



# Resource Taxes as an Instrument to Foster Circularity? Analysis of the Effects of Resource Taxation on Circular Economy Progress in Europe

Linda Deserno<sup>1</sup> · Ellen Sterk<sup>2</sup> 

Received: 12 January 2024 / Accepted: 23 September 2024 / Published online: 21 November 2024  
© The Author(s) 2024

## Abstract

The concept of Circular Economy (CE) keeps gaining momentum in political and societal debates as it is considered to contribute to a more sustainable use of natural resources. Policymakers seeking to foster CE progress require adequate regulatory instruments. One instrument often recommended is a tax on the use of natural resources. The present paper analyzes the effects of resource taxation on different CE indicators, especially resource productivity, based on panel data for 30 European countries from 1995 to 2021. The Augmented Mean Group (AMG) estimator is applied, and the results are checked for robustness using the Pooled Mean Group (PMG) estimator. Despite current low levels of resource taxation, the results indicate that resource taxation positively affects resource productivity at least in the short run. The effect differs substantially in different countries. Hence, resource taxation seems to foster circularity, but the results indicate that other factors are of influence and should be considered when designing policies.

**Keywords** Environmental tax · Resource taxation · Circular economy · CE indicators · Panel data regression analysis

**JEL Classification** F55 · H23 · L78 · Q58

## Introduction

### Motivation

Economic growth is strongly linked to investment, infrastructure, and construction activity which increases global material use [1]. Global material use is expected to rise from 89

---

✉ Ellen Sterk  
ellen.sterk@rwth-aachen.de

<sup>1</sup> RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany

<sup>2</sup> Research Unit International Economics, RWTH Aachen University, Templergraben 64, 52062 Aachen, Germany

Gigatons<sup>1</sup> in 2017 to 167 Gigatons by 2060 [1]. The sharply increasing resource demand does not only lead to the question of planetary limits to economic growth [2] but also— if further economic growth and prosperity are aimed at— requires society to significantly improve material management and its environmental impact. The impact of material use is not limited to resource depletion: Currently, extraction, processing, use, and disposal of materials are estimated to account for approximately 60% of global greenhouse gas (GHG) emissions [1]. Furthermore, material extraction directly contributes to 90% of total biodiversity loss and water stress impacts as well as up to 33% of health effects of air pollution [3]. The CE concept, which promotes the extension of resource use, is considered a solution component [4]. However, despite decreases in recycling costs due to technological progress, shares of secondary materials remain stable in current projections due to high labor costs and their high labor intensity compared to primary products and materials [1]. Consequently, implementation of further policy instruments is needed to foster economic transformation towards sustainability and circularity [5].

Mitigation of environmental impacts while ensuring resource supply and creating jobs through enhancement of resource efficiency and promotion of CE principles— e.g. through the creation of new job profiles along the value chain, especially with regard to recycling and maintenance— have been acknowledged as key societal goals by institutions at the national and international level [1]. In this vein, the United Nations' Agenda 2030 with its 17 Sustainable Development Goals (SDG) explicitly includes efficient use and sustainable management of natural resources in SDG 12 'Responsible consumption and production' [6]. Implementing these goals at the European level, the European Commission has launched the Green Deal which aims at increasing the economy's resource efficiency and competitiveness [5]. The latter shall be achieved by moving away from linear economic structures toward circular ones by fostering consecutive use of materials [5]. In this context, the CE Action Plan defines targets and strategies for a transformation towards a CE and sets up a monitoring framework with indicators aimed at measuring progress [4, 7]. The present paper makes use of these indicators in the context of the analysis.

For the regulation of natural resource management and resource efficiency, a multitude of potential policy instruments exists [8, 9]. In Europe, market-based policy instruments reinforcing the polluter-pays principle such as environmental taxes constitute an increasingly favored policy instrument for pollution control and natural resource management [10, 11]. Their effect is established through a price differential, making secondary resources more competitive in the market [12].

During the last decade, the topic of resource taxation has been intensively discussed as its implementation is requested and recommended by different stakeholders: At the EU level, the Commission outlines the importance of revising taxes and subsidies distorting real resource usage costs [13]. Resource taxation is also frequently discussed at national and sectorial levels, e.g. in Germany [12, 14–17]. At the same time, some European countries have already introduced resource taxes for specific resources, such as taxation on natural aggregates in place in Sweden, Denmark, and the UK [11, 18]. Nevertheless, robust empirical evidence on the effectiveness and steering effects of such taxes in European countries available at public scientific level is still lacking [19].

Therefore, the present article contributes to closing the research gap on the effectiveness of resource taxation for CE purposes by answering the following research question:

<sup>1</sup>Throughout this article, "ton" refers to a metric ton (1000 kg).

## *How do resource taxes impact the implementation of Circular Economy principles in European countries?*

The research question will be approached by regression analysis based on Eurostat and World Bank panel data applying AMG and PMG estimators. The remainder of this article will be structured as follows: **Background** section briefly summarizes current scientific literature on environmental taxation and its effects and, based on that, further explains the research gap the present paper aims to fill. Afterward, **Materials and Methods** section presents the data as well as the methods used. In **Results** section, results will be presented and then further discussed in **Discussion** section.

### **Background**

In the Eurostat definition, environmental taxes, i.e. “tax[es] whose tax base is a physical unit (or a proxy of a physical unit) of something that has proven, specific negative impact on the environment [...]” can be divided into energy, transport, pollution, and resource taxes [10]. Due to its direct relationship to material management, a core component of CE, the present paper focuses on resource taxation, even though resource and pollution tax together only account for 4% of total environmental taxes in Europe [20].

Many European countries have installed a resource tax, but their specific implementation differs strongly. One example is Sweden, which introduced a tax on the extraction of gravel in 1996 with a tax rate of around 0.57 EUR/t. Denmark introduced a more encompassing tax of around 0.67 EUR/t in 1990, which applies to stone, sand, gravel, peat, clay, and limestone and taxes not only the extraction but the import of these materials, too. A much higher tax rate is applied by the United Kingdom through their so-called aggregates levy. The extraction of sand, gravel, and crushed stone is taxed at around 2.30 EUR/t [21]. More current information on tax rates is not readily available, but the low values of change in relation to the countries’ GDP between 2010 and 2022 indicate that these rates have not changed much [22]. The experience with the taxation of natural resources in Europe is mixed and researchers argue that the impact of such a tax by itself is modest, but that the combination with other instruments is promising [11, 19].

For both researchers and policymakers, the implementation level, design, and effectiveness of environmental taxes in promoting sustainability goals are of great importance. In the scientific context, the role of environmental taxes in a transition towards CE is discussed rather sporadically. To obtain a comprehensive picture of the status quo of the scientific debate before diving deep into the analysis of the research question, a literature review<sup>2</sup> is conducted. The latter is not limited to resource taxation but also considers environmental taxation in general. The key results from the literature research are presented in the following.

Milios proposes a tax framework for fostering CE which includes resource and waste hierarchy taxation as well as tax reliefs for reuse and repair [23]. In this framework, raw material resource taxation constitutes the most mature component due to its implementation

<sup>2</sup>Literature was searched via the Scopus database searching for full papers using the following keyword combinations: “Circular Economy” AND “Environmental Tax” as well as “Circular Economy” AND “Resource Tax”.

in several European countries[22].<sup>3</sup> Virgin resource taxation may counter market failure, internalize environmental externalities of resource depletion, and prevent the transformation of materials into waste [11, 12]. A study by the European Environment Agency on the effects of aggregates taxation assumes positive effects of taxation on material use but declares data to be insufficient to provide robust statistical results [18].

At the empirical level, numerous studies analyze the impact of CE indicators or environmental taxes on economic growth [24–27], sectoral production [28], and life satisfaction [29] or the impact of macroeconomic variables on environmental performance [30]. However, literature on the impact of environmental taxes on CE progress remains scarce and does not draw a uniform picture of tax effects.

A study for Spain shows that incineration and landfill taxation would have positive environmental impacts while not causing significant negative effects at the national economy level [28]. At the European level, the effects of environmental taxation on CE are found to depend on the indicator used, but energy, pollution, and transport taxes are found to positively contribute to overall CE progress [31]. In another study, environmental tax revenues show moderate correlations with Circular Material Use Rate (CMUR; 28.9%), recycling rates for municipal waste (25.8%), and resource productivity (RP; 17.4%), whereas correlations with other variables studied are low [24]. In the same vein, the relative importance of environmental tax revenues compared to total tax revenues is shown to have a significantly positive impact on CMUR and recycling rates [32]. In contrast, no significant effects of environmental taxes are found on the recycling rate of municipal waste [33] or RP at the European level [34, 35], whilst environmental taxes are even found to have a significant negative impact on RP in another study [36]. However, in a study focusing on Poland, the Czech Republic, Slovakia, and Hungary, a significantly positive effect of environmental taxes on RP is found [35]. Appendix A provides an overview of recent studies on environmental tax effects on CE in Europe.

