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Performance in the treatment of municipal waste: Are European Union member states so different?

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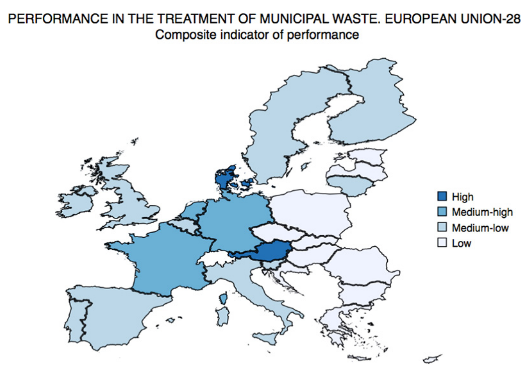
HIGHLIGHTS

- There are notable differences in performance in waste treatment across EU-28 members.
- Most European citizens live in countries with medium-low levels of performance.
- Policy measures aimed at reducing cross-country differences are needed in the EU-28.

GRAPHICAL ABSTRACT



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ABSTRACT

Efficient management and treatment of municipal waste is essential for achieving *green* growth. Recent studies have revealed convergence in European Union (EU) member states' performance in municipal waste treatment, particularly since the transposition of the 2008 European *Waste Framework Directive* into national laws. However, there are still notable differences between countries. In this paper, we calculate a composite indicator of performance in municipal waste treatment at the country-level. We also present an in-depth examination of differences in performance across EU member states. Our results show that the best performers—mainly high income Northern and Central European countries—treat larger quantities of waste per capita, mostly through recycling and composting and digestion. At the opposite end of the ranking, the worst performers—mostly poorer Eastern European countries—treat smaller amounts of waste per capita, largely through landfilling. Our main conclusion is that further policy measures aimed at reducing cross-country differences in waste treatment performance are needed in the EU.

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1. Introduction and background

In both developed and developing countries, there is growing societal demand for *green* growth, understood as the economic growth that is compatible with environmental preservation. As such, *green* growth is high on the agenda of policymakers worldwide, and plays a particularly relevant role in current environmental policies in the European Union (EU). Environmentally sustainable growth involves many different facets, and there are various barriers to its achievement. One of the main threats to sustainability is the generation of ever-greater amounts of municipal solid waste due to expanding populations and the associated levels of consumption. At the global level, waste production has risen tenfold in the past century. Currently, the world generates 2.01 billion tonnes of municipal waste a year, representing an average of 270 kg per inhabitant (Kaza et al., 2018), although the latter figure is much higher in developed countries. According to World Bank forecasts (Hoornweg and Bhada-Tata, 2012), annual global waste is expected to increase to 3.40 billion tonnes by 2050, a rise that is more than double the expected population growth. Even more worryingly, the figure is set to triple by the end of current century (Hoornweg et al., 2013). Furthermore, the current members of the European Union-28 (EU-28) produce nearly 0.25 billion tonnes of municipal waste annually, according to the most recent figures from the Statistical Office of the European Union (Eurostat), which correspond to 2017; this figure represents an average of 486 kg per inhabitant.

The fight against environmental damage from municipal solid waste —e.g., CO_2 emissions from waste treatment or plastic-filled rivers, seas and oceans—involves two main management strategies, namely: waste prevention and waste treatment. Waste prevention requires promoting sustainable consumption and production, which can be done through information campaigns targeted at shaping people's behaviour, financial incentives for beneficial initiatives, or even mandatory regulations imposing limits on waste generation. As far as municipal waste treatment is concerned, there are four main options: landfill, recycling, incineration (with and without energy recovery), and composting and digestion. According to the European *Waste Framework Directive* of 2008 (EC, 2008), the priorities of the EU's waste management policies are, in this order, prevention, preparing for re-use, recycling, energy recovery and disposal. Besides, treatment operations such as re-using and recycling also contribute to waste prevention; however, recent studies suggest that while the impact of recycling on municipal waste generation is positive and significant, that of re-using is barely significant (Minelgaitė and Liobikienė, 2019).

Regarding the related scientific literature, a strand of research in this field has addressed the issue of municipal waste management from an integrated perspective, with approaches that include the waste hierarchy (Gharfalkar et al., 2015; Van Ewijk and Stegemann, 2016) and the life cycle assessment (Liamsanguan and Gheewala, 2008; Clearly, 2009; De Feo et al., 2019). Other authors, however, have separately focused on either waste prevention (Hutner et al., 2017; Matsuda et al., 2018; Minelgaitė and Liobikienė, 2019), or performance in municipal waste management and treatment (Marin et al., 2017; Sanjeevi and Shahabudeen, 2015; Pomberger et al., 2017; Bassi et al., 2017; Callao et al., 2019; Castillo-Giménez et al., 2019). Furthermore, several papers have also separately addressed the issue of the treatment of other urban waste; e.g., see Kuriqi (2014) and Kuriqui et al. (2016) for the case of wastewater.

Within the strand of research focused on waste management and treatment, in which our work is framed, the papers of Marin et al. (2017) and Castillo-Giménez et al. (2019) are of particular interest. Whereas both are focused on the assessment of performance and convergence in municipal waste treatment, Marin et al. (2017) undertake separate analyses of convergence across EU countries in their performance regarding several waste treatment operations over the period 1995–2010. To that end, they use conventional β- and σ-convergence analysis techniques (Barro and Sala-i-Martin, 1992). Their results reveal that there has been statistically significant conditional convergence in both recycling and incineration; regarding the former, convergence occurs at a faster rate for countries that have a greater endowment of recycling technologies and stringent waste policies. Besides, these authors find that heterogeneity in performance across countries has decreased over time, although there are still substantial differences at the end of the period, in particular regarding the amount of waste treated per inhabitant and the type of treatment operation.

On the other hand, the very recent paper by Castillo-Giménez et al. (2019) goes much further: it analyses convergence using a composite indicator of performance in municipal waste treatment, which jointly includes landfill, recycling, incineration, and composting and digestion as treatment options. These treatment types represent the dimensions of the composite indicator, which is calculated using data for 1995–2016. Furthermore, more powerful approaches to convergence analysis are used, including those proposed by Phillips and Sul (2007; 2009) and, more recently, by Kong et al. (2019). The paper concludes that performance in the treatment of municipal waste has converged among the members of the EU-28 since the transposition of the 2008 *Waste Framework Directive* into national laws. However, the positive impact of such legislation on convergence should not hide the fact that differences in performance are still important among EU-28 countries; in fact, this is a finding that coincides with Marin et al. (2017), and also with the results of other recent papers that analyse efficiency in the management and treatment of municipal waste in Europe; e.g., Callao et al. (2019).

