. Moreover, incineration with and without energy recovery are equally weighted, while in the EWH, incineration without energy recovery has the lowest priority along with landfilling.

Besides waste treatment and compliance, there is also heterogeneity in the analyzed country characteristics. Table 2 shows the descriptive statistics of the dependent and independent variables. The variation between countries in the figure is higher than the variation within countries (over time). For example, the GDP per capita can be nearly four times lower in Eastern European countries such as Poland, Hungary, Croatia, and Latvia, than in Sweden and Denmark. The environmental regulation S&E indicator has values from below 8 (out of 14) in countries such as Bulgaria, Croatia, Greece, Hungary, Italy or Romania, and up to above 12 in countries such as Austria, Denmark, Finland, Germany, the Netherlands, and Sweden. Population density also differs. The Netherlands and Belgium are at the top of the list and can be more than 20 times denser than countries like Finland and Sweden. Heating degree days (HDD) in some years can be as low as 500 in Cyprus or above 5,000 in Finland and Sweden. Electricity prices can be up to 3 times cheaper in Eastern European countries than in Germany and Denmark.

Concerning independent variables, GDP per capita in 2010 thousand EUR represents income.[9] Population density is the average population per km^2.[10] Heating degree days (HDD) is a measure of the heating requirement. HDD is calculated according to the following condition: if $T_M \leq 15°C$, then $\left[HDD = \sum_i (18°C - T_M^i)\right]$; else $[HDD = 0]$. Where T_M^i is the mean air temperature of day i.[11] The electricity price is the average price (cent.EUR/kWh) for household consumption between 2,500 and 5,000 kWh per year.[12] This indicator excludes all taxes and levies because it aims to capture the net value that the energy companies receive to make decisions on WtE.

Table 2: Descriptive statistics

VARIABLES		Mean	SD	Min	Max	Observations
Independent variables						
GDP per capita (2010 EUR x 1000)	Overall	22.90	12.23	5.10	53.10	N = 104
	Between		12.32	5.48	44.80	n = 26
	Within		1.48	17.43	33.73	T = 4
Environmental regulation stringency	Overall	5.08	0.83	2.98	6.62	N = 104
	Between		0.82	3.35	6.30	n = 26
	Within		0.18	4.54	5.56	T = 4
Environmental regulation enforcement	Overall	4.70	0.97	2.81	6.38	N = 104
	Between		0.97	3.15	6.22	n = 26
	Within		0.19	4.31	5.17	T = 4
Environmental regulation (S&E)	Overall	9.78	1.78	5.79	13.01	N = 104
	Between		1.77	6.50	12.47	n = 26
	Within		0.35	9.07	10.73	T = 4
Population density (persons/km^2)	Overall	127	107	18	501	N = 104
	Between		109	18	497	n = 26
	Within		2	119	134	T = 4
Heating degree days	Overall	2987	1170	496	6191	N = 104
	Between		1154	629	5657	n = 26
	Within		273	2493	3621	T = 4
Electricity price (cent.EUR/kWh)	Overall	12.37	3.27	6.92	24.14	N = 104
	Between		3.06	7.54	18.87	n = 26
	Within		1.25	6.96	18.25	T = 4

[9] Eurostat uses chain-linked volumes. See https://ec.europa.eu/eurostat/cache/metadata/en/nama10_esms.htm
[10] See https://ec.europa.eu/eurostat/cache/metadata/en/demo_r_gind3_esms.htm
[11] See https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm
[12] See https://ec.europa.eu/eurostat/cache/metadata/en/nrg_pc_204_esms.htm

VARIABLES		Mean	SD	Min	Max	Observations
Dependent variables						
Compliance index	Overall	2.10	0.41	1.21	2.81	N = 104
(W_D=1; W_E=2; W_R=3)	Between		0.39	1.37	2.68	n = 26
	Within		0.14	1.44	2.55	T = 4
Compliance index	Overall	2.58	0.59	1.31	3.68	N = 104
(W_D=1; W_E=2; W_R=4)	Between		0.56	1.55	3.46	n = 26
	Within		0.21	1.59	3.26	T = 4
Compliance index	Overall	2.73	0.65	1.33	3.75	N = 104
(W_D=1; W_E=3; W_R=4)	Between		0.63	1.56	3.60	n = 26
	Within		0.21	1.73	3.40	T = 4
Compliance index	Overall	3.68	1.00	1.53	5.47	N = 104
(W_D=1; W_E=3; W_R=6)	Between		0.95	1.92	5.14	n = 26
	Within		0.35	2.03	4.82	T = 4
Landfilling / Total treatment	Overall	35.62	25.45	1.47	88.56	N = 104
(% share)	Between		24.76	2.25	80.85	n = 26
	Within		7.25	13.10	69.29	T = 4
Incineration / Total treatment	Overall	1.83	3.21	0	14.87	N = 104
(% share)	Between		2.74	0	8.95	n = 26
	Within		1.74	-4.38	12.94	T = 4
WtE / Total treatment	Overall	15.06	14.40	0	56.12	N = 104
(% share)	Between		13.81	1.01	49.06	n = 26
	Within		4.69	-4.67	30.11	T = 4
Recycling / Total treatment	Overall	47.49	18.54	9.75	89.18	N = 104
(% share)	Between		17.33	17.27	77.37	n = 26
	Within		7.22	15.17	71.04	T = 4