Existing studies consider a multitude of different variables in their panel data models using a large variety of analysis methods. Due to the limited panel size in both years and individual countries due to data availability, this multitude of explanatory variables includes the risk of model overfit [37] and makes it difficult to draw robust conclusions from these models. Except for Ha [31], the existing studies analyze the effects of environmental taxes without distinguishing between tax categories. The study by Ha [31] combines pollution and resource tax revenues into one variable and only covers nine years. Thus, the current scientific literature cannot provide robust results on the effects of resource taxation on CE. In addition, a study by the European Environment Agency, while indicating a positive effect of resource taxation on resource use, is qualitative [18]. The present study aims to contribute to this research gap.

However, the literature review and preliminary research reveal important drawbacks that should be kept in mind during the analysis. First, the concept of CE itself can be measured through numerous indicators [7] due to its large scope, which makes it difficult to derive unambiguous results, which is also reflected in the studies outlined above. Second, researchers suggest that resource taxation as well as environmental taxation in general cannot be the sole solution towards CE progress, which should instead be addressed by a multitude of different simultaneous measures [8, 9, 12]. These may include taxes on backfilling [17],

<sup>3</sup>For a detailed overview of countries having introduced a resource tax in the scope of our study, see the table in Appendix B.

subsidies incentivizing eco-innovation [38], as well as a change in labor taxation [39–41]. Therefore, Vence and López Pérez outline that current environmental taxation still differs from circular taxation, i.e. taxation models explicitly and comprehensively supporting CE progress [42]. These potential limitations identified during the literature review are considered in the analysis of data.

## Materials and Methods

### Data Collection

We use regression analysis on data that we collect for this purpose to answer the research question stated in [Introduction](#) section. Our units of observation are member countries of the European Union (EU) as well as of the Schengen Zone to increase our dataset. We collect data from Eurostat<sup>4</sup> and the World Bank.<sup>5</sup> Due to issues with data availability or reliability, we exclude Liechtenstein, Romania, and Switzerland from the sample. Apart from these three countries, all members of the EU and/or the Schengen Zone are included.

To measure the implementation of CE principles in different countries, we choose our dependent variable from the CE monitoring framework published by the European Commission [7]. The framework contains 27 indicators in total from which we select a set of five indicators that all refer to entire economies instead of specific sectors and for which sufficient data is available to conduct a robust panel data analysis. This set resembles the indicators chosen in previous studies as referred to in [Appendix A](#). A table showing the specific reasons for the exclusion of each rejected indicator from the framework can be found in [Appendix B](#). RP, i.e. the relationship between a country's GDP and its use of natural resources (domestic material consumption, DMC), shows the decoupling of economic growth from natural resource extraction, which reflects the state of the economy's circularity [7]. In particular, RP expresses the resource efficiency of an economy, which is likely to be affected by resource taxation. Hence, it is chosen as the main dependent variable to be tested. Data on RP is readily available in Eurostat, but only from 2000 onwards. To exploit a longer time range, we calculate this variable ourselves according to the formula used by Eurostat [43]. Since data on the limiting factor, DMC, are available from 1995, we hereby gain five years in our time range which is now 1995–2021. Because we compare countries over time, we use real GDP corrected for inflation using chain-linked volumes. To allow for comparisons between countries, we control for purchasing power by adding a conversion factor as a control variable. This method, in contrast to transforming the values into purchasing power parities, retains RP in its commonly used entity (EUR/kg).

To increase the reliability of our study and to make it less vulnerable to potential drawbacks of RP as a CE indicator (see [Discussion](#) section), we furthermore test the effects of resource taxation on the following alternative dependent variables taken from the EU CE monitoring framework [7]:

- Material Footprint,

---

<sup>4</sup><https://ec.europa.eu/eurostat>

<sup>5</sup><https://data.worldbank.org>

- CMUR,
- Gross value added (GVA) related to CE sectors,
- Patents related to waste management and recycling.

Material Footprint measures raw material consumption, i.e. raw material equivalents needed for the products consumed within a country, regardless of whether it is domestic or foreign extraction or direct or indirect use of these raw materials, and is measured in tons per capita [7]. In contrast, CMUR, also referred to as circularity rate, does not focus on total resource use but measures the percentage of circular material use expressed through waste recycled corrected for imports and exports compared to total DMC [7]. Hence, the indicator outlines how much of the primary resources in an economy can be substituted by secondary materials [7]. Our fourth indicator, GVA related to CE sectors, measures the contribution of CE to economic growth [7] and is measured as a percentage of GDP to allow for cross-country comparison. Unlike the aforementioned indicators, which refer to the outputs of a CE transition, we understand patents related to waste management and recycling as an indicator for an ongoing or even upcoming CE transition based on innovation [7]. The indicator outlines the number of patents per million inhabitants which can be classified as related to recycling and secondary raw materials according to the Cooperative Patent Classification [7]. All alternative indicators are directly taken from Eurostat as additional calculations—as is done for RP—are not needed as the data does not include economic indicators requiring correction.

Our independent variable, the resource tax rate (RTR), requires calculations depicted in the formula below. The revenue from resource taxes in absolute terms is available but is problematic as a measure to compare countries over time. On the one hand, it is neither adjusted for purchasing power nor for inflation, and on the other hand, it blends the number of resources extracted and the height of the resource tax. Hence, to obtain a tax rate, we correct the revenue for inflation using chain-linking and then divide it by the amount of natural resources extracted (domestic extraction, DE). Since the total value for DE includes fossil energy materials/carriers [44], but the resource tax revenues do not apply to these materials<sup>6</sup> [22, 45], we subtract this part from the total value to obtain our denominator. Note that this calculated tax rate represents the effective tax rate rather than the formal one. In reality, not all resources are subject to resource taxation and tax bases may differ according to tax regimes. The tax rate is expressed in monetary units per ton, like e.g. carbon taxes in Europe.

$$\text{RTR [EUR/t]} = \frac{\frac{\text{Resource Tax Revenues}}{\text{Chain Linked Volumes Index}}}{\text{Total DE} - \text{DE fossil energy carriers}}$$

We control for GDP since, being one of its components, it influences RP directly. Furthermore, productivity variables are shown to increase with increasing GDP and vice versa (so-called procyclical behavior) [46]. To correct for skewed distributions and highly variable scales, we use the natural logarithm of RP and all alternative dependent variables as well

<sup>6</sup>Taxes on the extraction of oil and gas are not classified as resource but as energy taxes.

**Table 1** Description of the variables in the model

Variable	Definition	Unit	Source <sup>a</sup>
Resource Productivity (RP; log)	GDP in relation to the total amount of materials directly used by an economy (measured as DMC; $RP = \text{GDP} / \text{DMC}$ ; [43])	EUR / kg	Own calculations based on data from Eurostat and The World Bank
Resource Tax Rate (RTR)	Resource tax revenue per ton of DE (excl. fossil energy materials/carriers)	EUR / ton	Own calculations based on data from Eurostat
GDP per capita (log)	Real GDP per capita corrected for purchasing power	EUR / capita	Own calculations based on data from Eurostat and The World Bank
Fossil Energy	Share of fossil fuels in final energy consumption (solid fossil fuels, natural gas, and oil and petroleum products excluding biofuels)	%	Own calculations based on data from Eurostat
Purchasing Power Conversion Factor	Spatial price deflator and currency converter that controls for price level differences between countries, designed for comparisons of GDP	Factor	The World Bank

<sup>a</sup>Details on the calculations applied are available from the authors upon request

as GDP. Furthermore, we control for the share of non-renewable energy sources (the sum of solid fossil fuels, natural gas, and oil and petroleum products excluding biofuels) in total energy use. The latter is expected to strongly influence resource use and hence RP [47] as well as the material footprint and the CMUR, since energy production and consumption significantly contribute to total resource consumption but are not accounted for in resource taxes [7, 22]. We choose to control for this effect by including the share of non-renewable energy as a control variable, since this share cannot accurately be extracted from RP.<sup>7</sup> We further control for purchasing power to enable the comparison between countries i.e. in order to account for different price levels among countries since e.g. resource taxation in EUR/kg needs to be related to the overall country's price level. See Table 1 for a detailed description of the variables in our model.

Our regression model has the following form:

$$\ln(\text{RP}) = \beta_0 + \beta_1 \text{RTR} + \beta_2 \ln(\text{GDP}) + \beta_3 \text{share of fossil energy} + \delta \text{power purchasing conversion factor} + \epsilon$$

<sup>7</sup>While the data allow for the subtraction of non-renewable energy materials or carriers from DMC, data is missing on the output generated with these materials, which can therefore not be extracted from GDP.