Against this background, our paper makes two main contributions to existing research in this field. First, following the proposal by Castillo-Giménez et al. (2019), we calculate a composite indicator of performance in the treatment of municipal waste at the level of the EU-28 member states, using the most current available data for the period 2015–17. This approach involves the use of Data Envelopment Analysis (DEA) and Multi-Criteria-Decision-Making (MCDM) techniques. Going a step further than the aforementioned paper, we check the robustness of our indicator in several theoretical scenarios. Second, beyond the evidence of convergence reported by previous literature, we carry out an in-depth analysis of the marked differences that still remain among EU-28 member states regarding their performance in municipal waste treatment. In particular, we propose a classification of countries in which the best performers, mostly the richer Northern and Central European countries, treat higher quantities of municipal waste per capita and make more use of recycling and composting and digestion operations. Conversely, the worst performers are the poorer Eastern European countries, which primarily treat municipal waste through landfilling. Furthermore, we find that a large proportion of European citizens live in countries that still achieve medium-low, or even low, performance levels in the management of the waste they produce.

The remainder of the paper is structured as follows: Section 2 describes the data and the methods; Section 3 presents and discusses the results, while Section 4 concludes and highlights some policy issues.

2. Data and methods

2.1. Dataset and sources

Our dataset comes from the Statistical Office of the European Union, Eurostat. In order to calculate the set of indicators used to monitor the EU's sustainable development strategy, Eurostat has collected and published annual country-level data on municipal waste generation and treatment since 1995. Municipal waste comprises the waste generated by households and other sources such as commerce and trade, small businesses and public entities, which is collected by local governments —or other organisations acting on their behalf—and disposed of through diverse waste management systems. Eurostat reports information about four categories of waste treatment: landfill, incineration, recycling, and composting and digestion. In addition, a distinction is made between incineration with and without energy recovery. As defined by the European Commission (EC, 2017), *landfill* consists of depositing municipal waste into or onto land; *incineration* involves thermal treatment of waste in an incineration plant; *recycling* includes any treatment by which waste materials are reprocessed into materials for either their original use or other usages; lastly, *composting and digestion* include biological decomposition processes of biodegradable waste under controlled conditions. Of these four categories, landfill is considered to be the least desirable treatment option because it is so costly in terms of pollution and landscape deterioration; conversely, recycling is viewed as the most desirable waste treatment.

We have gathered data on the volumes of municipal waste (in both thousand tonnes and kilograms per capita) treated by the members of the EU-28 in 2015, 2016 and 2017, including the four abovementioned treatment operations.[1] Fig. 1 offers a first glance at the performance of EU-28 member states in terms of kilograms of municipal waste treated per inhabitant, calculated as averages for 2015–17.[2] While the amount of aggregate waste treated averages 475 kg per capita in the EU-28, differences across member states are striking, ranging from 785 kg in Denmark to 228 kg in Romania. There are also major differences at the level of specific waste treatment operations; e.g., for landfill, the amount of waste treated ranges from 513 kg per capita in Malta to just 3 kg in Sweden. These variations are due to differences in countries' consumption patterns and their economic development; however, to a great extent, they are also due to the organisation and management of municipal waste collection, particularly the waste coming from commerce, business and administration (Blumenthal, 2011).[3]

In the period 2015–17, an average of 247 million tonnes of municipal waste was generated in the EU-28, 98.1% of which was treated. Treatment rates even reached 100% in some Central and Northern European countries such as Denmark, Sweden and Luxembourg, as well as Southern countries such as Greece and Spain. As can be seen in Fig. 2, the average share of municipal waste that was landfilled, incinerated, recycled, and composted and digested in the EU-28 was 25.1%, 28.1%, 30.1% and 16.7%, respectively. Moreover, as a rule of thumb, the members that treat larger aggregate quantities of waste per capita are also those that make less use of landfill (only Cyprus, Malta and Greece seem to buck this pattern). In this respect, Sweden, Belgium, Denmark, the Netherlands, Germany and Austria report landfill rates of below 5%, mostly due to the implementation of national measures aimed at reducing this treatment option. For instance, national law in Sweden and Denmark—where landfill rates are as low as 0.6% and 1%—has banned landfilling combustible waste since 2002 and 1997, respectively; these two countries have the highest incineration rates in the EU-28 (52.5% and 51.5%, respectively), only surpassed by Estonia (53.8%).

At the opposite end, the worst performing countries in terms of municipal waste treatment per inhabitant still predominantly use landfill, with incineration, recycling and composting and digestion playing a far less important role. This group mostly includes newer Eastern European member states, with the highest landfill rates corresponding to Malta (92.5%), Greece (82%), Cyprus (81.4%) and Romania (80.5%). Most of these countries are characterised by having very little municipal waste incineration infrastructure and poorly developed collection and recycling facilities.

In summary, this preliminary exploratory analysis based on a simple description of the dataset reveals that, despite convergence in recent years, notable disparities still remain among EU-28 member states regarding their performance in municipal waste treatment.

2.2. Methods

2.2.1. Computing a composite indicator of performance in municipal waste treatment

In this paper, we calculate a composite indicator of performance in the treatment of municipal waste by the EU-28 member states. To that end, as noted in the Introduction, we follow the approach recently proposed by Castillo-Giménez et al. (2019). Hence, in this Section, we present only the main features of this methodology, referring interested readers to the original paper for more details. The indicator is calculated using Data Envelopment Analysis (DEA) and Multi-Criteria-Decision-Making (MCDM). On the one hand, DEA has been extensively used to assess performance in the waste sector; e.g., Simões and Marques (2012a; 2012b); Marques et al. (2018); Callao et al. (2019). Moreover, several MCDM methods have also been employed to assess municipal waste management; e.g., Coban et al., (2018).