The environmental regulation's stringency and enforcement indicator is based on two questions in the World Economic Forum's Executive Opinion Survey for the Global Competitiveness Report. The questions to business executives[13] were: "In your country, how do you assess the *stringency* of environmental regulations? [1 = Very lax – among the worst in the world; 7 = Among the world's most rigorous]". An equivalent question was about the *enforcement* of environmental regulations. The scores and sample sizes by country are reported in Appendix B. They were calculated for each question as the weighted moving average of the sample for each country.[14] Table 2 shows that, on average, the assessment of stringency is higher than enforcement. As noted, stringency and enforcement,

[13] Business executive levels in the survey were, e.g., top executive/owner, senior executive/board management, head of a business unit/head of a region, middle management and advisers, and functional staff.
[14] See https://reports.weforum.org/global-competitiveness-report-2018/appendix-b-the-executive-opinion-survey-the-voice-of-the-business-community/

together, affect the effectiveness of environmental regulations. The S&E indicator used in this paper was built on adding up the scores of the two questions to capture both stringency and enforcement.[15] It is important to note that this indicator reflects the S&E of environmental regulation in general and is not specific to waste management. This indicator captures social preferences towards the environment because the S&E of environmental regulation is a result of how society values the environment.

The use of indexes that aim to capture the stringency or enforcement of environmental policy is not free from criticism, especially due to multidimensionality (Brunel and Levinson, 2016). Multidimensionality in waste policy is a challenge because each policy has different targets, and policies affect all waste treatment options because they are substitutes for each other. Moreover, a comparison among countries may not be accurate because the design of each policy instrument may differ from one location to another. For example, landfill taxes and recycling subsidies may have similar aims to increase compliance with the EWH, but they will have different effects on a country's waste treatment mix. Aggregated indicators that are intended to reflect the stringency and enforcement of environmental policy cannot capture the multidimensional characteristics of waste policy. Another challenge is potential collinearity if the stringency or enforcement of environmental policy is highly correlated with other explanatory variables such as income.

Sauter (2014) has presented an overview of environmental policy enforcement indicators, including survey, monetary, policy-specific, and performance indicators. Monetary and policy-specific indicators such as landfill taxes, waste tariffs, or sorting systems can be seen in country-specific studies (Antonioli et al., 2018; Dijkgraaf and Gradus, 2017; Ichinose et al., 2011; Mazzanti et al., 2009a, 2009b). These may be suitable for single country studies, but policies may not be

[15] The Pearson correlation coefficient between the stringency and enforcement scores was 0.9557. Multicollinearity may arise if interaction variables are used. Therefore, adding up the stringency and enforcement scores into a single S&E indicator is a better option than using interaction variables.

comparable in analyses of different countries. Performance indicators can be the share of landfilling and other waste treatment methods. However, as noted in the literature reviewed in section III, these have been assessed mostly as dependent variables of landfill diversion and not as policy regressors. This paper uses a survey-based indicator from the WEF that reflects the perceptions of the respondents on the stringency and enforcement of environmental regulation. A downside of these types of surveys is that they rely on perceptions. Nevertheless, the WEF's survey is designed with large samples to reflect the structure of each country's economy.[16]

Econometric design

This paper hypothesizes that the differences in country characteristics explain why they treat their waste differently and, therefore, exhibit different degrees of compliance with the EWH (see Table 1). In this context, the econometric design consisted of two different estimations. In the first estimation, the compliance index was regressed on the country characteristics described previously, and time-specific effects. In the second estimations, instead of the compliance index, the dependent variables were the shares of landfilling, incineration, WtE, and recycling. These shares were regressed on the same country characteristics as before but as a system of equations. Both estimations are conjointly discussed since compliance is a result of the waste treatment mix.

Equation (4) represents the first estimation:

$$CI_{it} = \beta_0 + \beta_1 Y_{it} + \beta_2 REG_{it} + \beta_3 PD_{it} + \beta_4 HDD_{it} + \beta_5 EL_{it} + \gamma DYear_t + u_i + \varepsilon_{it} \qquad \text{Eq. (4)}$$

Where CI is the compliance index, i is the country, t is the year, β_0 is the constant term, Y is the GDP per capita, REG is the environmental regulation S&E indicator, PD is population density, HDD are heating degree days, EL is the electricity price, $DYear$ is a dummy for each observed year with a vector of

[16] See http://www3.weforum.org/docs/GCR2018/04Backmatter/2.%20Appendix%20B.pdf

coefficients γ, u_i is the time-invariant country effect, and ε_{it} is the error term. In random effects, there is no u_i, and the error term is composed of between- and within-country error terms.

The system of equations in Eq. (5) – (8) contains the shares of landfilling, incineration, WtE, and recycling as dependent variables. Since these waste treatment options are substitutes for each other, it is reasonable to assume that the error terms are correlated across the equations.[17] Therefore, a multiple equation approach was used to fit Zellner's seemingly unrelated regression models.