## Model Selection

To choose an appropriate estimator for our data, we run several diagnostic tests. These can be found in Appendix C. The tests show that our data are cross-sectionally dependent in the errors, (at least partly) non-stationary, cointegrated, and have heterogeneous slopes. An estimation procedure that can deal with this type of data is the Augmented Mean Group (AMG) estimator by Eberhardt and Teal [48]. This estimator is also suitable for our data dimensions since it is designed for macro panels (moderate cross-section and time dimensions) [49]. The AMG estimator is applied to a model of the following form:

$$y_{it} = \beta_i x_{it} + u_{it}$$

where  $y_{it}$  is an observable variable that is regressed on an observable variable  $x_{it}$  with a country-specific slope  $\beta_i$ . The unobservable variables as well as the error term are included in  $u_{it}$ :

$$u_{it} = \alpha_{1i} + \lambda_i f_t + \varepsilon_{it}$$

with  $\alpha_{1i}$  being country-fixed effects that capture time-invariant heterogeneity across countries,  $f_t$  being an unobserved common factor, and  $\lambda_i$  the respective country-specific heterogeneous coefficients. The latter captures heterogeneity that varies over time as well as cross-sectional dependence [49]. Just like the related Mean Group (MG) estimator by Pesaran and Smith [50] and the Common Correlated Effects Mean Group (CCEMG) estimator by Pesaran [51], the AMG estimator first estimates an OLS regression for each country and then averages the resulting coefficients. The AMG estimator augments these OLS regressions with the so-called “common dynamic process” (cdp), which is derived from a pooled first-difference OLS with time dummies [49]. To test for a causal relationship between the RTR and RP, we apply a Granger-causality test [52] in two steps. Firstly, we fit a panel vector autoregression model with three lags of the RTR and RP. Then, we estimate the Granger causality Wald test for each equation in the panel VAR model. This tests the hypothesis that the RTR and its lags are jointly zero in the equation for RP (and vice versa) [53].

## Robustness Checks

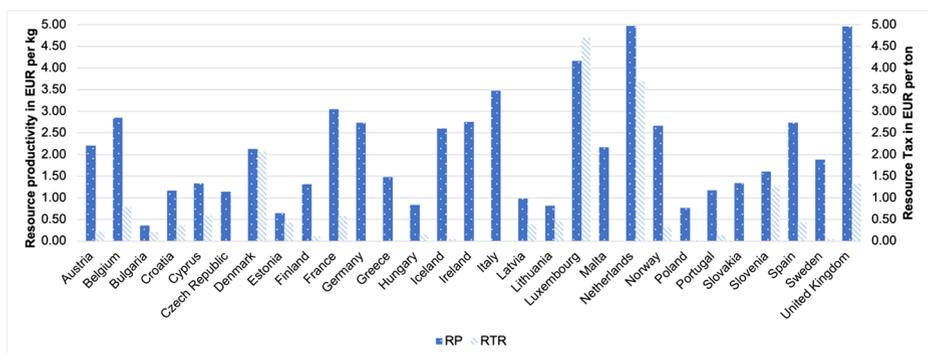
As a robustness check, we additionally apply the Pooled Mean Group (PMG) estimator by Pesaran et al. [54]. The PMG and MG [50] estimators have been developed to deal with slope heterogeneity, which often occurs in macro panels. Both estimators allow short-run coefficients, intercepts, and variances to vary between groups. In PMG, long-run coefficients are constrained to equality across countries assuming long-term equilibrium, while the MG estimator also allows for heterogeneity in the long run [55]. Both estimators are apt to deal with non-stationarity in the variables [55] and potential endogeneity issues. Since one could argue that resource taxes might be raised or installed to improve the country’s RP, or further unobserved variables are of influence, endogeneity could play a role in our case. While the AMG estimator does not take endogeneity into account, Eberhardt and Teal [48] argue that “adopting a nonstationary panel econometric approach that accounts for cross-section dependence [...] is a sound empirical alternative to address both these concerns” (p.

20), referring to endogeneity and instrument validity in macro panel data. Nevertheless, we apply an estimator that can deal with potential endogeneity (i.e., PMG) to check whether our results are potentially influenced in this way. Drawbacks of the PMG estimator to be kept in mind when interpreting the results are its lack of control for cross-sectional dependence as well as the assumption of long-term homogeneity. With the approach described, we follow the methodology of Sencer Atasoy [56] with the following deviations: Firstly, we choose only the PMG instead of both the PMG and the MG estimator as a robustness check, because it is more efficient if the assumption of long-run homogeneity is valid [56]. In samples where the observational units are arguably similar assuming a common equilibrium relationship in the long run is reasonable. With regard to EU countries, we assume that the fact of being subject to certain standards for political and regulatory frameworks, similar conditions in terms of climate and raw material accessibility as well a common history which is characterized by frequent mutual exchanges justifies the assumption of similarity among the observational units. Potential differences in economy among European countries are accounted for through the control variables. Secondly, we refrain from using the Common Correlated Effects Mean Group (CCEMG) estimator, because it requires too many degrees of freedom for our sample size.

## Results

### Descriptive Results

RP has a mean of 1.69 EUR/kg. Its minimum value is found in Bulgaria in 2001 at 0.26 EUR/kg and its maximum value of 5.88 EUR/kg belongs to the Netherlands in 2021. These values are based on our calculation of RP but are in line with those by Eurostat [57]. The mean RTR is 0.50 EUR/t. In a little less than one-third of our observations (excluding missing values), there is no RTR at all. Only four countries have introduced a resource tax during our time range from 1995 to 2021: Norway (2007), Luxembourg (2010), Iceland (2014), and Lithuania (2015). The highest RTR is found in Luxembourg in 2015 at 7.63 EUR/t. Note that these values depict the effective tax rates (see [Data Collection](#) section) and do not necessarily reflect the actual rates applied. See [Fig. 1](#) for an overview of RP and the RTR



**Fig. 1** Resource productivity and effective resource tax rate of European countries in 2019

**Table 2** Descriptive results

Variable	Nr. of obs	Unit	Mean	Std. Dev	Min	Max
RP	691	EUR/kg	1.69	1.02	0.26	5.88
RTR	641	EUR/t	0.50	1.00	0	7.63
GDP per capita	776	EUR	28,356.35	19,161.26	3191.15	101,321.90
Fossil energy consumption	781	%	59.30	14.13	16.55	83.66

*The purchasing power conversion factor is included in the model as a control variable, but omitted from this table as its parameters are not of interest*

per country in 2019.<sup>8</sup> The descriptive statistics of the variables in our model are listed in Table 2.<sup>9</sup>

A list of the included countries can be found in Appendix D ( $N=29$ ). The table also shows which years are included in the regression per country. In most cases, early observations are excluded because data on DMC, DE, and/or resource tax revenues in these years are not available. The earliest and latest data in our sample are from 1995 and 2021, respectively ( $T_{\max}=27$ ). The dataset is unbalanced.

## Regression Results

Table 3 shows the regression results of the AMG estimator with and without a time trend. We find a statistically significant positive effect of the RTR on RP. The results suggest that an increase in resource taxation of one EUR per ton of extracted material leads to an 8 to 10% increase in RP on average.

Since the AMG estimator calculates country-specific regressions in the first step, we can get these country-specific results. Table 4 shows large differences in the effect of a resource tax on the country's RP. We find strong evidence for a positive effect in Denmark, Portugal, Slovenia, Spain, and the United Kingdom and weak evidence for a positive effect in Sweden. In Latvia and Luxembourg, we find a negative effect of resource taxes on RP. In the other countries in which a resource tax is implemented, we find no significant effect.

Applying the model to alternative dependent variables that measure the progress of CE, we find an effect of the resource tax on some of them (see Table 5). While the RTR does not seem to influence the CMUR or the number of patents related to recycling and secondary raw materials, we find effects with respect to the material footprint and GVA from CE-related activities. The statistically significant effects in columns 3 and 4 imply that increasing the RTR (by one EUR/t) negatively influences a country's material footprint (by 11 to 16% on average). The effect of resources taxes on GVA is positive in both and statistically significant in the specification without a time trend (column 7), suggesting that an increase of tax rates by one EUR/t leads to an increase in GVA from CE-related activities as a share of GDP by around 9%. Note that the number of observations is decreased substantially when indicators other than RP are used because data is only available from later years on and/or not yet available until 2021.

Based on the test for Granger causality, we accept the null hypothesis that the RTR does not Granger-cause RP and RP does not Granger-cause the RTR (see Table 6). This means that previous values of the RTR cannot be used to predict current values of RP or vice versa.

<sup>8</sup>2019 is chosen as the most recent year that is not influenced by the Covid-19 pandemic.

<sup>9</sup>The descriptive values refer to the variables in their base form. We partly use logarithmic transformation in the regressions.