DEA is a non-parametric approach based on mathematical programming pioneered by Charnes et al. (1978), which was initially proposed as a way of assessing production efficiency (Farrell, 1957). Later on, Lovell et al. (1995) extended it to the calculation of composite indicators; since then, dozens of papers have used this approach in empirical analyses involving a range of economic, social and environmental issues (see Zhou et al., 2007). In essence, extending the original DEA models to the calculation of a composite indicator requires the use of a *dummy* input equal to one (see Lovell et al., 1995; p. 509) and, in our case, replacing outputs with the quantities of municipal waste per capita treated through each one of the four treatment options described in Section 2.1, which are the dimensions of our composite indicator. Following Reig-Martínez et al. (2011), we employ the output-oriented slacks-based measure proposed by Tone (2001), which has the advantage of integrating radial and non-radial (the so-called *slacks*) potential improvements into a single measure of performance (see Cooper et al., 2007; pp. 96–98). Considering our sample of $c = 1, \ldots, 28$ countries in the EU-28 and $i = 1, \ldots, 4$ municipal waste treatments, the DEA composite indicator of performance of country c′ can be obtained by solving the program:

$$\text{Composite indicator}^{*}_{c'} = \text{Minimise}_{\lambda_c S_i^+} \frac{1}{1 + \frac{1}{4}\sum_{i=1}^{4}\left(S_i^+/\text{treatment}_{i_{c'}}\right)} \quad (1)$$

Subject to:

$$x_{c'} \geq \sum_{c=1}^{28} \lambda_c x_c$$

$$\text{Treatment}_{i_{c'}} = \sum_{c=1}^{28} \lambda_c \text{treatment}_{i_c} - S_i^+ \quad i = 1, \ldots, 4$$

$$S_i^+ \geq 0 \quad i = 1, \ldots, 4$$

$$\lambda_c \geq 0 \quad c = 1, \ldots, 28$$

In Expression (1), $\text{treatment}_{i_{c'}}$ represents the number of kilograms per capita treated in country c′ through waste treatment i—as noted in Section 2.1, the data are averages for the three-year period 2015–17—; x stands for the abovementioned *dummy* input of one; S_i^+ is the *slack* in waste treatment i; and, finally, λ_c represents the intensity with which each country c enters the composition of the reference set country c′ is compared to. Furthermore, the indicators of performance range

[1] The data were accessed on 4 April 2019 through https://ec.europa.eu/eurostat/data/database.

[2] Throughout this paper, we always represent current performance in the treatment of municipal waste using this three-year average; we do so in an attempt to mitigate the impact of possible measurement errors on our results. Data for Ireland are only available for years 2015 and 2016. In the case of incineration treatment in Portugal we have used the most recent available data, which correspond to year 2014; for the remaining treatment operations, data on this country are available for the entire 2015–17 period.

[3] Performance in the management and treatment of municipal waste is also influenced by the type of management structure—e.g., public or private—of the organisations that provide the service; e.g., see Plata-Díaz et al. (2014); Campos-Alba et al. (2019).

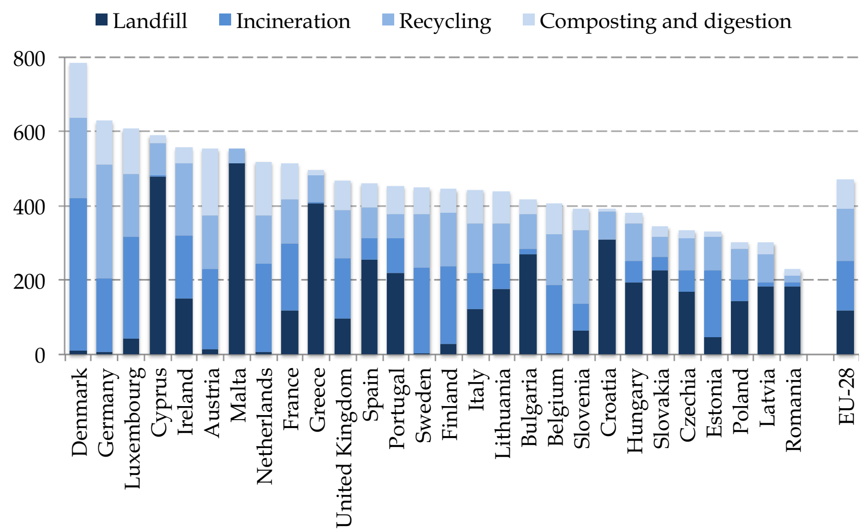

Fig. 1. Municipal waste treatment, EU-28 member states. Average 2015–17 (*Kilograms* per capita). Source: *Eurostat*.

from zero to one, scores that represent the lowest and the highest performance, respectively.

A notable advantage of DEA is that the weights assigned to our four waste treatments in building the composite indicator of performance are endogenously determined at the country level, thus avoiding exogenous weighting schemes based on expert opinions or other ad hoc criteria. In this regard, weights are assigned according to the *Benefit-of-the-Doubt*[4] principle proposed by Cherchye et al. (2007). Under this principle, each country is assigned the set of weights that maximises its score for the composite indicator of performance when compared to all other countries in the sample assessed with the same set of weights.[5]

Leaving aside the flexibility they offer in determining the optimal set of weights, DEA-based composite indicators have several shortcomings when they are used to rank countries. A particularly worrying drawback in the case of our research—in which we have few observations relative to the number of variables involved—is that more than one country could be assigned a performance score of one, i.e., full-efficient performance. This limitation is due to a lack of discriminatory power (Dyson et al., 2001) and could prevent us from producing a complete ranking of countries in the sample. Moreover, several authors have argued that cross-country comparisons of performance with DEA-based composite indicators might be worthless because performance is assessed using country-specific sets of weightings (Kao and Hung, 2005).

The literature in this field has suggested several ways to overcome the abovementioned limitations (for a review, see Reig-Martínez et al., 2011; pp.563–64). Following Castillo-Giménez et al. (2019), we combine DEA and MCDM techniques—as originally proposed by Despotis (2002)—to improve the discriminatory power of our DEA composite indicator of performance while maintaining a common weighting scheme for its four dimensions, i.e., waste treatments, across countries. The resulting composite indicator, i.e., the DEA-MCDM indicator, allows both meaningful comparisons across countries and full rankings, and its computation requires separately solving the following program for each country in the EU-28 (see Despotis, 2005):

$$\text{Minimise}_{m_c \omega\ z}\ t\frac{1}{28}\sum_{c=1}^{28} m_c + (1-t)z \tag{2}$$

Subject to:

$$\sum_{i=1}^{4}\omega_i \text{treatment}_{i_c} + m_c = \text{Composite indicator}^*_{c'}\ c = 1, \ldots, 28$$

$$(m_c - z) \le 0 \qquad c = 1, \ldots, 28$$

$$m_c \ge 0 \qquad c = 1, \ldots, 28$$

$$\omega_i \ge \varepsilon \qquad i = 1, \ldots, 4$$

$$z \ge 0$$

In this program, ω_i is the common weight assigned to waste treatment i; ε is a non-*Archimedean* small number which ensures that all four waste treatments enter the composite indicator with positive weights (in our case study, it has been set to 0.0001); m_c denotes the deviation between the DEA scores of performance for country c, i.e., the solution to program (1), and its DEA-MCDM score; z is a non-negative parameter to be estimated; and t is a parameter ranging from 0 to 1 that allows us to account for different scenarios in the objective function in Expression (2).