$$L_{it} = \alpha_0 + \alpha_1(Y)_{it} + \alpha_2(REG)_{it} + \alpha_3(PD)_{it} + \alpha_4(HDD)_{it} + \alpha_5(EL)_{it} + \gamma_L(D.Year)_t + u_i + \varepsilon_{it} \quad \text{Eq. (5)}$$
$$I_{it} = \beta_0 + \beta_1(Y)_{it} + \beta_2(REG)_{it} + \beta_3(PD)_{it} + \beta_4(HDD)_{it} + \beta_5(EL)_{it} + \gamma_I(D.Year)_t + u_i + \varepsilon_{it} \quad \text{Eq. (6)}$$
$$E_{it} = \theta_0 + \theta_1(Y)_{it} + \theta_2(REG)_{it} + \theta_3(PD)_{it} + \theta_4(HDD)_{it} + \theta_5(EL)_{it} + \gamma_E(D.Year)_t + u_i + \varepsilon_{it} \quad \text{Eq. (7)}$$
$$R_{it} = \lambda_0 + \lambda_1(Y)_{it} + \lambda_2(REG)_{it} + \lambda_3(PD)_{it} + \lambda_4(HDD)_{it} + \lambda_5(EL)_{it} + \gamma_R(D.Year)_t + u_i + \varepsilon_{it} \quad \text{Eq. (8)}$$

Where L, I, E, and R are the shares of landfilling, incineration, WtE, and recycling over total treated waste, respectively. There is no u_i if the system is estimated as a pooled SURE. An underlying assumption is that all waste is treated in one of the four alternatives. Therefore, $L_{it} + I_{it} + E_{it} + R_{it} = 1$. The estimation procedure of the SURE involves two steps to fulfill the rank condition. First, one equation is left out of the estimation. Then, the system is estimated again, including the equation that was previously left out, but the second time, another equation is left out.

The SURE estimation in this paper can be reduced to ordinary least squares (OLS) because all equations use the same regressors and values (Cameron and Trivedi, 2010). This implies that the coefficients of running these equations independently or as a system are the same. However, standard errors may differ. Bootstrapped standard errors were computed for the SURE estimations.[18] Bootstrapping is a flexible way to estimate robust standard errors because it

[17] The SURE estimations were supported by the Breusch-Pagan tests of independence.
[18] Bootstrapped standard errors were computed using 400 repetitions, as suggested by Cameron & Trivedi (2010).

allows the errors to be heteroskedastic, and if they are homoscedastic, the outcome is not affected (Cameron and Trivedi, 2010).

Including country fixed effects allows controlling for the unobserved country-specific effects that may explain waste treatment mix and compliance. Therefore, country fixed effects estimations are useful to reveal the context-specific nature of waste management, especially since countries are free to choose which policy instruments they want to use to comply with the EWH. However, including country-specific effects is not useful to analyze the effect of time-invariant variables (Petersen, 2012). The between variation is higher than the within variation in all the variables of interest. Therefore, random effects can be helpful in highlighting the differences between countries. Estimations of fixed effects are equivalent to independent OLS estimations in SURE panel data but include country dummies.[19] An estimation with random effects is not based on OLS and could be more challenging.[20] An alternative would be a pooled SURE estimation but without country dummies.[21]

For comparability, if Hausman specification tests favored the use of fixed effects in the first estimations, then country-specific fixed effects were also included as dummy variables in the system of equations. If random effects were favored, the system of equations were estimated as a pooled SURE without country dummies but keeping the time fixed effects. Hereinafter, when country-specific fixed effects are said to be excluded, the estimation will refer to random effects where the dependent variable is the compliance index; or pooled SURE where the shares of waste treatment are modeled as a system of equations.

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[19] Note that this only applies if all equations use the same regressors and values.

[20] XTSUR is an independent-user written program in STATA for one-way random effects estimations of seemingly unrelated regressions in unbalanced panel data (Biørn, 2004; Nguyen & Nguyen, 2010). However, it does not allow for imposing the adding up condition to satisfy $L_{it} + I_{it} + E_{it} + R_{it} = 1$.

[21] Note that these pooled SURE estimations that exclude country-specific fixed effects are not the same as random effects estimations. The latter uses a weighted average of between and within country variations.

The estimations above assume a linear specification of the regressors. Alternative functional forms, such as a quadratic form of income as in EKC studies, may complicate the interpretation of the coefficients because the SURE models reflect the substitution dynamics between waste treatment alternatives. In this context, an EKC hypothesis would be required for each ladder in the EWH. An inverted U-shaped relationship between income and the share of landfilling may be wanted for landfilling. However, it is ambiguous how to frame further hypotheses for WtE that is listed between landfilling and recycling in the EWH.

5. Results

Results of the sensitivity analysis of scenarios with different weighting coefficients for the compliance index show that all statistically significant relationships hold in all scenarios. However, Hausman specification tests for the first group of estimations favor country fixed effects only for the anti-landfill scenario, and random effects for the baseline and remaining scenarios. See Appendices C and D. Therefore, the anti-landfill scenario was the reference for analyzing the results using the country fixed effects in Table 3. The baseline scenario was used for analyzing the results without country fixed effects in Table 4.[22] The dotted line separates the first estimation (to the left) and the SURE models (to the right). These were cojointly analyzed since compliance is a result of the waste treatment mix.

If country fixed effects are included, the results in Table 3 show that income and the S&E of environmental regulation had a positive effect on compliance with the EWH, and that compliance was higher in 2016 than in previous years. Results from the SURE estimations show that the positive relationship of compliance with the EWH and S&E is mainly driven because higher stringency and enforcement of environmental regulation is associated with a decrease in the share of landfilling. A one point increase (on a scale of 14) in the S&E of environmental

[22] For reference, if the shares of waste treatment are modeled separately, i.e., not as a system of equations, Hausman specification tests favor the random effects models for all waste treatment methods, except for the share of landfilling. See Appendices E and F.

regulation represents a decrease of 7 percentage units in the share of landfilling.[23] A negative relationship was found between income and the share of landfilling and a positive relationship was found between income and incineration, WtE, and recycling. However, bootstrapped standard errors do not show statistical significance. Higher compliance in 2016 can be explained by less landfilling than in 2014, less incineration than in 2010, and more recycling than in 2014.