**Table 3** Regression results using the AMG estimator

	(1)	(2)
	AMG	AMG with trend
RTR	0.0841** (0.0323)	0.104* (0.0447)
Log GDP p.c	0.0437 (0.129)	-0.175 (0.171)
Fossil Energy Consumption	-0.00581 (0.00418)	-0.00247 (0.00399)
Purchasing Power Conv. Factor	0.0899 (0.168)	0.142 (0.114)
c_d_p	0.716*** (0.142)	0.606** (0.201)
trend		0.00404 (0.00499)
_cons	0.189 (1.249)	2.133 (1.344)
<i>N</i>	625	625

Standard errors in parentheses

+ $p < 0.10$ , \* $p < 0.05$ , \*\* $p < 0.01$ ,\*\*\* $p < 0.001$ **Table 4** Country-specific regression results

Country	Resource Tax Rate	
	Without trend	With trend
Austria	0.212	0.368
Belgium	-0.041	-0.068
Bulgaria	0.016	-0.042
Croatia	0.158	0.163
Cyprus	0.230	0.207
Denmark	0.082*	0.081+
Estonia	-0.148	-0.121
Finland	1.184	1.205
France	0.258	0.233
Hungary	0.342	0.322
Iceland	0.032	0.632
Ireland	9.710	4.452
Latvia	-3.487**	-4.519**
Lithuania	0.049	0.056
Luxembourg	-0.029**	-0.030**
Netherlands	0.023	0.001
Norway	0.448	0.447
Poland	0.310	0.737
Portugal	3.113***	2.565***
Slovenia	0.158**	0.132*
Spain	0.705**	0.767***
Sweden	1.626	2.720+
United Kingdom	0.058**	0.053**

Countries in which no resource tax is implemented are omitted from the table

+ $p < 0.10$ , \* $p < 0.05$ , \*\* $p < 0.01$ ,\*\*\* $p < 0.001$

**Table 5** Regression results with alternative dependent variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	RP	RP with trend	Material Footprint	Material Footprint with trend	CMUR	CMUR with trend	GVA	GVA with trend	Patents	Patents with trend
RTR	0.0841** (0.0323)	0.104* (0.0447)	-0.163** (0.0593)	-0.108* (0.0516)	0.00395 (0.137)	0.0183 (0.0821)	0.0891* (0.0446)	0.0466 (0.0369)	0.343 (0.309)	0.177 (0.312)
Log GDP p.c	0.0437 (0.129)	-0.175 (0.171)	0.966*** (0.154)	0.844*** (0.243)	0.112 (0.369)	0.232 (0.706)	-0.482** (0.162)	-0.591** (0.183)	-2.164 (1.653)	-0.671 (1.818)
Fossil Energy	-0.00581 (0.00418)	-0.00247 (0.00399)	0.00528 (0.00547)	0.00280 (0.00732)	-0.00728 (0.0138)	-0.0170 (0.0117)	0.00173 (0.00430)	0.00262 (0.00378)	-0.0282 (0.0238)	-0.0749** (0.0233)
PPP	0.0899 (0.168)	0.142 (0.114)	0.168 (0.370)	-0.755 (0.578)	-1.166 (1.360)	-1.231 (1.318)	-0.387 (0.355)	-0.485 (0.413)	-1.378 (1.830)	-0.701 (1.389)
c_d_p	0.716*** (0.142)	0.606** (0.201)	0.883*** (0.170)	0.984*** (0.176)	0.527 (0.544)	0.472 (0.805)	0.896*** (0.172)	1.004*** (0.197)	0.496 (0.454)	0.392 (0.596)
trend		0.00404 (0.00499)		-0.00594 (0.0128)		0.00375 (0.0280)		-0.00390 (0.00722)		-0.0320 (0.0540)
_cons	0.189 (1.249)	2.133 (1.344)	-7.553*** (1.218)	-7.199*** (1.886)	7.602 (5.654)	8.763 (7.913)	6.060*** (1.826)	7.073*** (1.961)	21.37 (15.84)	16.77 (14.38)
N	625	625	346	346	299	299	422	422	386	379

Standard errors in parentheses

All dependent variables are logarithmized

+*p*<0.10, \**p*<0.05, \*\**p*<0.01, \*\*\**p*<0.001

**Table 6** Results of the Granger-causality test

	chi2	p-value
RTR → RP	0.260	0.967
RP → RTR	1.296	0.730

## Robustness of Results

The regression results using the PMG estimator show an insignificant long-run, but marginally significant and positive short-run effect (see Table 7), suggesting that the positive effect of the RTR on RP is limited to a short-run effect. The coefficient of the error correction term (ec) is negative and statistically significant, meaning that the variables indeed converge to a long-run equilibrium [55]. Note that, since the PMG estimator is not apt to deal with cross-sectional dependence, the result should be interpreted with care.

The results are also checked for robustness against outliers. We apply the criteria of being more than 1.5 times the interquartile range (IQR) above the third quartile of the RTR to

**Table 7** Regression results using the PMG estimator

	(1) PMG
Long Run	
RTR	– 0.0100 (0.0210)
Log GDP p.c	0.304*** (0.0393)
Fossil Energy Consumption	–0.0195*** (0.00226)
PPP	– 0.00265 (0.00193)
Short Run	
Ec	– 0.320*** (0.0595)
D.RTR	0.718+ (0.422)
D. Log GDP p.c	– 0.337* (0.161)
D. Fossil Energy Consumption	– 0.00307 (0.00390)
D.PPP	– 0.704** (0.266)
_cons	– 0.570*** (0.141)
N	596

Standard errors in parentheses

+ $p < 0.10$ , \* $p < 0.05$ , \*\* $p < 0.01$ ,  
\*\*\* $p < 0.001$

identify outliers. Excluding these observations, the regression results remain qualitatively the same with respect to the positive and statistically significant effect of the RTR on RP.<sup>10</sup>

## Discussion

### Discussion of Results

As outlined in the previous section, our analysis indicates that resource taxation contributes to CE progress when considering RP, material footprint, or the share of GVA related to CE activities as CE indicators. However, for two other CE indicators—CMUR and patents related to recycling and secondary materials—no significant impact of resource taxation could be found. This ambiguity in results depending on the indicator used is in line with findings from previous studies on environmental tax effectiveness for CE progress purposes shown in the introduction. The concept of CE itself has multiple definitions and can be understood differently depending on the focus set [58, 59]. After analyzing and categorizing a variety of different CE indicators at different levels, Moraga et al. [58] conclude that CE requires a set of indicators to be holistically assessed. However, such a set of indicators is not currently available and would furthermore cause substantial difficulties for regression analysis due to the multitude of dependent variables. Thus, with the knowledge of the possible shortcomings of a single indicator and the absence of a combined indicator encompassing all dimensions of CE, it was decided to target multiple indicators for the analysis. Nevertheless, the different CE indicators and their advantages and potential drawbacks as well as further limitations to the results will be discussed in more detail in this section.

The effect of an increase of 8 to 10% in RP if resource taxes are increased by one EUR per ton might seem extremely high at first sight. However, it needs to be considered that the dataset is based on aggregate country data even though resource taxation is most probably currently only applied to a relatively small number of resources, so the total calculated RTR only has a mean of 0.50 EUR per ton. Hence, an increase of one EUR would, in relative terms, correspond to an increase of 200% in resource taxation. To put these values in perspective, note that tax rates of 2 to 3 EUR per ton<sup>11</sup> are recommended for the implementation of a resource tax on construction minerals in Germany [12, 17, 21].

Despite the positive results in the main analysis, the results using the PMG estimator do not show a significant long-run effect and the Granger causality test does not show a causal relationship between resource taxation and RP, the latter meaning we cannot predict future RP based on previous or current resource taxation values with reasonable certainty. The lack of a significant long-run effect and statistical causality may be explained by different factors, such as the limited time span in data availability, the isolation of resource taxation as one measure of a potential policy mix as well as potential distortions in the resource tax variable. These will each be explained in detail in the following.

According to the OECD [1], transformations of industrial sectors and their value chains are assumed to take 25 years. Even though our dataset comprises 25 years, the effects of changes in resource taxation which occurred within this time might only become visible in

<sup>10</sup>The results are available from the authors upon request.

<sup>11</sup>Note that such a tax rate would be reflected in our data as much lower, since construction materials only make up a part, although significant, of all materials consumed within an economy.

the future and cannot be displayed in the dataset at the current point of time. In addition, for many countries in our sample, 25 consecutive years after resource tax implementation or increase are not available. Especially with the ongoing CE debate, our study can only be understood as a first step, and it would be worth analyzing the effects of resource taxation again at a later point in time with a larger database.

Furthermore, it should be kept in mind that major resource problems are often addressed by a multitude of different simultaneous measures since the use of multiple policy instruments is seen as more efficient than a single instrument in many cases [8, 9, 60]. Such instruments could e.g. include criteria for public tenders, restricted mining licenses, or regulations for selective demolition [19]. Thus, it might seem expected that resource taxation as a single instrument cannot be proven to have a significant causal impact on RP. In this context, it is also important to remember that the RTR used during the analysis only reflects part of the actual resource taxation in Europe since taxation and especially environmental tax reform competencies fostering resource efficiency are not limited to the national level, but regions also play a supplementary role [9]. The environmental tax data considered includes central, state, and local government taxes as well as social security funds [10] which on the one hand enables to capture all environmental taxes in a country but, on the other hand, makes it more difficult to analyze single effects as the area and/or sector they apply to cannot precisely be delimited, limiting the accuracy of results.

