



## Article

# Impact of Municipal Waste Recycling and Renewable Energy Consumption on CO<sub>2</sub> Emissions across the European Union (EU) Member Countries

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**Abstract:** The world population maintains a growing trend and in turn, the amount of municipal waste is also increasing. Rising municipal waste quantity poses a challenge for human beings and the environment, therefore recycling becomes important for environmental sustainability and circular economy. This study explores the effects of municipal waste recycling and renewable energy on the environment sustainability proxied by CO<sub>2</sub> emissions in EU member states over the period from 2004 to 2017 through panel cointegration and causality analyses. Recycling is considered an efficient way to reduce CO<sub>2</sub> emission, but surprisingly our results indicate mixed findings. The causality analysis revealed no significant interaction among recycling rate, renewable energy and CO<sub>2</sub> emissions. However, in the long run, the negative impact of recycling and renewable energy use on CO<sub>2</sub> emissions were revealed but varied among the countries. Results indicate that increasing renewable energy consumption will play a significant role in reducing greenhouse gas emissions. These findings must raise awareness among policymakers that should focus on the adoption and implementation of different types of sustainable energy policies that can affect directly or indirectly renewable energy sector development.

**Keywords:** municipal waste recycling; renewable energy; CO<sub>2</sub> emissions; panel cointegration and causality analyses



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## 1. Introduction

Climate change and CO<sub>2</sub> reduction as well as environmental pollution and recycling of municipal waste are seen as important and interrelated topics in society as well as in science these days [1].

Waste management, waste recovery, reuse and recycling are not new concepts or activities. As a result of increasing population levels, economic development and rapid urbanization, waste management has become a global issue. The World Bank report released in 2018 estimates that global waste generation will reach 3.40 billion tons by 2050 [2], therefore urgent measures to reduce negative impacts on health and the environment need to be adopted.

With climate change being an increasingly discussed topic, there is a move towards reducing greenhouse gas (GHG) emissions. In the European Union, waste management activities are a non-negligible source of greenhouse gases, it is estimated that in 2017 they represented about 3% of the total greenhouse gas emissions [3]. In this context, as part of the Circular Economy Action Plan [4] and the New Circular Economy Action Plan [5], a set of directives addressing waste management were adopted and implemented.

Transition from the traditional linear economy to a circular economy is not simple. Starting from the principles of a circular economy, is necessary to rethink the way that

resources are used and managed, trying to reduce waste and pollution and regenerating natural systems. Increasing life standards has positive but also negative impacts: this will increase consumption that in turn will generate more waste per capita. The increasing volume of waste forces countries to find and impose waste prevention and reduction programs, and also to find proper solutions for waste reuse and recycling. Special attention should be paid to municipal waste, since the population tends to be concentrated in large cities and spending habits of citizens from urban areas are increasing. Today, cities have become important centers of economic growth that comprise around 55% of the global population [6] and consume nearly two-thirds of total energy that generate around 70% of CO<sub>2</sub> emissions from the energy sector [7]. Waste is not only a problem associated with resource depletion but also has a harmful effect on the environment, and the recycling process can help us to conserve raw materials and to protect the environment for future generations.

The European Union focused on the problem of waste management and different strategies, programs, and policies were adopted to prevent waste generation and to increase reuse and waste recycling. The Waste Framework Directive (2008/98/EC) [8] that imposed EU country members to reach a 50% recycling rate for municipal waste has been revised and new targets have been included to be achieved by 2035. The disposal of municipal waste to landfills is to be gradually replaced by recycling. It is a certain fact that landfills are important sources of greenhouse gas emissions [9] and contribute significantly to ground waters and soil contamination, which can then enter into the food chain.

High recycling rates help municipalities to decrease waste disposal costs and to reduce negative impacts on the environment by reducing the amount of waste sent to landfills. Even the quantity of municipal waste is increasing across countries [10]; according to EUROSTAT [3] the total amount of municipal waste from EU countries that was landfilled during the period between 1995 and 2017 decreased by 60% as a result of increasing recycling or composed rates combined with waste burning.

Recycling emits less carbon dioxide than what would be emitted by extracting and processing raw materials [11], or by waste incineration and landfills [12], but the net emissions savings will differ based on each type of material that is recycled [13]. Resources demand can be decreased by focusing on the 3R concept: reduce, reuse, and recycle [14].

Pajula et al. [14] consider that besides the circular economy concept, life cycle thinking, and life cycle assessment concepts must be taken into account when the environmental impacts of the entire life cycle of products and services are analyzed.

Different studies highlight the fact that this situation is similar all over the world: the contribution of the waste sector to climate change is significant.

Zhang et al. [15], Sun et al. [16] have conducted studies that analyze the carbon emission from municipal solid waste in China or Asia. A study by Zhang et al. [15] was focused only on the Shenzhen region using a 10-year analysis period. Their results indicate that landfills can release a relatively significant amount of carbon emissions that can be reduced “by carrying a series of measures to recycle landfill gas”. These results are similar to other studies that acknowledge that waste incineration for power generation is a quick and thorough method, which could convert waste into heating energy that will contribute to resource recycling and will reduce carbon emissions.