Table 3: Regressions results with country fixed effects

	(FE)	Seemingly unrelated regression equations (SURE)			
	Compliance	% shares of:			
	(W_D=1; W_E=3; W_R=4)	Landfilling	Incineration	WtE	Recycling
GDP per capita	0.0245**	-1.162	0.146	0.602	0.414
(2010 EUR x 1000)	(0.00983)	(1.810)	(0.199)	(1.006)	(1.367)
Environmental regulation	0.158*	-6.671**	1.056	1.026	4.589
(S&E)	(0.0810)	(3.068)	(0.736)	(2.239)	(3.798)
Population density	-0.0124	0.701*	-0.175	-0.334	-0.193
(persons/km^2)	(0.00990)	(0.423)	(0.138)	(0.407)	(0.516)
Heating degree days	-0.000357	0.0130	0.000515	-0.00482	-0.00870
	(0.000237)	(0.00868)	(0.00155)	(0.00570)	(0.0107)
Electricity price	-0.00691	0.0481	0.160	0.0675	-0.275
(cent.EUR/kWh)	(0.0137)	(0.788)	(0.217)	(0.792)	(0.938)
Years (Reference: 2016)					
2010	-0.132	3.093	1.568*	-0.744	-3.917
	(0.0991)	(4.193)	(0.925)	(3.249)	(5.637)
2012	-0.135**	3.838	0.590	0.256	-4.684
	(0.0626)	(2.889)	(0.647)	(2.151)	(3.590)
2014	-0.207**	6.268*	0.555	0.215	-7.038*
	(0.0884)	(3.717)	(0.629)	(2.167)	(4.232)
Constant	3.476**	12.37	-1.017	31.55	57.10
	(1.631)	(118.0)	(20.99)	(75.99)	(99.21)
Observations	104	104	104	104	104
Number of countries	26	26	26	26	26
Country fixed effects	YES	YES	YES	YES	YES
R^2	0.448	0.958	0.782	0.914	0.888

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

[23] An increase of one point in the S&E score may be substantial for one country, considering that the within group standard deviation of the S&E indicator is 0.35. In contrast, the between and overall standard deviations were 1.8 in a comparison of countries. See Table 2.

Table 4: Regressions results without country-fixed effects

	(RE)	Pooled seemingly unrelated regression equations (SURE)			
	Compliance (W_D=1; W_E=2; W_R=3)	% shares of: Landfilling	Incineration	WtE	Recycling
GDP per capita (2010 EUR x 1000)	0.00435 (0.00389)	-0.0864 (0.230)	0.0389 (0.0432)	0.576*** (0.114)	-0.528** (0.215)
Environmental regulation (S&E)	0.116*** (0.0405)	-9.674*** (2.011)	0.0994 (0.383)	2.817*** (0.915)	6.757*** (1.900)
Population density (persons/km^2)	0.00109** (0.000432)	-0.0644*** (0.0144)	0.0125*** (0.00413)	-0.0301*** (0.00780)	0.0820*** (0.0137)
Heating degree days	7.18e-06 (4.64e-05)	-0.00289* (0.00148)	3.56e-06 (0.000330)	0.00262** (0.00104)	0.000271 (0.00170)
Electricity price (cent.EUR/kWh)	-0.0174*** (0.00645)	1.501*** (0.472)	0.0716 (0.129)	-1.443*** (0.331)	-0.130 (0.526)
Years (Reference: 2016)					
2010	-0.188*** (0.0499)	10.51*** (3.726)	1.838** (0.823)	-3.589 (2.303)	-8.763** (3.665)
2012	-0.125*** (0.0322)	5.863 (3.658)	0.794 (0.655)	0.940 (2.156)	-7.597** (3.863)
2014	-0.0884** (0.0386)	3.176 (3.944)	0.648 (0.650)	2.704 (2.730)	-6.528 (4.149)
Constant	1.020*** (0.185)	125.6*** (13.36)	-3.339 (2.905)	-11.84** (4.936)	-10.44 (12.27)
Observations	104	104	104	104	104
Number of countries	26	26	26	26	26
Country fixed effects	NO. Random effects	NO	NO	NO	NO
R^2		0.741	0.344	0.724	0.485
R^2 (within)	0.341				
R^2 (between)	0.626				
R^2 (overall)	0.593				
rho	0.775				
theta	0.740				

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Results in Table 4 do not include country-specific fixed effects, which should highlight the variation between countries in the variables of interest. The following subsections analyze the results in Table 4 for each of the included country characteristics.

Income

Changes in waste treatment attributable to income are driven by changes in social preferences towards the environment due to decreasing marginal utility, and also because income facilitates the investments in technology and infrastructure required by, for example, WtE or recycling. In this study, the environmental regulation S&E indicator aims to capture social preferences towards the environment. Therefore, the effect of income can be interpreted mainly as a technological progress component.