The resource tax variable itself may also be subject to distortions: as resource tax revenues depend on the number of primary resources used, tax revenues would not constitute a suitable manner for comparing regulatory measures across countries. Changes in tax revenues could result from both changes in tax rates or bases as well as from changes in economic agents' behavior [22]. Hence, it was decided to manually calculate the effective RTR. However, the actual resource taxes may only tax specific raw materials. Thus, as no comprehensive information on the respective tax bases is available, the tax rates calculated are an approximation. Hence, the results can only be interpreted as an indication of the effectiveness of resource taxation but an in-depth analysis at sector or resource level is strongly recommended once sufficient data is available. In such analysis, the motivation for tax introduction should also be taken into consideration since even an environmental tax may be only fiscally motivated [22] and motivation could be crucial for tax design and hence effectiveness regarding environmental effects. The variety in country-specific results gives another potential reason why RP progress cannot reliably be predicted from resource taxation only and will be discussed later. Furthermore, the metrics used in this analysis treat im- and exports of materials differently. In addition, imports fall under the resource tax in some but not all countries. Therefore, it is not possible to neatly calculate RP or a tax rate taking material trade into account. The results were checked for robustness to this impurity in data by adding im- and exports of materials as control variables as well as calculating RP with domestic extraction as a denominator only. The results are qualitatively unchanged in both cases.<sup>12</sup>

Despite these limitations, the fact that not only RP but also material footprint and the share of CE-related GVA seem to be significantly affected by resource taxation strengthens our conclusion of a positive effect of resource taxation on CE progress. Even though RP seems to perfectly illustrate if a country has achieved decoupling economic growth from resource use at first sight, it needs to be considered that RP increases may also result from outsourcing of

<sup>12</sup>The results are available from the authors upon request.

material-intensive production steps [61]. However, the material footprint is explicitly outlined to be robust to production outsourcing and includes raw material consumption from products produced abroad [7]. At the same time, it should be noted that material footprint does not account for the countries' level of economic prosperity which is included in RP by correcting GDP for purchasing power. Despite these limitations, since resource taxation seems to decrease the material footprint per capita whilst increasing RP, we conclude that the positive impact on CE indicators is not distorted by potential drawbacks of the indicators caused by the globalization of value chains or different levels of economic prosperity. However, it still needs to be considered that the economic crisis between 2007 and 2014 led to an increase in RP due to declined construction activity, resulting in a stronger decrease in DMC compared to GDP [62]. As material footprint is a mass-based indicator that is as such heavily influenced by construction activity, the crisis will most likely have had the same effect on the material footprint. Based on these considerations, we checked CE-related GVA, which also seemed to be positively affected by resource taxation, for any decline or other obvious impact from the financial crisis. However, we could not depict any anomalies in the dataset during this period. Therefore, we conclude that the effects of resource taxation on our indicators are not driven by the economic crisis.

It seems astonishing that no significant effect of resource taxation on CMUR is found. Thus, it seems necessary to analyze the indicator in more detail. Recent research on the CMUR showed that variation in the indicator during the last almost 20 years was rather driven by changes in the denominator, DMC, whilst recycling amounts remained more or less stable [63]. This might explain why we find an effect when applying indicators that are more directly related to total material consumption than CMUR. Furthermore, the maturity of the indicator needs to be questioned since it only considers recycling [63] but cannot properly display other circular material uses. These would currently only be reflected through a decrease in the denominator, i.e. DMC, but not an increase in the numerator of the indicator, even though they would—at least theoretically—be part of it. Furthermore, Eurostat data induces that definitions used to collect data should be further clarified [64]. If there were different understandings of definitions amongst European countries, this might distort and hence weaken the indicator in its current state. Finally, a large share of the CMUR data is marked as a “Eurostat estimate”, while for some countries, there is no data at all. The finding that resource taxation does not seem to influence the relative number of patents related to waste management and recycling in a country could be a result of not distinguishing between different material flows. For example, one major stream of resource consumption is minerals, for which the recycling process is already advanced enough to produce secondary materials of high quality. Thus, progress in this area would not necessarily be reflected in new patents.

As mentioned above, the country-specific results show that resource taxes are far from uniformly effective. We find evidence—whether strong or weak—of a positive effect of the tax on RP in six countries. Further two countries even show a negative effect and six countries do not have any resource tax installed. This leaves 16 countries in which the tax does not seem to influence RP. In addition, the effect sizes also vary strongly between the countries with a significantly positive effect. This suggests that there are further unobserved factors that influence this relationship. One candidate for such a factor is the specific implementation of the tax. As mentioned above, tax systems fall under the jurisdiction of the national governments or even federal states, leading to a wide range of specifications of the same tax in different countries. These differences are not reflected in our data and could thus explain the differences

in the effects. The countries with a negative effect are especially interesting. For Latvia, data on resource tax revenues are only available from 2008. The effective tax rates we calculate range from 0.20 to 0.42 EUR per ton. Luxembourg draws a very different picture: The country installed a resource tax in 2010, which shows very high variation (the effective tax rate ranges from 2.37 to 7.63 EUR per ton). It is conceivable that the effects are artifacts or reflect a potential issue of reverse causality: The countries might have implemented or raised resource taxes to foster the CE based on low performances thus far. However, unequivocally explaining the effects of resource taxation for Latvia and Luxembourg would require an in-depth analysis of other potential influencing factors leading to the effects of resource taxation seemingly strongly deviating from tendencies observed in other countries or the cross-country analysis.

## Outlook

As mentioned, regulatory environmental incentivization most likely includes a set of different measures. As tax incentives are rarely installed in isolation (see above), it is conceivable that at least some countries implemented the resource tax in combination with other measures. The potential variety of these accompanying measures and their interplay with the resource tax is another conceivable factor that determines whether and to what extent the resource tax affects RP. One endeavor for future research could be to identify these distinguishing factors to inform policymakers regarding the most efficient way to design policy instruments and their combinations. In the introduction, it was already outlined that regulatory incentivization of circular practices might also include changes in labor taxation [39–41]. An example is the environmental tax reform, which implies shifting taxation from labor and capital to pollution and resource depletion [65]. For simplicity and data availability reasons, labor taxation is not included in the present model.

Similarly, our model could be extended by including waste taxation, which is suggested in the CE taxation framework by [23]. However, lack of data availability is the reason why this variable is not included in the model: Environmental taxation data at the European level only reports pollution taxes [10], which, besides waste taxes, also includes taxes on emissions to air and water, as well as noise taxes [10]. In addition, these taxes are only reported as revenues [10] which would— analogously to resource taxation— lead to additional uncertainties due to different tax bases being mixed up if tax rates were calculated.

A profound understanding of policy intervention effects on resource efficiency would also require detailed analysis at the sectoral level [1]. Throughout the elaboration of the present paper, attempts have been made to conduct a corresponding regression analysis for the construction sector since it is specifically known to have significant impacts in terms of resource consumption and waste generation [4]. However, due to the unavailability of sector-split DMC data in the Eurostat database, alternative databases were taken into consideration. During the analysis, significant differences in the total economy's DMC data manifested between Eurostat and its considered alternatives. To ensure data reliability as well as coherence between different datasets considered for the analysis, only total economy data are analyzed in the present analysis.

In summary, resource taxation— even though it might still play a smaller role in Europe than other environmental taxes— seems to contribute to CE progress even in its current stadium. Nevertheless, further research should be conducted to investigate the effects and moderating factors of regulatory measures on CE progress in more detail.

The research conducted in the present paper could not only be extended by a more detailed analysis of different sectors, but also by enlarging the geographic scope of the study to other regions of the world since resource depletion can be considered as a global problem. However, data availability and comparability currently constitute a major barrier to such avenues for further research.

## Appendix A: Overview of selected empirical studies analyzing the effects of environmental taxation (highlighted in italics) in the CE context in Europe at country-level (own table)

Authors	Period observed	Empirical methods	Dependent Variables (CE indicators)	Independent variables
Ha, 2022 [31]	2011–2019	- Panel-corrected Standard Errors Model - Feasible Generalized Least Squares Estimates - Autoregressive Distributed Lag Method	- Patents associated with recycling & secondary raw materials - Generation of municipal waste - CMUR - Waste recycling share (total & for specific waste fractions)	- <i>Environmental tax revenues (total/energy/resource &amp; pollution/transportation)</i> - Gross Domestic Product (GDP) per capita - Trade share - Net inflow of foreign direct investment - Industrialization level - Environmental Performance Index - Natural rents - Democratization
Kostakis & Tsagarakis, 2022 [32]	2010–2017	- Fixed effect panel data analysis - Instrumental variable fixed effect panel analysis	- CMUR - Recycling rate of municipal waste	- Real GDP per capita - Tertiary education level - Fertility rate - Urbanization - <i>Environmental taxes (% of total tax revenues)</i> - Research & Development (R&D) expenditure
Robaina et al., 2020 [36]	2000–2016	- Cluster analysis - Panel unit root test - Panel cointegration test - Vector autoregression model	- RP	- <i>Environmental tax revenues (% of GDP)</i> - Renewable energy consumption - R&D expenditure - Recycling rate - Population density - Gross value added (GVA) per sector
Tantau et al., 2018 [33]	2010–2014	- Random and fixed effects panel data analysis	- Recycling rate of municipal waste	- CMUR - R&D expenditure - RP - Trade in recyclable raw materials - <i>Environmental tax revenues</i>