Fig. 3 provides a graphical illustration of our methodology. Furthermore, going beyond Castillo-Giménez et al. (2019), we have calculated our DEA-MCDM composite indicator under different theoretical scenarios regarding parameter t, which allows us to test the robustness of our results regarding both waste treatment performance and the rankings of countries. First, we consider a value for this parameter equal to 1, as the abovementioned paper does. In this scenario, the objective function in program (2) minimises the average distance between the DEA score of performance obtained from program (1), and the DEA-MCDM score, i.e., the city-block or *Manhattan* concept of distance. Second, we assume that t equals 0, i.e., the chessboard or *Tchebychev* concept of distance. This scenario involves maximising the waste treatment performance of the country that is most penalised with the DEA composite indicator. Borrowing the terminology in Bernini et al. (2013), we refer to these two scenarios as to the *collective optimum* and the *most penalised country optimum*, respectively. And third, we consider a final scenario that consists of taking the definite integral of the composite indicators

[4] Rogge et al. (2017) have recently performed a conditional directional distance *Benefit-of-the-Doubt* analysis of waste performance of regions in the EU.

[5] These weights can be obtained from the dual formulation of program (1) (see Tone, 2001; p.503).

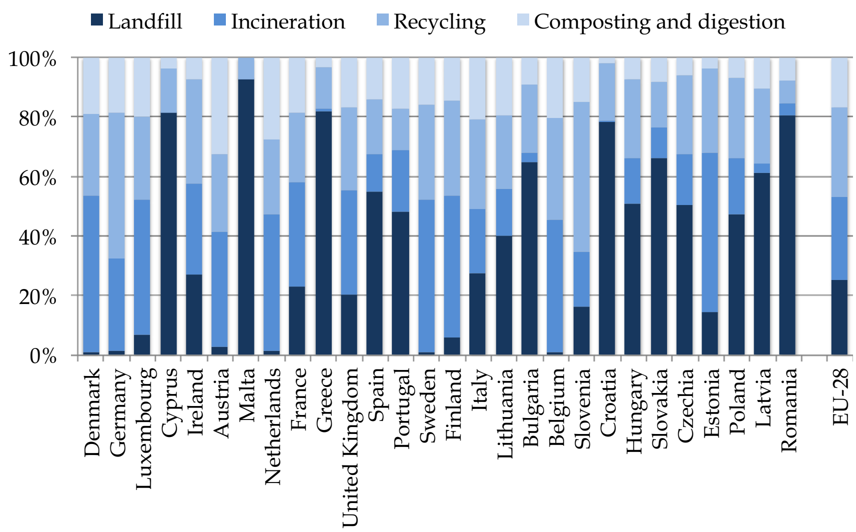

Fig. 2. Municipal waste treatment by type of operation, EU-28 member states. Average 2015–17 (%). Source: *Eurostat*. Note: *Countries are sorted as in* Fig. 1.

obtained with values of t ranging from 0 to 1 as each country's single indicator of waste performance[6]; this solution, which Reig-Martínez et al. (2011) call the *integer* scenario, avoids subjectivity in choosing the value for the parameter t.

2.2.2. Second stage: kernel densities and cluster analysis

For a more in-depth examination of performance in municipal waste treatment, a couple of additional analyses can be carried out through kernel densities and cluster analysis. Kernel densities, both weighted and unweighted, help uncover highly valuable information about the distribution of waste treatment performance across both EU-28 member states and citizens. Furthermore, cluster analysis allow us to identify clubs of countries within the sample that display similar patterns of performance.

In the field of non-parametric statistics, kernel densities are tools that enable in-depth exploratory data analysis (Fox, 1990; Henderson and Parmeter, 2015). In our case study, they entail computing the following density function for the composite indicator of performance in the municipal waste treatment:

$$\hat{f}(\text{composite indicator}) = \frac{1}{28h}\sum_{c=1}^{28} K\left[\frac{1}{h}(\text{composite indicator} - \text{composite indicator}_c)\right] \quad (3)$$

where composite indicator_c represents the indicator of the performance of country c; K is a kernel function; and h is a smoothing bandwidth parameter (Jones et al., 1996).

Regarding the kernel function, for the sake of computational ease, we use the *Gaussian* function, which is given by the following expression[7]:

$$K(\text{composite indicator}) = \left(\sqrt{2\pi}\right)^{-1} \exp\left(-\frac{1}{2}\text{composite indicator}^2\right) \quad (4)$$

In terms of the density function of Expression (3), when the probability mass is concentrated around a given value of the composite indicator of performance then convergence to that value exists. Conversely, when the density function has several modes, groups of countries can be identified concentrating around different levels of performance.

A salient feature of the EU-28 is the marked differences between some of its members in terms of population; as such, unweighted kernels might offer a biased picture of the distribution of performance in waste treatment across citizens. For example, as we explain later, our results show that Luxembourg is one of the best performers in the EU-28 at treating waste, but it barely has 0.6 million inhabitants, equivalent to only 1.5% of the population of Poland, one of the worst performers. In order to account for such disparities, a weighting element can be easily included in the kernel function as:

$$\hat{f}(\text{composite indicator}) = \frac{1}{28h}\sum_{c=1}^{28} \gamma_c K\left[\frac{1}{h}(\text{composite indicator} - \text{composite indicator}_c)\right] \quad (5)$$

where γ_c stands for the weighting for country c, calculated in our case study as the share of its population in the aggregate EU-28 population.[8]

The computation of kernel densities allows us to analyse the entire distribution of performance in the treatment of municipal waste across EU-28 member states and their citizens, at the same time as offering evidence of the concentration of performance around given scores. However, this approach does not allow the endogenous identification of groups or clubs of countries with similar levels of performance, information that might be of great interest for EU policymakers in charge of environmental policies. In order to overcome this limitation, a cluster analysis can subsequently be carried out. In this paper, we employ hierarchical clustering methods[9] to identify groups of countries behaving similarly in terms of their performance in the treatment of municipal waste. This approach relies on establishing a hierarchical structure to assess the links between observations (Everitt et al., 2011). Taking the *Euclidean* distance and its squared value as (dis)similarity measures (Lance and Williams, 1967), we apply several agglomerative methods, including the single-, complete- and average-linkage ones, in addition to Ward's method (Everitt et al., 2011 describe the differences between these methods), to test for the robustness of the groups' compositions.