The relationship between income and compliance with the EWH was found to be positive but statistically insignificant if country dummies are not included. See Table 4. This result can be explained as the relationship between GDP per capita and the share of WtE is positive, and the relationship between GDP per capita and the share of recycling is negative. A 1,000 EUR increase in GDP per capita represents an increase of 0.6 percentage units in the share of WtE, but also a decrease of 0.5 percentage units in the share of recycling. These results indicate that WtE replaces recycling as income increases. The technological component of WtE may explain this outcome since income mainly reveals the technological progress component.

The literature shows a negative relationship between income and recycling, e.g., Huhtala (1999) argues that the opportunity cost of time spent on recycling efforts increases with income. However, Huhtala's work is from the household perspective. From a country perspective, the present results suggest that as income increases, the relative costs and benefits of WtE make recycling less attractive. However, recycling has a higher hierarchy in the EWH. Recycling could be incentivized either by making incineration more expensive or recycling cheaper in relative terms. Waste incineration taxes may increase the costs for WtE. However, their effectiveness is questionable because, as long as waste is still produced, waste incineration facilities have limited capacity to influence the flows of waste they get to incinerate. Given these challenges, policies to make recycling more attractive such as deposit and refund systems may be more appealing in the context of the EWH.

Stringency and enforcement of environmental regulation

Results in Table 4 show a positive relationship between regulatory S&E and compliance with the EWH. This is mainly driven by a negative relationship between S&E and the share of landfilling and a positive relationship between S&E and the shares of WtE and recycling. A one-point increase (on a scale of 14) in the S&E of environmental regulation represents a decrease of 10 percentage units in the share of landfilling and an increase of 3 and 7 percentage units in the shares of WtE and recycling, respectively. Therefore, a higher S&E of environmental regulations promotes the substitution of landfilling with WtE and recycling. Landfilling would be costly for society in this example, so stringent and enforceable environmental regulations to replace landfilling are socially supported. Communicating the population about the social costs and benefits of the different waste treatment alternatives may facilitate stringent and enforceable environmental regulations. These results complement the studies by Antonioli et al. (2018) and Mazzanti and Zoboli (2008), who have used other indicators to capture the effect of environmental policy.

Population density

Population density does not change much over time, but it differs among countries. Results in Table 4 show a positive relationship between population density and compliance with the EWH. Population density was found to have a negative relationship with landfilling and WtE in terms of the waste treatment mix, and population density was found to have a positive relationship with incineration and recycling. These relationships mean that an increase in population favors incineration and recycling over landfilling and WtE. Land competition and the relative cost of space justify the negative relationship of population density with landfilling in favor of alternative methods such as incineration. This positive relationship with incineration is in line with findings in the studies by Antonioli et al. (2018) and Mazzanti and Zoboli (2008). Economies of scale for sorting and collection explain the positive relationship of population density with recycling. A positive relationship with recycling has also been observed in previous studies by Berglund et al. (2002) and Karousakis (2009). The negative relationship of population density with WtE can be explained as the costs and benefits are higher than for incineration and recycling, in relative terms.

Heating demand

Results support the expected positive relationship between heating demand (represented by heating degree days) and the share of WtE. WtE plants are mainly intended to generate heat for local district heating networks, and the relative utility of heat increases when the weather is cold. Results also show a negative relationship between heating degree days and the share of landfilling. In this scenario, a higher demand for heating stimulates the substitution of landfilled waste in favor of WtE.

Electricity prices

As noted in the introductory section, a positive relationship between electricity prices and the share of WtE is expected because electricity can be a byproduct of CHP plants, and also because district heating from WtE competes with other heat alternatives that use electricity, such as heat pumps. Results show this positive relationship between electricity prices and WtE if country fixed effects are included, but the effect is not statistically significant. See Table 3. The relationship between electricity prices and the share of WtE becomes negative if country fixed effects are excluded, together with a positive relationship between electricity prices and the share of landfilling. See Table 4. This unexpected outcome can be explained by the fact that, among other reasons, investments in

WtE require time, and the timeframe in this paper's dataset may not fully capture such long-term relationships.

Time trends

Compliance with the EWH has improved over time, which suggests a positive effect of the Waste Framework Directive from 2008. In 2010, compared to 2016, the shares of landfilling and incineration in Table 4 were 11% and 2% higher, respectively, while the share of recycling was 9% lower in 2016.

6. Conclusions and discussion

Countries treat waste based on the relative costs of different waste treatment options. This study estimated the effect of income, the stringency and enforcement of environmental regulation, population density, heating demand, and electricity prices on the waste treatment mix and the compliance with the EWH. Previous research shows that these country characteristics affect the relative costs and benefits of waste treatment options, and subsequently compliance with the EWH. This paper adds to the literature by constructing a waste hierarchy compliance index, which is regressed in these country characteristics. A better understanding of these determinants provides useful insights for the design of EU waste policy.

This study illustrated that stringency and enforcement of environmental regulation matter. The positive effect of environmental regulation S&E on compliance with the EWH is robust regardless of whether country fixed effects are included in the econometric estimations or not. Higher compliance was found to mainly occur because S&E had led to a reduction in the share of landfilling. A positive relationship between S&E and the shares of WtE and recycling was also found for the pooled SURE estimation. If social preferences are in line with the objectives of the EWH, society will strive for stringent and enforceable regulations to increase compliance with the EWH, which requires time . This study also found that compliance with the EWH has improved over time.