Authors	Period observed	Empirical methods	Dependent Variables (CE indicators)	Independent variables
Taušová et al., 2022 [35]	1990–2020	- Multiple linear regression analysis	- RP	- Domestic material consumption (DMC) per capita - Energy productivity - Recycling rate - Water productivity - Landfill rate - GHG emissions per capita - Energy dependence - Eco-Innovation - Energy taxation - <i>Environmental taxes (% of GDP)</i> - Share of renewable energy - Waste generation - CMUR
Vuță et al., 2018 [34]	2005–2016	- Panel data regression analysis	- RP - Real GDP growth rate	- Recycling rates (packaging, biowaste, municipal waste) - <i>Environmental tax revenues (% of GDP)</i> - CE research activity (patents, R&D expenditure) - Real GDP growth rate

## Appendix B: CE Monitoring Framework Indicators: Reasons for in- or exclusion in the model

No	Indicator	Inclusion in the model (Yes (Y)/No (N))	Indicator description and rationale for in-/exclusion
1a	Material footprint	Y	The material footprint measures an economy's raw material consumption, i.e. domestic and foreign extractions required directly or indirectly for the consumption of an economy [7]. As it is robust to production outsourcing [7], it is particularly interesting to consider this indicator in addition to RP. A drawback to this indicator is that the data are only fully available from 2008 on
1b	Resource productivity (RP)	Y	RP is deemed suitable for the analysis because it sets resource consumption into relation to economic activity. Hence it expresses if an economy becomes more resource-efficient which might potentially also be fostered by resource taxation
2	Green public procurement	N	Indicator is still being developed [7]
3a	Total waste generation per capita	N	Sustainable resource use which could be fostered by resource taxation should also result in decreasing amounts of waste. While we would have liked to include the indicator in our analysis, data is only available from 2004 on and recorded biannually. This leaves us with an insufficient database to run any meaningful regressions
3b	Total waste generation (excl. major mineral waste) per GDP	N	The indicator explicitly excludes major mineral waste which accounts for a large share of resource use and hence of resources potentially taxed [66]. We assume that mining and quarrying as well as construction sector could be a main focus area of resource taxation

No	Indicator	Inclusion in the model (Yes (Y)/No (N))	Indicator description and rationale for in-/exclusion
3c	Generation of municipal waste per capita	N	Resource taxation has a broad scope and may include all kinds of natural resource use or depletion [10]. In the absence of reliable EU-wide data on which types of resource taxes account for the largest share in resource taxation, we refrained from applying sector-specific CE indicators because we cannot reliably assume sector-specific causal effects
3d	Food waste	N	
3e	Generation of packaging waste per capita	N	
3f	Generation of plastic packaging waste per capita	N	
4a	Recycling rate for municipal waste	N	
4b	Recycling rate for all waste excl. major mineral waste	N	Major mineral waste includes mainly construction/demolition and mining wastes [67]. However, we assume that mining and quarrying as well as construction sector could be a main focus area of resource taxation. Hence, the indicator does not seem to be suitable for our analysis
5a	Recycling rate for overall packaging waste	N	Resource taxation has a broad scope and may include all kinds of natural resource use or depletion [10]. In the absence of reliable EU-wide data on which types of resource taxes account for the largest share in resource taxation, we refrained from applying sector-specific CE indicators because we cannot reliably assume sector-specific causal effects
5b	Recycling rate for plastic packaging waste	N	
5c	Recycling rate for electrical and electronic equipment waste that is separately collected	N	
6a	Circular material use rate (CMUR)	Y	Primary resource taxation is assumed to increase resource prices. The latter might also increase the demand for and use of secondary materials which would then be reflected in the circular material use rate expressing the ratio of recycled waste material to overall material demand [7]. A drawback of this indicator is that the data are only fully available from 2010 on and declared as “estimates” by Eurostat. Data for some countries are lacking entirely [68]
6b	End-of-life recycling input rate	N	Limited data availability, data is only collected every three years from 2013 onwards [7]
7a	Recyclable raw material imports from outside the EU	N	The indicator focuses on specific material categories. In the 2023 update of the EC CE Monitoring framework, the following categories were added to the indicator: ‘glass’, ‘wood’, ‘textiles’, ‘minerals’, and ‘animal and vegetal’ products [7]. The latter categories do not yet seem to be integrated in the dataset [69], but constitute important shares of total material use [66]. Since we assume them to be potentially relevant targets for resource taxation, we consider the indicator as not suitable for our purposes in the status quo of data available
7b	Recyclable raw material exports to outside the EU	N	
7c	Intra-EU trade in recyclable raw materials	N	

No	Indicator	Inclusion in the model (Yes (Y)/No (N))	Indicator description and rationale for in-/exclusion
8a	Private investments related to CE sectors	N	To keep analysis of resource taxation effects clear and concise, we decided to limit the total number of indicators analyzed. Hence, it was decided to include only one of the competitiveness indicators. Out of these three indicators, the share of CE-related GVA seemed to be most directly influenced by resource taxation. Moreover, we assume private investments to potentially have a delayed effect that we cannot control for.
8b	Employment related to CE sectors	N	Finally, employment figures might not necessarily reflect all improvements in CE activities (i.e., CE progress can also occur to a certain extent with constant employment levels)
8c	Gross value added related to CE sectors	Y	
9	Patents related to waste management and recycling	Y	The indicator reflects innovation activity related to recycling and secondary raw materials [7]. As transformation of industrial sectors and its value chains are assumed to take 25 years [1] which exceeds the time span for which data is available. Indicators such as RP illustrate the results of a transition process towards CE whilst patents could also show the transition in progress
10a	Consumption footprint	N	Data availability: data only available from 2010 onwards
10b	GHG emissions from production activities	N	To our understanding, there is no direct link between resource taxation and GHG emission, except for the emissions caused by recycling activities. We would expect other environmental taxes to have significant effects on GHG emissions (e.g., energy or pollution taxes)
11a	Material import dependency	N	The indicator reflects the ratio between (net) material imports and material inputs or material consumption [7]. If total material input decreases due to CE transition, the ratio may not reflect this progress properly if e.g., the imports decrease at the same rate as input or if they even remain stable since the material group imported cannot yet be replaced by secondary materials.
11b	EU-self sufficiency of raw materials	N	Hence, we decided not to include the indicator in our analysis

## Appendix C: Diagnostic tests for the choice of an estimation procedure

While panel data offer a large potential for (economic) research, they come with the risk of cross-sectional dependence. Ignoring the interdependence between observational units leads to biased estimation results (e.g., [70]). Therefore, we test for the presence of cross-sectional dependence in our data using Pesaran's [71] CD test. The null hypothesis for this test is cross-sectional independence. The result indicates that we should reject the null hypothesis and thus that we are dealing with cross-sectional dependence in our data (see Table 8). To support this result, we also apply the Lagrange Multiplier (LM) test by Breusch and Pagan [72] and the bias-adjusted LM test by Pesaran, Ullah, and Yamagata [73] on a balanced subset of our data,<sup>13</sup> which confirm the presence of cross-sectional dependence.

As a next step, we apply the CIPS test by Pesaran [74] instead of first-generation unit root tests to test for stationarity, as it allows for cross-sectional dependence. As can be seen in Table 9, we accept the null hypothesis of non-stationarity for the RTR but not RP and the consumption of energy from fossil sources. These variables appear to be stationary in their

<sup>13</sup>These tests are only applicable to balanced datasets.

**Table 8** Results of Pesaran's [71] CD test

Test	Statistic	p-value
Pesaran (2004) CD Test (postestimation after xtreg, fe)	7.641	0.000

level form. The results further suggest that GDP per capita and the purchasing power conversion factor are stationary in their first difference, but only in the specifications without and with a time trend, respectively.

To test the cointegration relationship between the variables, we again apply a second-generation test that takes cross-sectional dependence into account. Table 10 shows the results of the Westerlund [75] test of cointegration. The test rejects the null hypothesis of no cointegration and both alternative hypotheses – cointegration in some as well as in all panels – are accepted.

A final test of our data is that of slope homogeneity. The assumption of slope homogeneity is often invalid in panels with fairly large cross-sectional and time dimensions and consequently, estimation procedures that assume slope homogeneity are biased [50]. We apply the test by Pesaran and Yamagata [76], which is robust to cross-sectional dependence. As expected, we find slope heterogeneity in our data (see Table 11).