The results from the cluster analysis can be further represented in the form of tree diagrams commonly known as *dendrograms*, from

[6] In practice, approximating the definite integral requires computing a series of composite indicators with enough values for t –e.g., at intervals of 0.001, as we do in this paper– and then calculating their average.

[7] Other alternatives are the *Epanechnikov*, the cosine, the triangular or the rectangular kernel functions, although in practice there should be little difference between them.

[8] Herrerias (2012) highlights the importance of employing weighted kernel densities.

[9] An alternative is the use of non-hierarchical clustering methods; however, these are much less popular mainly due to issues with implementation.

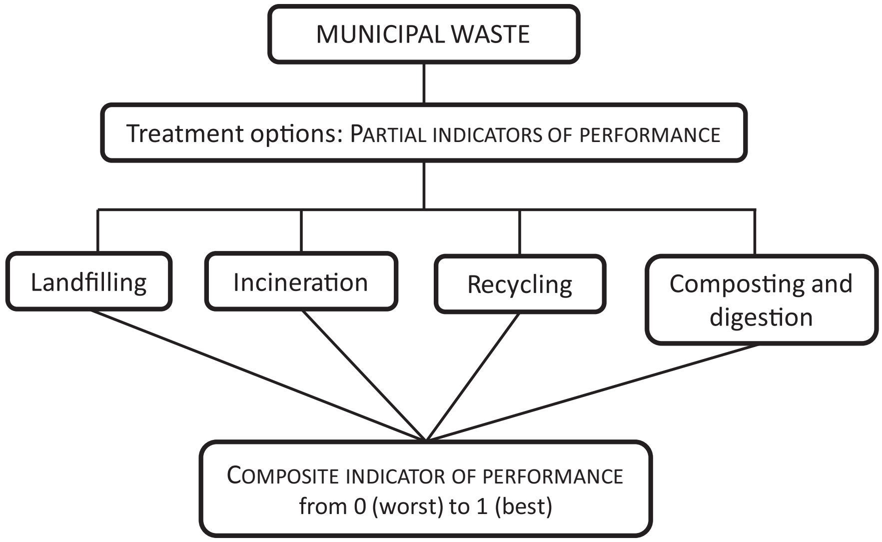

Fig. 3. From partial indicators to a composite indicator of performance in municipal waste treatment.

which the researcher can select the number of representative groups or clusters in the sample. This is not, however, an easy task, since decisions can be made on the basis of different criteria; in this respect, the most common approach is to assume that when there is a large distance between two groups of observations—countries in our case study—they belong to different clusters.

3. Results and discussion

3.1. Performance in the treatment of municipal waste: results and rankings

Let us start by commenting on the results for performance in the treatment of municipal waste by EU-28 member states. Table 1 displays some descriptive statistics for our composite indicators of performance calculated in the collective optimum, most penalised country optimum and integer scenarios[10]; the averages are 0.035, 0.046 and 0.042, respectively. Furthermore, Table 2 presents the full ranking of countries in these DEA-MCDM scenarios. In all three scenarios, the best performers are Denmark, Austria, the Netherlands and Luxembourg,[11] while the worst performers are Eastern European countries that joined the EU from the 2000s onwards, such as Romania, Croatia, Poland and Malta.[12] These results confirm that the ranking of the EU-28 member states remains fairly stable regardless of the scenario in which performance in municipal waste treatment is assessed. In this respect, bilateral Spearman-rank correlations between indicators are in all cases positive and statistically significant at the 1% confidence level (Table 3). In addition, the results of a Kruskal-Wallis test (see Conover, 1999) do not allow us to reject the null hypothesis that the three composite indicators of performance are from the same population, also at standard confidence levels.

In short, our assessment of performance and the ranking of the EU-28 member states are not notably sensitive to the theoretical assumptions made in the second stage of the computation of our DEA-MCDM composite indicator. Thus, in order to avoid subjectivity, we henceforth focus our analysis on the performance scores calculated in the integer scenario, which, as noted in Section 2.2.1, averages the performance scores in all potential scenarios from the collective optimum to the most penalised country one.

3.2. Distribution of waste treatment performance and cluster analysis

Having ranked the EU-28 member states according to their municipal waste treatment performance, in a second stage we carried out a couple of further analyses involving kernel densities and clustering techniques. As mentioned above, both of these analyses are based on the performance results obtained in the integer scenario. Fig. 4 shows the kernel distribution of unweighted (solid line) and population-weighted (dashed line) performance in waste treatment. The mode of the distribution of unweighted performance stands slightly above 0.03, with a significant dispersion that further supports the existence of notable differences in performance across countries.

Nevertheless, disparities in population size among EU-28 member states (around 82 million people live in Germany, whereas Malta has only half a million inhabitants) make it difficult to address the distribution of waste treatment performance across EU citizens using unweighted kernels. Conversely, the population-weighted kernel density in Fig. 4 reveals a well-defined mode around 0.05, which covers a large proportion of the EU-28 population, including France (66.6 million citizens), the United Kingdom (65.4 million), Italy (60.7 million) and Spain (46.5 million), along with other less populated countries. Moreover, there is a second mode around a performance score of 0.02; a number of (relatively) highly-populated countries register performance

Table 1
Composite indicators of performance in the treatment of municipal waste.

DEA-MCDM scenario	Average	Standard deviation	Maximum	Minimum
Collective optimum	0.035	0.018	0.092	0.011
Most penalised country optimum	0.046	0.027	0.114	0.012
Integer	0.042	0.023	0.097	0.015

[10] In this respect, the DEA composite indicator designates five countries as full efficient, i.e., awarded a performance score of one: Denmark, Germany, Cyprus, Malta and Austria. This means that these countries cannot be ranked against each other with this indicator, and highlights the importance of combining DEA with MCDM in order to overcome the lack of discriminatory power of the DEA indicator, and to obtain a full ranking of all the countries.