One limitation of this study is that the S&E indicator refers to environmental regulation in general and not specifically to waste management. Further research assessing specific waste policies could enable specific suggestions to be made about which policy instruments improve compliance in different contexts. The extent to which waste policies should be stringent or enforceable is also a question for future research. What this study found in the WEF survey is that stringency is perceived as more rigorous than enforcement. Future studies can test the pollution haven and Porter hypotheses to explore other effects of policy stringency in the context of waste management.

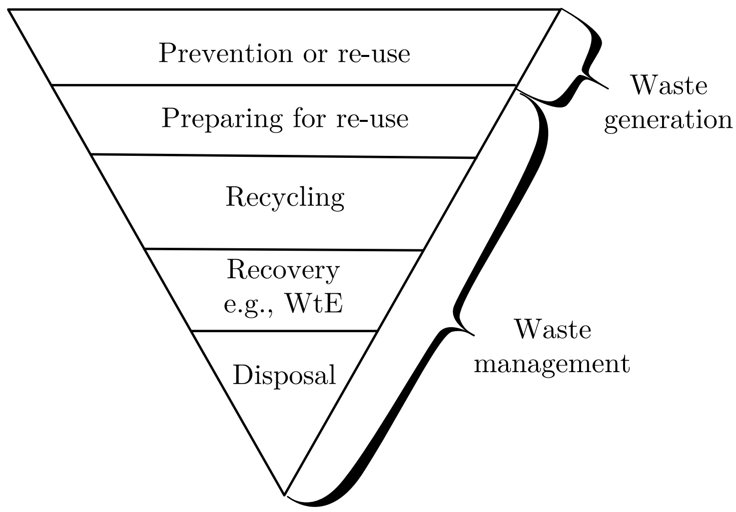
The present study is unique in that it addresses the effect of heating demand and electricity prices on WtE. WtE plants provide not only energy in the forms of heat and electricity, but also a waste treatment service that the EWH ranks between disposal and recycling. The links between the heat, electricity, and waste markets make WtE an important subject for further research, particularly in terms of comprehensive benefits and costs. Olsson et al. (2015) have highlighted the lack of consensus on the climate impact of district heating systems, given their sensitivity to assessment methods and local conditions. The results from the pooled SURE show a positive relationship between WtE and demand for heating. This outcome implies that the relative value of WtE is higher in colder countries with already installed WtE capacity. However, results also showed an unexpected negative relationship between the share of WtE and electricity prices. The limited timeframe in the dataset can have influenced this result. Future studies with more extended time series are required.

The compliance index developed herein adds to the existing literature and is designed to reflect the hierarchy in the EWH. Nevertheless, future research can be undertaken to improve these types of indexes. Ideally, an index of this type can use weights that reflect the cost-optimality of waste treatment methods, a feature that the EWH does not necessarily reflect. Another limitation of the EWH compliance index used in the present study is that it does not reflect waste reduction, which is a top priority of the EWH. Further research can help to fill this gap.

Last but not least, this study and its results relied on the data quality of sources. Countries report to Eurostat based on a harmonized methodology, but the reported data is not entirely free from errors. Audit processes are recommended due to the importance of these types of datasets for research and policymaking.

APPENDICES

Appendix A:
Waste Hierarchy under EU's Directive 2008/98/EC on Waste



Appendix B:
Environmental policy stringency and enforcement scores

Stringency:
How do you assess the *stringency* of your country's environmental regulations?

Enforcement:
In your country, how do you assess the *enforcement* of environmental regulations?

[1 = Very lax – among the worst in the world; 7 = Among the world's most rigorous]

(Sample size in parenthesis)

	2010	2012	2014	2016
Austria				
Stringency	6.45	6.28	6.20	6.18
Enforcement	6.17	5.88	5.99	6.08
	(80)	(105)	(71)	(111)
Belgium				
Stringency	5.89	5.81	6.00	5.50
Enforcement	5.45	5.47	5.63	5.16
	(76)	(83)	(64)	(51)
Bulgaria				
Stringency	2.98	3.37	3.47	3.59
Enforcement	2.81	3.25	3.26	3.27
	(115)	(120)	(104)	(116)
Croatia				
Stringency	4.37	4.31	4.52	4.42
Enforcement	3.71	3.53	4.05	4.12
	(97)	(107)	(82)	(85)
Cyprus				
Stringency	4.35	4.20	4.70	4.00
Enforcement	4.2	3.98	4.47	4.06
	(95)	(79)	(52)	(65)
Czechia				
Stringency	5.26	5.24	5.13	5.20
Enforcement	4.8	4.69	4.71	4.43
	(78)	(163)	(77)	(106)
Denmark				
Stringency	6.00	6.15	6.34	5.81
Enforcement	6.05	6.09	6.24	5.97
	(35)	(128)	(89)	(110)
Estonia				
Stringency	5.31	5.37	5.37	5.37
Enforcement	4.92	5.17	5.26	5.33
	(87)	(85)	(89)	(89)