**Table 9** Results of Pesaran's [74] CIPS test for unit-root

	Intercept	Intercept+Trend
Log RP	-4.255***	-5.199***
RTR	3.394	2.692
Log GDP p.c	0.792	2.839
Fossil Energy Consump	-1.550 <sup>+</sup>	-2.906**
Purchasing Power Conv. Factor	1.915	-0.427
Δ Log RP	-2.232*	-3.371***
Δ RTR	4.619	3.823
Δ Log GDP p.c	-1.464 <sup>+</sup>	0.879
Δ Fossil Energy Consump	0.499	-1.631 <sup>+</sup>
Δ Purchasing Power Conv. Factor	0.512	-2.172*

<sup>+</sup> $p < 0.10$ , \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$

**Table 10** Results of Westerlund's [75] test for cointegration

	Statistic	p-value
Variance ratio (some panels)	-3.7013	0.0001
Variance ratio (all panels)	-2.1094	0.0175

**Table 11** Results of Pesaran and Yamagata's [76] test for slope homogeneity

	Delta	p-value
Non-adjusted	17.412	0.000
adjusted	20.497	0.000

*The table shows the values for the overall model with all three explanatory variables. Separate tests show that all individual explanatory variables have heterogeneous slopes*

## Appendix D: Overview of the countries in the model

Country	Resource Tax (1995–2021)	Years included in regression
Austria	yes	1995–2020
Belgium	yes	1995–2020
Bulgaria	yes	2000–2020
Croatia	yes	2000–2020
Cyprus	yes	2008–2020
Czechia	no	1995–2020
Denmark	yes	1995–2020
Estonia	yes	2000–2020
Finland	yes	2000–2020
France	yes	2008–2020
Germany	no	2000–2020
Greece	no	2000–2020
Hungary	yes	1995–2020
Iceland	since 2014	1995–2019
Ireland	yes	1995–2021
Italy	no	1995–2021
Latvia	yes	2008–2020
Lithuania	since 2015	2000–2020
Luxembourg	since 2010	2000–2020
Malta	no	2000–2020
Netherlands	yes	1996–2020
Norway	since 2007	2006–2020
Poland	yes	2003–2020
Portugal	yes	1995–2020
Slovakia	no	1998–2021
Slovenia	yes	1995–2020
Spain	yes	2000–2020
Sweden	yes	2008–2020
United Kingdom	yes	2000–2019

**Acknowledgements** This work was carried out within the framework of the Research Group Verbund.NRW, which is funded by the Ministry of Culture and Science of the State of North Rhine- Westphalia (Germany).

**Funding** Open Access funding enabled and organized by Projekt DEAL. The research leading to these results received funding from the Ministry of Culture and Science of the State of North Rhine- Westphalia (Germany).

**Data Availability** The corresponding data is available under <https://doi.org/10.57760/sciencedb.14597>.

## Declarations

**Competing Interests** The authors have no competing interests to declare that are relevant to the content of this article.

## References

1. OECD (2019) Global material resources outlook to 2060: economic drivers and environmental consequences. OECD Publishing, Paris
2. Meadows DH, Club of Rome (1972) The Limits to growth: a report for the Club of Rome's project on the predicament of mankind. Universe Books, New York
3. World Bank (2022) Squaring the Circle: Policies from Europe's Circular Economy Transition. World Bank, Washington. <https://hdl.handle.net/10986/38380>
4. European Commission (2020) Circular Economy Action Plan - For a cleaner and more competitive Europe. Brussels
5. European Commission (2019) The European Green Deal. Brussels
6. United Nations (2015) Transforming Our World: The 2030 Agenda for Sustainable Development
7. European Commission (2023) COMMISSION STAFF WORKING DOCUMENT Measuring progress towards circular economy in the European Union– Key indicators for a revised monitoring framework Accompanying the document Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions on a revised monitoring framework for the circular economy. European Commission, Brussels
8. Coria J, Sterner T (2011) Natural resource management: challenges and policy options. *Annu Rev Resour Econ* 3:203–230. <https://doi.org/10.1146/annurev-resource-083110-120131>
9. Bahn-Walkowiak B, Wilts H (2017) The institutional dimension of resource efficiency in a multi-level governance system—Implications for policy mix design. *Energy Res Soc Sci* 33:163–172. <https://doi.org/10.1016/j.erss.2017.09.021>
10. Eurostat (2013) Environmental taxes: a statistical guide: 2013 edition, 2013th edn. Publications Office, Luxembourg
11. Söderholm P (2011) Taxing virgin natural resources: Lessons from aggregates taxation in Europe. *Resour Conserv Recycl* 55:911–922. <https://doi.org/10.1016/j.resconrec.2011.05.011>
12. Ludewig D, Meyer E (2012) Ressourcenschonung durch die Besteuerung von Primärbaustoffen. Green budget Germany (GBG), Berlin
13. European Commission (2011) Roadmap to a Resource Efficient Europe. Brussels
14. Bahn-Walkowiak B, Bleischwitz R, Sanden J (2010) Einführung einer Baustoffsteuer zur Erhöhung der Ressourceneffizienz im Baubereich
15. Meyer E (2012) Der Beitrag von Ressourcensteuern zu wirksamer Ressourcenschonung. In: Diskussionspapier. Forum ökologische-soziale Marktwirtschaft. <https://foes.de/pdf/2012-08-Diskussionspapier-Ressourcensteuern.pdf>
16. Baronick M, Burger A, Golde M, et al (2019) Positionspapier zur Primärbaustoffsteuer. Umweltbundesamt, Dessau-Roßlau
17. Ostertag K, Pfaff M, Jacob K, et al (2021) Optionen für ökonomische Instrumente des Ressourcenschutzes. Umweltbundesamt, Dessau-Roßlau
18. European Environment Agency (2008) Effectiveness of environmental taxes and charges for managing sand, gravel and rock extraction in selected EU countries. European Environment Agency, Copenhagen
19. Postpischil R, Jacob K (2018) Evaluationen von Abgaben auf Primärbaustoffe und wechselwirkenden Instrumenten: Eine Auswertung von Evaluationen aus GB, SE, DK und EE hinsichtlich ökologischer Lenkungswirkung, Effizienz und weiterer Effekte

20. Eurostat (2019) Environmental taxes in the EU: countries compared. <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20190212-1>
21. Bahn-Walkowiak B, Bleischwitz R, Distelkamp M, Meyer M (2012) Taxing construction minerals: a contribution to a resource-efficient Europe. *Miner Econ* 25:29–43. <https://doi.org/10.1007/s13563-012-0018-9>
22. European Commission (2022) Taxation trends in the European Union: Data for the EU Member States, Iceland, Norway, 2022nd edn. Publications Office of the European Union, Luxembourg
23. Milios L (2021) Towards a Circular Economy Taxation Framework: Expectations and Challenges of Implementation. *Circ Econ Sustain* 1:477–498. <https://doi.org/10.1007/s43615-020-00002-z>
24. Busu M, Trica CL (2019) Sustainability of circular economy indicators and their impact on economic growth of the European Union. *Sustain Switz* 11. <https://doi.org/10.3390/su11195481>
25. Hysa E, Kruja A, Rehman NU, Laurenti R (2020) Circular economy innovation and environmental sustainability impact on economic growth: An integrated model for sustainable development. *Sustain Switz* 12. <https://doi.org/10.3390/SU12124831>
26. Sabău-Popa CD, Bele AM, Dodescu AO, Boloş MI (2022) How Does the Circular Economy Applied in the European Union Support Sustainable Economic Development? *Sustain Switz* 14. <https://doi.org/10.3390/su14169932>
27. Georgescu I, Kinnunen J, Androniceanu A-M (2022) Empirical evidence on circular economy and economic development in Europe: a panel approach. *J Bus Econ Manag* 23:199–217. <https://doi.org/10.3846/jbem.2022.16050>
28. Freire-González J, Martínez-Sánchez V, Puig-Ventosa I (2022) Tools for a circular economy: Assessing waste taxation in a CGE multi-pollutant framework. *Waste Manag* 139:50–59. <https://doi.org/10.1016/j.wasman.2021.12.016>
29. Ortega-gil M, Cortés-sierra G, Elhichou-ahmed C (2021) The effect of environmental degradation, climate change, and the european green deal tools on life satisfaction. *Energies* 14. <https://doi.org/10.3390/en14185839>
30. Apalkova V, Tsyganov S, Meshko N et al (2022) Evaluation models for the impact of pricing factor on environmental performance in different countries. *Probl Perspect Manag* 20:135–148. [https://doi.org/10.21511/ppm.20\(2\).2022.12](https://doi.org/10.21511/ppm.20(2).2022.12)
31. Ha LT (2022) Is environmental tax an enabler of circularity: new insights from the unique database. *Environ Sci Pollut Res*. <https://doi.org/10.1007/s11356-022-23422-w>
32. Kostakis I, Tsagarakis KP (2022) Social and economic determinants of materials recycling and circularity in Europe: an empirical investigation. *Ann Reg Sci* 68:263–281. <https://doi.org/10.1007/s00168-021-01074-x>
33. Tantau AD, Maassen MA, Fratila L (2018) Models for analyzing the dependencies between indicators for a circular economy in the European Union. *Sustain Switz* 10. <https://doi.org/10.3390/su10072141>
34. Vuță M, Vuță M, Enciu A, Cioacă S-I (2018) Assessment of the circular economy's impact in the EU economic growth. *Amfiteatru Econ* 20:248–261
35. Taušová M, Tauš P, Domaracká L (2022) Sustainable development according to resource productivity in the EU environmental policy context. *Energies* 15. <https://doi.org/10.3390/en15124291>
36. Robaina M, Villar J, Pereira ET (2020) The determinants for a circular economy in Europe. *Environ Sci Pollut Res* 27:12566–12578. <https://doi.org/10.1007/s11356-020-07847-9>
37. Hawkins DM (2004) The problem of overfitting. *J Chem Inf Comput Sci* 44:1–12. <https://doi.org/10.1021/ci0342472>
38. Bimonte G, Ioppolo G, Senatore L, Trinconne B (2022) Government eco-innovation incentives in a recycling system: A Stackelberg-type model. *Bus Strategy Environ*. <https://doi.org/10.1002/bse.3337>
39. The Ex'tax Project (2014) New era. New plan. Fiscal reforms for an inclusive, circular economy. Case study the Netherlands. [https://ex-tax.com/wp-content/uploads/2019/09/The\\_Extax\\_Project\\_New\\_Era\\_New\\_Plan\\_report.pdf](https://ex-tax.com/wp-content/uploads/2019/09/The_Extax_Project_New_Era_New_Plan_report.pdf)
40. Kimla-Walenda K (2021) Circular economy calls for a tax system restructuring. In: *The Economics of Sustainable Transformation*. Taylor and Francis, pp 220–240
41. Vence X, López Pérez SJ (2021) Taxation for a circular economy: new instruments, reforms, and architectural changes in the fiscal system. *Sustainability* 13:4581. <https://doi.org/10.3390/su13084581>
42. Vence X, López Pérez SJ (2021) Taxation for a circular economy: New instruments, reforms, and architectural changes in the fiscal system. *Sustain Switz* 13. <https://doi.org/10.3390/su13084581>
43. Eurostat (2016) Glossary:Resource productivity. In: *Stat. Explain*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Resource\\_productivity](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Resource_productivity)
44. Eurostat (2018) Economy-wide material flow accounts - Handbook. Publications Office of the European Union, Luxembourg
45. Eurostat (2020) Environmental taxes by economic activity (NACE Rev. 2) (env\_ac\_taxind2). [https://ec.europa.eu/eurostat/cache/metadata/en/env\\_ac\\_taxind2\\_esms.htm](https://ec.europa.eu/eurostat/cache/metadata/en/env_ac_taxind2_esms.htm)