[11] It is worth commenting here that being the best performers in waste management might not be entirely good news since, as pointed out by Castillo-Giménez et al. (2019), it could imply poor performance in waste prevention. However, as explained in the Introduction, our composite indicator of performance only assesses waste treatment and not waste prevention.

[12] The largest jump in the rankings corresponds to Estonia, which ranks 28th in the collective optimum scenario and 12th in the most penalised country optimum scenario. Any other changes in the rankings are far less notable.

Table 2
Performance in the treatment of municipal waste: Ranking of countries.

Country	DEA-MCDM scenario			Population (Million inhabitants)
	Integer	Collective optimum	Most penalised country optimum	
Denmark	1	2	1	5.7
Austria	2	1	4	8.7
Netherlands	3	3	3	17.0
Luxembourg	4	4	2	0.6
Germany	5	5	6	82.0
France	6	6	8	66.6
United Kingdom	7	10	10	65.4
Sweden	8	13	5	9.9
Italy	9	7	14	60.7
Belgium	10	11	11	11.3
Portugal	11	9	13	10.3
Lithuania	12	8	15	2.9
Finland	13	14	7	5.5
Spain	14	12	16	46.5
Ireland	15	16	9	4.7
Slovenia	16	15	20	2.1
Cyprus	17	18	17	0.9
Bulgaria	18	17	25	7.2
Hungary	19	20	19	9.8
Estonia	20	28	12	1.3
Slovakia	21	21	24	5.4
Greece	22	22	22	10.8
Latvia	23	19	27	2.0
Czechia	24	23	21	10.6
Malta	25	26	18	0.5
Poland	26	24	23	38.0
Croatia	27	27	26	4.2
Romania	28	25	28	19.8

Note: Countries are ordered according to their score or performance in the integer scenario.

scores around this left mode, including Greece (10.8 million inhabitants), Czechia (10.6 million) and, particularly, Poland (38 million). Finally, it is striking that from a performance score of approximately 0.075, the unweighted density outstrips the population-weighted density; this indicates that the best performers in municipal waste treatment are, in general, less populated countries, e.g., Denmark (5.7 million inhabitants), Austria (8.7 millions), the Netherlands (17 million) and Luxembourg (only 0.6 million).

All in all, a large proportion of EU-28 citizens live in countries that achieve medium-low performance in the treatment of the municipal waste they generate. Moreover, a smaller group of citizens, although important in relative terms, experiences low performance, while only a small fraction of European citizens enjoy high-performance waste treatment.

Although much more informative than cold figures on waste treatment performance, kernel densities do not allow EU-28 member states to be properly classified in homogeneous groups. In order to do so, we

Table 3
Spearman-rank correlations between indicators of performance calculated in the different DEA-MCDM scenarios.

	Collective optimum	Most penalised country optimum	Integer
Collective optimum	1	–	–
Most penalised country optimum	0.776***	1	–
Integer	0.955***	0.897***	1

*** Indicates statistical significance at 1%.

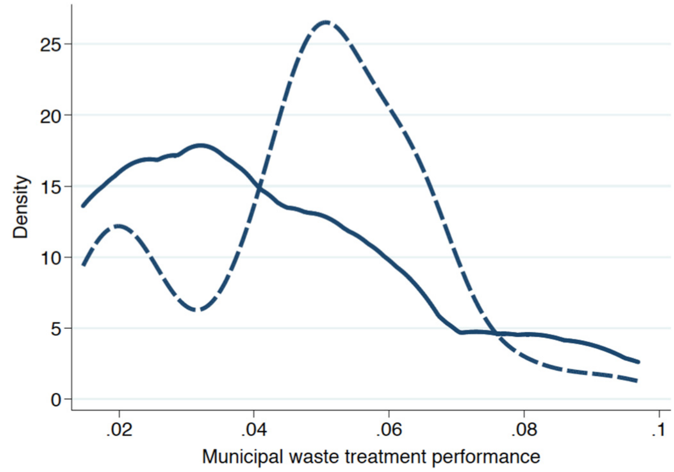

Fig. 4. Kernel densities of the DEA-MCDM composite indicator of performance in municipal waste treatment (integer scenario): unweighted (*solid line*), population-weighted (*dashed line*). Source: *Own elaboration*.

have carried out a hierarchical cluster analysis using the aggregation methods described in Section 2.2.2. Mihai and Apostol (2012) have previously studied the disparities in municipal waste management across the members of the European Union-27 using cluster analysis; these authors carried out three separate analyses for grouping countries according to their rates of waste generation, and waste treatment through both landfill and incineration. In a similar vein, the European Environment Agency (EEA) (Blumenthal, 2011) offers a reasonable approach for grouping countries that accounts for the combined rates of incineration and material recovery, the latter being represented by the sum of recycling and composting treatments. Our research contributes with a classification of countries in the EU-28 by means of a composite indicator of performance that jointly accounts for different types of municipal waste treatment, i.e., landfill, incineration, recycling, and composting and digestion.

That said, Fig. 5 shows the dendrograms resulting from our cluster analyses; they depict the step-by-step aggregation procedures for the sample of countries, with the height of the lines representing the distance between countries or groups of countries. At first glance, the structure of clusters seems to be largely consistent across clustering methods. Nonetheless, an objective comparison of the results from different methods is unfeasible; thus, for the sake of simplicity, we have assigned each country to the cluster in which it is most often classified. The results, which are shown in Table 4, indicate that we have identified four clusters. Ordered from high to low waste treatment performance, these clusters are:

i) Cluster #1: Denmark and Austria.
ii) Cluster #2: the Netherlands, Luxembourg, Germany and France.
iii) Cluster #3: the United Kingdom, Sweden, Italy, Belgium, Portugal, Lithuania, Finland, Spain, Ireland and Slovenia.
iv) Cluster #4: Cyprus, Bulgaria, Hungary, Estonia, Slovakia, Greece, Latvia, Czechia, Malta, Poland, Croatia and Romania.