	2010	2012	2014	2016
Finland				
Stringency	6.13	6.42	6.22	6.21
Enforcement	6.03	6.38	6.26	6.21
	(35)	(36)	(49)	(47)
France				
Stringency	5.27	5.10	5.17	5.12
Enforcement	5	4.76	4.9	4.89
	(128)	(129)	(184)	(94)
Germany				
Stringency	6.62	6.44	6.14	6.01
Enforcement	6.38	6.21	6.08	5.7
	(68)	(127)	(99)	(103)
Greece				
Stringency	3.63	3.71	4.04	4.43
Enforcement	3.08	2.93	3.47	3.78
	(91)	(83)	(85)	(81)
Hungary				
Stringency	4.68	4.78	4.68	3.98
Enforcement	3.5	3.52	3.83	3.42
	(81)	(103)	(99)	(52)
Ireland				
Stringency	5.26	5.62	5.36	5.23
Enforcement	5.06	5.28	5.07	5.13
	(48)	(62)	(52)	(38)
Italy				
Stringency	4.15	4.48	4.80	4.46
Enforcement	3.3	3.42	3.85	3.64
	(90)	(87)	(87)	(122)
Latvia				
Stringency	4.26	4.42	4.92	4.70
Enforcement	3.92	4.17	4.69	4.43
	(138)	(98)	(81)	(89)

	2010	2012	2014	2016
Lithuania				
Stringency	4.93	4.82	5.01	4.93
Enforcement	4.3	4.19	4.62	4.7
	(137)	(153)	(146)	(121)
Netherlands				
Stringency	6.09	6.04	5.84	5.78
Enforcement	5.93	5.88	5.73	5.6
	(99)	(82)	(88)	(75)
Poland				
Stringency	4.61	4.83	4.64	4.46
Enforcement	4.16	4.17	4.06	3.79
	(311)	(206)	(200)	(206)
Portugal				
Stringency	5.22	5.20	5.43	5.25
Enforcement	4.2	4.33	4.89	4.75
	(103)	(115)	(140)	(220)
Romania				
Stringency	3.69	3.19	3.75	3.81
Enforcement	3.24	3.01	3.67	3.29
	(100)	(98)	(72)	(100)

	2010	2012	2014	2016
Slovakia				
Stringency	5.16	4.70	4.89	4.91
Enforcement	3.94	3.8	4.08	4.11
	(62)	(68)	(85)	(109)
Slovenia				
Stringency	5.02	5.07	5.18	5.38
Enforcement	4.4	4.48	4.79	4.85
	(101)	(110)	(84)	(85)
Spain				
Stringency	4.82	4.82	4.55	4.78
Enforcement	4.22	4.5	4.3	4.68
	(177)	(91)	(76)	(104)
Sweden				
Stringency	6.46	6.12	5.87	6.22
Enforcement	6.36	6.07	5.78	6.07
	(37)	(77)	(62)	(54)
United Kingdom				
Stringency	5.43	5.46	5.45	5.38
Enforcement	5.2	5.43	5.32	5.26
	(102)	(102)	(79)	(73)

Source: WEF (2018)

Appendix C:
Sensitivity analysis for the compliance index (Fixed effects)

	Compliance index (CI)			
	W_D=1 W_E=2 W_R=3	W_D=1 W_E=2 W_R=4	W_D=1 W_E=3 W_R=4	W_D=1 W_E=3 W_R=6
GDP per capita	0.0143**	0.0184*	0.0245**	0.0327*
(2010 EUR x 1000)	(0.00653)	(0.00982)	(0.00983)	(0.0163)
Environmental regulation	0.102*	0.148*	0.158*	0.250*
(S&E)	(0.0551)	(0.0852)	(0.0810)	(0.140)
Population density	-0.00719	-0.00911	-0.0124	-0.0163
(persons/km^2)	(0.00697)	(0.0112)	(0.00990)	(0.0182)
Heating degree days	-0.000222	-0.000309	-0.000357	-0.000531
	(0.000166)	(0.000263)	(0.000237)	(0.000429)
Electricity price	-0.00483	-0.00758	-0.00691	-0.0124
(cent.EUR/kWh)	(0.00883)	(0.0134)	(0.0137)	(0.0221)
Years (Ref: 2016)				
2010	-0.0858	-0.125	-0.132	-0.211
	(0.0717)	(0.117)	(0.0991)	(0.189)
2012	-0.0911**	-0.138*	-0.135**	-0.229**
	(0.0431)	(0.0679)	(0.0626)	(0.111)
2014	-0.139**	-0.209**	-0.207**	-0.348**
	(0.0609)	(0.0948)	(0.0884)	(0.156)
Constant	2.493**	3.002*	3.476**	4.495
	(1.090)	(1.662)	(1.631)	(2.747)
Observations	104	104	104	104
R^2	0.408	0.361	0.448	0.380
Number of countries	26	26	26	26
Country fixed effects	YES	YES	YES	YES
rho	0.979	0.971	0.984	0.975
Hausman test (χ^2)	10.55	8.57	12.58	9.35
Hausman test (Prob>χ^2)	0.0610	0.1274	0.0277	0.0960

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

The highlighted cells show that the Hausman test favors fixed effects.