46. Basu S, Fernald J (2001) Why Is Productivity Procyclical? Why Do We Care? In: Hulten CR, Dean ER, Harper MJ (eds) *New Developments in Productivity Analysis*. University of Chicago Press, pp 225–302
47. European Environment Agency (2012) *The European environment: State and outlook 2010– Material resources and waste: 2012 update*. Publications Office, LU
48. Eberhardt M, Teal F (2010) Productivity analysis in global manufacturing production. *Univ Oxf*
49. Eberhardt M (2012) Estimating panel time-series models with heterogeneous slopes. *Stata J* 12:61–71
50. Pesaran MH, Smith R (1995) Estimating long-run relationships from dynamic heterogeneous panels. *J Econom* 68:79–113. [https://doi.org/10.1016/0304-4076\(94\)01644-F](https://doi.org/10.1016/0304-4076(94)01644-F)
51. Pesaran MH (2006) Estimation and Inference in Large Heterogeneous Panels with a Multifactor Error Structure. *Econometrica* 74:967–1012. <https://doi.org/10.1111/j.1468-0262.2006.00692.x>
52. Granger CWJ (1969) Investigating Causal Relations by Econometric Models and Cross-spectral Methods. *Econometrica* 37:424. <https://doi.org/10.2307/1912791>
53. Abrigo MRM, Love I (2016) Estimation of panel vector autoregression in Stata. *Stata J* 16:778–804
54. Pesaran MH, Shin Y, Smith RP (1999) Pooled mean group estimation of dynamic heterogeneous panels. *J Am Stat Assoc* 94:621–634. <https://doi.org/10.1080/01621459.1999.10474156>
55. Blackburne EF, Frank MW (2007) Estimation of nonstationary heterogeneous panels. *Stata J* 7:197–208
56. Sencer Atasoy B (2017) Testing the environmental Kuznets curve hypothesis across the U.S.: Evidence from panel mean group estimators. *Renew Sustain Energy Rev* 77:731–747. <https://doi.org/10.1016/j.rser.2017.04.050>
57. Eurostat (2022) Resource productivity statistics. In: *Stat. Explain*. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Resource\\_productivity\\_statistics#Resource\\_productivity\\_of\\_the\\_EU\\_and\\_across\\_Member\\_States\\_over\\_time](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Resource_productivity_statistics#Resource_productivity_of_the_EU_and_across_Member_States_over_time)
58. Moraga G, Huysveld S, Mathieux F et al (2019) Circular economy indicators: What do they measure? *Resour Conserv Recycl* 146:452–461. <https://doi.org/10.1016/j.resconrec.2019.03.045>
59. Vranjanac Ž, Radenović Ž, Radenović T, Živković S (2023) Modeling circular economy innovation and performance indicators in European Union countries. *Environ Sci Pollut Res* 30:81573–81584. <https://doi.org/10.1007/s11356-023-26431-5>
60. Benneer LS, Stavins RN (2007) Second-best theory and the use of multiple policy instruments. *Environ Resour Econ* 37:111–129. <https://doi.org/10.1007/s10640-007-9110-y>
61. Eurostat (2023) Resource Productivity Statistics. [https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Resource\\_productivity\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Resource_productivity_statistics)
62. European Environment Agency, ETC/WMGE (2016) *More from less, material resource efficiency in Europe: material resource efficiency in Europe: 2015 overview of policies, instruments and targets in 32 countries*. Publications Office, LU
63. Christis M, Vercauteren A, Nuss P et al (2023) Analysis of the circular material use rate and the doubling target. *European Topic Centre on Circular economy and resource use*. [https://youthstudies.co/pdf/etc-ce-report\\_cmur\\_final-for%20publication.pdf](https://youthstudies.co/pdf/etc-ce-report_cmur_final-for%20publication.pdf)
64. Eurostat, (2018) *Circular material use rate: calculation method: 2018 edition, 2018th edn*. Publications Office of the European Union, Luxembourg
65. Ekins P (2009) *Resource Productivity, Environmental Tax Reform and Sustainable Growth in Europe*. Anglo-German Foundation for the Study of Industrial Society, London
66. Eurostat (2023) Material flow accounts (env\_ac\_mfa). [https://ec.europa.eu/eurostat/cache/metadata/en/env\\_ac\\_mfa\\_sims.htm](https://ec.europa.eu/eurostat/cache/metadata/en/env_ac_mfa_sims.htm)
67. Eurostat (2022) Generation of waste excluding major mineral wastes per GDP unit (cei\_pc032). [https://ec.europa.eu/eurostat/cache/metadata/en/cei\\_pc032\\_esmsip2.htm](https://ec.europa.eu/eurostat/cache/metadata/en/cei_pc032_esmsip2.htm)
68. Eurostat (2023) Circular material use rate. [https://ec.europa.eu/eurostat/databrowser/view/cei\\_srm030/default/table?lang=en](https://ec.europa.eu/eurostat/databrowser/view/cei_srm030/default/table?lang=en)
69. Eurostat (2022) Trade in recyclable raw materials (cei\_srm020). [https://ec.europa.eu/eurostat/cache/metadata/en/cei\\_srm020\\_esmsip2.htm](https://ec.europa.eu/eurostat/cache/metadata/en/cei_srm020_esmsip2.htm)
70. Sarafidis V, Robertson D (2009) On the impact of error cross-sectional dependence in short dynamic panel estimation. *Econom J* 12:62–81. <https://doi.org/10.1111/j.1368-423X.2008.00260.x>
71. Pesaran MH (2004) General diagnostic tests for cross section dependence in panels. *SSRN Electron J*. <https://doi.org/10.2139/ssrn.572504>
72. Breusch TS, Pagan AR (1980) The lagrange multiplier test and its applications to model specification in econometrics. *Rev Econ Stud* 47:239. <https://doi.org/10.2307/2297111>
73. Pesaran MH, Ullah A, Yamagata T (2008) A bias-adjusted LM test of error cross-section independence. *Econom J* 11:105–127. <https://doi.org/10.1111/j.1368-423X.2007.00227.x>
74. Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. *J Appl Econom* 22:265–312. <https://doi.org/10.1002/jae.951>
75. Westerlund J (2005) New simple tests for panel cointegration. *Econom Rev* 24:297–316. <https://doi.org/10.1080/07474930500243019>

76. Pesaran MH, Yamagata T (2008) Testing slope homogeneity in large panels. *J Econom* 142:50–93. <https://doi.org/10.1016/j.jeconom.2007.05.010>

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.