Sun et al. [16] compared the carbon footprint of the waste management sector in China and Japan, and found that in China there were significantly higher CO<sub>2</sub> emissions from municipal solid waste treatment processes when compared to Japan.

Abdel-Shafy and Mansour [17], de la Barrera and Hooda [18], and Turner et al. [19], found that recycling helps in saving carbon emissions through different processes. They stipulate that GHG emissions savings can be achieved through the recycling of source-segregated waste materials (with some exceptions like soil, paint, plasterboard).

Recycling is becoming a powerful tool that improves sustainability performance. Through this process, both the direct and indirect emissions output can be reduced firstly by decreasing the extraction and production of raw materials, and secondly by the reduction in emissions from the disposal.

Referring to the relationship between renewable energy consumption and CO<sub>2</sub> emissions, empirical studies provide mixed results. Analyzing 24 Asian countries, Lu [20] found a long-running relationship between renewable energy consumption and CO<sub>2</sub> emissions and a bidirectional causal relationship between these variables.

Zoundi [21] focused on a panel of 25 selected African countries and found a negative impact of renewable energy on CO<sub>2</sub> emissions in the long run. Lee [22] examined the effect of renewable energy consumption on CO<sub>2</sub> emissions in EU countries for the period of 1961–2012 and revealed a negative effect of renewable energy consumption on CO<sub>2</sub> emissions in the short and long term.

While Danish et al. [23] show that the impact of renewable energy is low, Dong et al. [24] consider that the impact of natural gas and renewable energy can be effective substitutes for fossil fuels while reducing CO<sub>2</sub> emissions. Most articles use the environmental Kuznets curve (EKC) model, but studies using other models such as STIRPAT reveal the same negative correlation between renewable energy and CO<sub>2</sub> emissions [25].

Our study attempts to answer the following questions:

Is there any relationship between municipal waste recycling and CO<sub>2</sub> emissions? If so, what is the causality direction between these variables?

Is there any relationship between renewable energy consumption and CO<sub>2</sub> emissions? If so, what is the causality direction between them?

To answer these questions an empirical analysis has been performed by taking into consideration all EU member states for the 2004–2017 period. The second generation of panel unit root and cointegration tests have been employed.

This research aims to contribute to the relevant literature in two ways: firstly, it is one of the early studies that investigates the impact of municipal waste recycling on CO<sub>2</sub> emissions in a sample of EU member states, trying to fill the gap related to our research area. Secondly, the second generation of econometric tests have been used and that will lead us to more robust and reliable findings.

The attention was focused on municipal waste recycling in EU countries for several reasons: more than half of the EU population lives in urban areas and the amount of municipal waste continues to increase in these areas, and also due to EU imposed quantitative targets for recycling municipal waste. Aiming to become the first climate-neutral continent by 2050, EU countries try to find the best solution to face rapid urbanization and municipal waste management challenges. Countries selected for our analyses are characterized by increased expansion and densification of cities and by high recycling rates of municipal waste, therefore our results can have an important role in helping different entities in the decision-making process on carbon emission reduction.

Even waste prevention programs were adopted at EU level and countries receive support for the implementation of EU environmental legislation there are big differences among countries in reaching waste recycling targets. The necessity of moving towards a circular economy must mobilize all individuals, companies, and local, regional, and national authorities to take appropriate measures to improve resource utilization efficiency and to limit the environmental impact of all product life cycles.

The next section explains the data and methods used in this research, then the empirical analysis is conducted, and the findings are discussed in Section 3. Conclusions and proposals for future investigation are exposed in Section 4.

## 2. Materials and Methods

Environmentally friendly renewable energy sources, energy efficiency, and recycling are important instruments to decrease CO<sub>2</sub> emissions. The main focus of the study is to explore the impact of municipal waste recycling together with renewable energy on CO<sub>2</sub> emissions regarding the limited literature about our research topic through Westerlund and Edgerton [26] panel cointegration test and Dumitrescu and Hurlin [27] causality test. Our study concentrates on the period 2004–2017 and the sample includes all EU member countries. The pre-tests of cross-sectional dependence and heterogeneity, unit root test,

cointegration and causality tests were implemented by using Stata 14.0, Gauss 10.0, and Eviews 10 software.

The recycling rate of municipal waste (% of total waste generated) was used as a proxy variable for recycling, this indicator being employed by different researchers to monitor recycling efficiency. Dijkgraaf and Gradus [28] used it to establish some function of socio-economic variables. Their findings indicate that decreasing the frequency of unsorted waste collection leads to an increase in the recycling rate for compostable waste. Similarly, Abbott, Nandeibam, and O'Shea [29], based on a study conducted in the UK, found that the reduction of residual waste collection frequency increased the recycling rate.

The new set of waste management indicators presented by Eurostat to “monitor progress towards more recycling and less disposal” [30] indicate that the recycling rate of municipal waste is an indicator that “gives an indication of how waste from final consumers is used as a resource in the circular economy” [31]. All the variables (CO<sub>2</sub> emissions, recycling rate, and renewable energy consumption are positive values and annual data were collected from EUROSTAT as it is indicated in Table 1. Furthermore, the use of second-generation tests considerably raised the reliability of the findings.