Appendix D:
Sensitivity analysis for the compliance index (Random effects)

	Compliance index (CI)			
	W_D=1 W_E=2 W_R=3	W_D=1 W_E=2 W_R=4	W_D=1 W_E=3 W_R=4	W_D=1 W_E=3 W_R=6
GDP per capita	0.00435	0.00306	0.00994*	0.00742
(2010 EUR x 1000)	(0.00389)	(0.00598)	(0.00580)	(0.00985)
Environmental regulation	0.116***	0.166***	0.183***	0.282***
(S&E)	(0.0405)	(0.0633)	(0.0587)	(0.104)
Population density	0.00109**	0.00184***	0.00144**	0.00293***
(persons/km^2)	(0.000432)	(0.000665)	(0.000642)	(0.00109)
Heating degree days	7.18e-06	-2.97e-07	2.20e-05	6.89e-06
	(4.64e-05)	(6.87e-05)	(7.08e-05)	(0.000115)
Electricity price	-0.0174***	-0.0232**	-0.0290***	-0.0407**
(cent.EUR/kWh)	(0.00645)	(0.00982)	(0.00981)	(0.0162)
Years (Ref: 2016)				
2010	-0.188***	-0.266***	-0.297***	-0.454***
	(0.0499)	(0.0782)	(0.0725)	(0.128)
2012	-0.125***	-0.189***	-0.187***	-0.314***
	(0.0322)	(0.0512)	(0.0471)	(0.0831)
2014	-0.0884**	-0.145**	-0.121**	-0.233**
	(0.0386)	(0.0580)	(0.0589)	(0.0963)
Constant	1.020***	1.088***	0.969***	1.108**
	(0.185)	(0.293)	(0.266)	(0.477)
Observations	104	104	104	104
Number of countries	26	26	26	26
R^2 (within)	0.341	0.304	0.371	0.319
R^2 (between)	0.626	0.588	0.660	0.604
R^2 (overall)	0.593	0.552	0.629	0.569
rho	0.775	0.763	0.783	0.768
theta	0.740	0.732	0.746	0.735
Hausman test (χ^2)	10.55	8.57	12.58	9.35
Hausman test (Prob>χ^2)	0.0610	0.1274	0.0277	0.0960

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The light-highlighted column shows the model with the highest R^2 among the models where random effects are favored by the Hausman test.

The dark-highlighted cells show that the Hausman test favors random effects.

Appendix E:
Regressions results
(Independent fixed effects models)

	% shares of:			
	Landfilling	Incineratio n	WtE	Recycling
GDP per capita	-1.162***	0.146***	0.602***	0.414
(2010 EUR x 1000)	(0.332)	(0.0402)	(0.160)	(0.336)
Environmental regulation	-6.671**	1.056	1.026	4.589
(S&E)	(2.751)	(0.666)	(1.799)	(3.093)
Population density	0.701**	-0.175*	-0.334	-0.193
(persons/km^2)	(0.340)	(0.100)	(0.316)	(0.439)
Heating degree days	0.0130*	0.000515	-0.00482	-0.00870
	(0.00668)	(0.00102)	(0.00403)	(0.00974)
Electricity price	0.0481	0.160	0.0675	-0.275
(cent.EUR/kWh)	(0.548)	(0.144)	(0.591)	(0.518)
Years (Ref: 2016)				
2010	3.093	1.568**	-0.744	-3.917
	(2.740)	(0.694)	(2.633)	(4.585)
2012	3.838*	0.590	0.256	-4.684*
	(2.041)	(0.462)	(1.854)	(2.582)
2014	6.268**	0.555	0.215	-7.038*
	(2.758)	(0.330)	(1.543)	(3.438)
Constant	-4.583	6.265	47.36	50.96
	(58.51)	(14.99)	(39.55)	(59.39)
Observations	104	104	104	104
R^2 (within)	0.487	0.255	0.187	0.261
Number of countries	26	26	26	26
rho	0.993	0.992	0.976	0.939
Hausman test (χ^2)	16.93	8.54	9.09	5.33
Hausman test (Prob>χ^2)	0.0046	0.1287	0.1056	0.3775

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The highlighted cells show that the Hausman test favors fixed effects.

Appendix F:
Regressions results
(Independent random effects models)

	% shares of: Landfilling	Incineratio n	WtE	Recycling
GDP per capita	-0.546***	-0.00591	0.589***	-0.130
(2010 EUR x 1000)	(0.197)	(0.0574)	(0.151)	(0.218)
Environmental regulation	-7.489***	0.565	2.154*	4.952**
(S&E)	(2.020)	(0.501)	(1.173)	(2.309)
Population density	-0.0434*	0.0110*	-0.0327**	0.0746***
(persons/km^2)	(0.0227)	(0.00582)	(0.0147)	(0.0241)
Heating degree days	-0.00120	-0.000182	0.00314**	-0.000782
	(0.00253)	(0.000499)	(0.00152)	(0.00231)
Electricity price	1.016***	0.117	-0.827***	-0.561
(cent.EUR/kWh)	(0.369)	(0.152)	(0.292)	(0.363)
Years (Ref: 2016)				
2010	9.054***	1.868**	-3.714**	-7.805***
	(2.406)	(0.818)	(1.847)	(2.918)
2012	5.450***	0.727	0.166	-6.381***
	(1.692)	(0.538)	(1.859)	(2.037)
2014	2.889	0.431	2.567	-5.648***
	(2.147)	(0.313)	(1.766)	(2.060)
Constant	113.6***	-6.615*	-14.23**	6.762
	(8.874)	(3.710)	(6.389)	(11.10)
Observations	104	104	104	104
Number of countries	26	26	26	26
R^2 (within)	0.379	0.179	0.118	0.224
R^2 (between)	0.730	0.390	0.783	0.503
R^2 (overall)	0.701	0.327	0.710	0.461
rho	0.799	0.576	0.598	0.735
theta	0.757	0.606	0.621	0.712
Hausman test (χ^2)	16.93	8.54	9.09	5.33
Hausman test (Prob>χ^2)	0.0046	0.1287	0.1056	0.3775

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

The highlighted cells show that the Hausman test favors random effects.

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