Table 5 includes additional information that allows a further characterisation of these groups of countries. Cluster #1 includes the two top performers, but these countries only represent 2.8% of the aggregate population in the EU-28. The average performance in this group weighted by population is 0.092. The population-weighted rate of waste treatment per capita is the highest of all the groups at 645.1 kg per inhabitant. Landfill represents a minor proportion of the total waste treated—only 1.9%—whereas recycling, composting and digestion account for more than half. Lastly, the population-weighted average

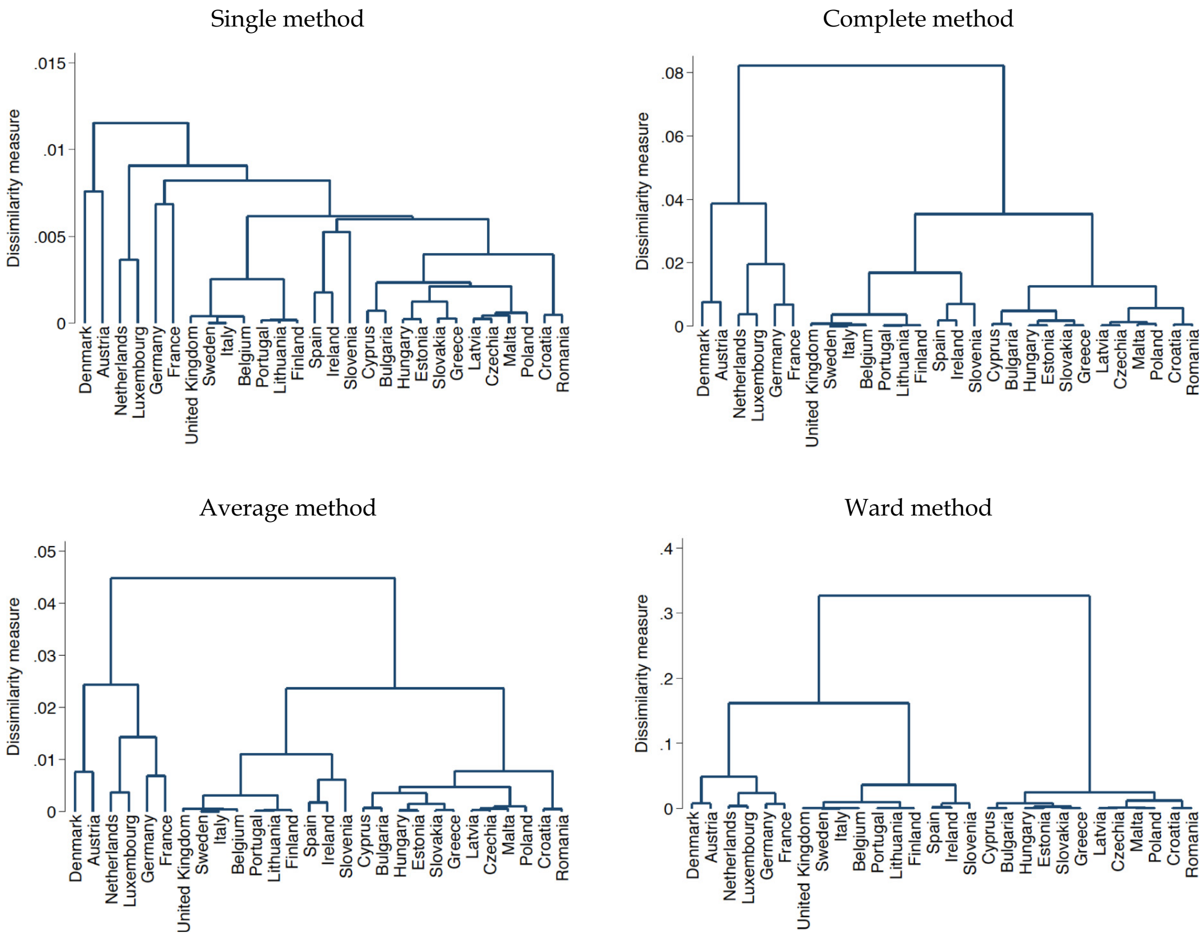

Fig. 5. Dendrograms from cluster analyses: Clubs of countries defined according to their performance in waste treatment. Source: *Own elaboration.*

Table 4
Results from the cluster analyses.

Country	Clustering method				Assigned cluster
	Simple	Complete	Average	Ward	
Denmark	1	1	1	1	1
Austria	1	1	1	1	1
Netherlands	2	2	2	2	2
Luxembourg	2	2	2	2	2
Germany	3	2	2	2	2
France	3	2	2	2	2
United Kingdom	4	3	3	3	3
Sweden	4	3	3	3	3
Italy	4	3	3	3	3
Belgium	4	3	3	3	3
Portugal	4	3	3	3	3
Lithuania	4	3	3	3	3
Finland	4	3	3	3	3
Spain	4	3	3	3	3
Ireland	4	3	3	3	3
Slovenia	4	3	3	3	3
Cyprus	4	4	4	4	4
Bulgaria	4	4	4	4	4
Hungary	4	4	4	4	4
Estonia	4	4	4	4	4
Slovakia	4	4	4	4	4
Greece	4	4	4	4	4
Latvia	4	4	4	4	4
Czechia	4	4	4	4	4
Malta	4	4	4	4	4
Poland	4	4	4	4	4
Croatia	4	4	4	4	4
Romania	4	4	4	4	4

Note: Countries are assigned to the cluster in which they are most often classified.

income per capita—in PPPs to ensure comparability across countries—is €37,900, the highest of all the groups.[13]

At the opposite end, cluster #4 brings together the worst performers, which are mostly countries that joined the EU from the 2000s onwards, in addition to Greece. This group displays a weighted average performance of 0.021 and represents 21.6% of the total EU-28 population. Countries in this cluster mostly form the left mode of the population-weighted kernel density in Fig. 4. The amount of municipal waste treated is 339.6 kg per capita, largely managed through landfill (60.4%); accordingly, recycling, composting and digestion together only score 27%, which is by far the lowest rate across groups. Lastly, most countries in this cluster are among the poorer European economies, i.e., population-weighted average income per capita scarcely reaches €20,700.

Clusters #2 and #3 are larger, representing 32.6% and 43% of the total population, respectively. These figures indicate that performance in the treatment of municipal waste generated by more than three-quarters of EU-28 citizens is medium or even medium-low, as already suggested by the main mode of the weighted kernel density in Fig. 4. Population-weighted average performance is 0.064 and 0.047 in clusters #2 and #3, respectively; and these groups treat a weighted average of 572.2

[13] As noted by Minelgaitė and Liobikienė (2019), waste generation (and thus its treatment) largely depends on the level of economic development, so that richer countries tend to generate higher amounts of municipal waste. In order to assess performance, our composite indicator—which, as highlighted in the Introduction, is focused only on waste treatment—takes into account both the quantity of waste treated and the way it is are treated; e.g., the quantities of waste treated by Cyprus and Malta are among the highest in the EU-28, but both these countries are included in the group of the worst performers because their waste is mostly managed through landfill.

Table 5
Characterisation of clusters.

	Cluster #1	Cluster #2	Cluster #3	Cluster #4
Average performance	0.093	0.069	0.045	0.021
Standard deviation	0.005	0.009	0.006	0.004
Population-weighted average performance[a]	0.092	0.064	0.047	0.020
Share of EU-28 population (%)	2.8	32.6	43.0	21.6
Population-weighted municipal waste treated (*kilograms* per capita)[a]	645.1	572.2	457.2	339.6
Landfill *(% of total waste treated)*[b]	1.9	8.9	29.2	60.4
Recycling, composting and digestion *(% of total waste treated)*[b]	52.8	56.8	43.6	27.0
Income per capita (*thousands € in PPPs*)[c]	37.8	45.6	31.9	21.8
Population-weighted income per capita (*thousands € in PPPs*)[c]	37.9	34.9	30.4	20.7

[a] Population-weighted performance at the cluster level has been calculated using the share of countries' population in the total population of the cluster they belong to as weights.
[b] These are weighted averages calculated using the share of countries' treated municipal waste in the aggregate waste treated by the cluster as weights.
[c] For the sake of comparability, the data correspond to PIB per capita in 2017 in purchasing power parities (PPPs), and they come from AMECO (accessed on 12 April 2019 through http://ec.europa.eu/economy_finance/ameco).

Table 6
Further clustering of countries in the group of worst performers (cluster #4).

	Sub-cluster #4a	Sub-cluster #4b
Countries	Cyprus; Bulgaria; Hungary; Estonia; Slovakia; Greece	Latvia; Czechia; Malta; Poland; Croatia; Romania
Average performance	0.025	0.018
Standard deviation	0.018	0.051
Population-weighted average performance[a]	0.024	0.018
Share of population in cluster #4 (%)	32.1	67.9
Population-weighted municipal waste treatment (*kilograms* per capita)[a]	421.2	291.2
Landfill (*% of total waste treated*)[b]	66.6	56.2
Recycling, composting and digestion (*% of total waste treated*)[b]	25.7	27.8
Income per capita (*thousands € in PPPs*)[c]	21.4	20.0
Population-weighted income per capita (*thousands € in PPPs*)[c]	22.2	21.0

Notes: Please see the footer of Table 5.

and 457.2 kg of waste per inhabitant, mainly through recycling, composting and digestion. Lastly, generally speaking, countries in both groups are high-income economies.[14]

Given that more than 40% of the members of the EU-28—12 out of 28—are included in the group of worst performers, and that performance in this group might be of particular interest to policymakers in charge of European environmental policies, we have further analysed the characteristics of countries in cluster #4. Results are shown in Table 6, in which two distinct sub-clusters are identified:

i) Sub-cluster #4a, including Cyprus, Bulgaria, Hungary, Estonia, Slovakia and Greece; these countries are home to 32.1% of the citizens in cluster 4.
ii) Sub-cluster #4b, which includes Latvia, Czechia, Malta, Poland, Croatia and Romania, countries that are home to the remaining 67.9% of the population in the group.

The population-weighted average performance in sub-clusters #4a and 4#b is 0.024 and 0.018 respectively, while municipal waste treated per inhabitant is 421.2 and 291.2 kg. Differences between the two subgroups in the relative shares of landfill, recycling, and composting and digestion waste treatments are not statistically significant; nor is the difference in income per capita.

In short, our cluster analyses provide robust empirical evidence that performance in the management of municipal waste by the current members of the EU-28 is positively correlated with their level of development, the amount of municipal waste treated per capita, and the share of recycling, composting and digestion in total waste treatment. The worst performers are, in general, poorer countries, which treat smaller quantities of municipal waste per capita, mainly through landfilling.

4. Summary, conclusions and policy issues

There is growing societal demand for sustainable growth, for which achieving an efficient management of municipal waste is a necessary condition. Recent literature has brought to light European Union (EU) members' convergence in performance in municipal waste treatment, particularly since the transposition of the 2008 *Waste Framework Directive* into national laws. However, there are still notable differences in performance. In this paper, we calculate a series of composite indicators of performance in the treatment of municipal waste by the members of the European Union-28 (EU-28). A salient feature of these indicators is that they jointly account for the amount of waste treated through four treatment types, namely, landfill, incineration, recycling, and composting and digestion. Moreover, we present an in-depth examination of the differences in performance across EU-28 member states.

Regarding our results, we find that, despite the efforts made by environmental policymakers and the convergence accomplished in recent years, differences in performance in the treatment of municipal waste across EU-28 member states are fairly significant. In general, the best performers are richer Northern and Central European countries that treat higher quantities of waste per inhabitant, mostly through recycling and composting and digestion. On the opposite, the worst performers are low-income Eastern European countries that joined the EU from the 2000s onward, and treat smaller amounts of waste per capita, mostly through landfilling. Our results also reveal that most European citizens live in countries that provide medium, or medium-low, performance levels in the treatment of municipal waste.

It is our belief that our results might be of interest to those responsible for setting European environmental policies, helping them to better design their strategies aimed at improving the management of municipal waste in the EU-28. In our opinion, these strategies should seek to further harmonise European legislation aimed at banning landfilling, or articulate other related policy measures aimed at reducing waste generation such as pay-as-you-throw schemes. At the same time, the use of alternative treatment procedures, particularly recycling, should be incentivised. Furthermore, additional national environmental policies targeted at improving the management and treatment of municipal waste are also needed in the worst performing members of the EU-28. Only in this way can the EU meet the targets and objectives (EEA, 2013) it has established for municipal waste generation and treatment in the period 2010–50.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

[14] Note that the unweighted income per capita in cluster #2 in Table 5 (€45,600 per inhabitant) is much higher than that of countries in cluster #1. This is exclusively due to the fact that Luxembourg, which is by far the richest country in the EU-28 (€75,700 per capita, as compared to an average of €30,000) is included in this group. However, only 0.6 million inhabitants reside in Luxembourg, so the population-weighted average income per capita of countries in cluster #2 is much lower.

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