**Table 1.** Description of variables.

Variables	Description	Source
CO	CO <sub>2</sub> emissions (million tonnes)	[32]
RECYC	Recycling rate of municipal waste (percent of total waste generated)	[33]
RENENG	Renewable energy consumption (percent of total final energy consumption)	[34]

Source: own processing.

The following equation was elaborated to analyze the influence of recycling (RECYC) and renewable energy consumption (RENENG) on carbon dioxide emissions (CO) and is expected that improvements in recycling and renewable energy use negatively affect the CO<sub>2</sub> emissions.

$$CO_{it} = \beta_0 + \beta_1 RECYC_{it} + \beta_2 RENENG_{it} + e_{it} \quad (1)$$

Table 2 highlights the main characteristics of the dataset. The average CO<sub>2</sub> emissions was about 113.8991 million tons in the sample and the average recycling rate of municipal waste was about 29.21% of total waste generated. Lastly, the average renewable energy share in total final energy consumption was about 16.66%. However, all the variables exhibited significant variations among the countries.

**Table 2.** Dataset main characteristics summary.

	CO	RECYC	RENENG
Mean	113.8991	29.21614	16.66836
Median	43.17322	29.10000	14.59950
Std. Dev.	174.3190	17.55899	11.33280
Skewness	2.627937	0.225648	0.923007
Kurtosis	10.27130	1.987393	3.520498

Source: own processing.

### *Econometric Methodology*

Firstly, three tests were selected to check the presence of cross-sectional dependence: Breusch and Pagan Lagrange multiplier (LM) test [35], Pesaran's cross-sectional dependence (CD) test [36] and bias-adjusted LM test of Pesaran et al. [37]. Furthermore, Pesaran and Yamaga homogeneity tests [38] were used to question the homogeneity of cointegrating coefficients. Also, using CIPS (Cross-Sectionally Augmented IPS) test [39] the integration levels of the series have been examined, considering the presence of cross-sectional dependence.

In the third step, the panel cointegration test with multiple structural breaks developed by Westerlund and Edgerton [26] was carried out in order to explore the long term relationships between variables.

Based on the following two equations we have shown the statistic of cointegration test:

$$y_{it} = \alpha_i + \psi_i t + \delta_i D_{it} + \beta_i x_{it} + (D_{it} x_{it}) \gamma_i + v_{it} \quad (2)$$

$$x_{it} = x_{it-1} + w_{it} \quad (3)$$

$i = 1, 2, \dots, N$  are the cross-sections,

$t = 1, 2, \dots, T$  indicate the time dimension of the panel.

$D_{i,t}$  dummy variable in Equation (3) is described in Equation (4). Furthermore  $\alpha_i$  and  $\beta_i$  are respectively constant and slope coefficients before the break,  $\delta_i$  and  $\gamma_i$  indicate the variation after the structural break and  $w_{i,t}$  is the error term.

$$D_{i,t} = \begin{cases} 1, & t > T_i \\ 0, & \text{Others} \end{cases} \quad (4)$$

$z_{i,t}$  error term in Equation (2) calculated from the following equation allowing cross-sectional dependence through use of common factors:

$$z_{i,t} = \lambda_i' F_t + v_{i,t} \quad (5)$$

$$F_{j,t} = \rho_j F_{j,t-1} + u_{j,t} \quad (6)$$

$$\varnothing_i(L) \Delta v_{i,t} = \varnothing_i v_{i,t-1} + e_{i,t} \quad (7)$$

$F_t$  and  $F_{j,t}$  indicate the common vector with  $k$  dimension ( $j = 1, 2, \dots, k$ ),  $\lambda_i$  the compatible vector of the factor loadings.  $F_t$  is stationary for all  $j$  values under the assumption of  $\rho_j < 1$ . Therefore, Equation (2) is cointegrate under the condition of  $\varnothing_i < 0$ .

$\hat{S}_{i,t}$  is calculated as following in case of cross-sectional dependency:

$$\hat{S}_{i,t} = y_{i,t} - \hat{\eta}_i t - \hat{\delta}_i D_{i,t} + x_{i,t}' \hat{\beta}_i + (D_{i,t} x_{i,t})' \hat{\gamma}_i - \lambda_i' \hat{F}_t \quad (8)$$

$$\Delta \hat{S}_{i,t} = \text{sabit} + \varnothing_i \hat{S}_{i,t-1} + \sum_{j=1}^{p_i} \varnothing_i \Delta \hat{S}_{i,t-j} + \text{hata} \quad (9)$$

Westerlund and Edgerton [26] calculates the following statistics in the context of calculations above:

$$LM_{\varnothing}(i) = T \hat{\varnothing}_i \left( \frac{\hat{w}_i}{\hat{\sigma}_i} \right) \quad (10)$$

$$LM_{\tau}(i) = \frac{\hat{\varnothing}_i}{SE(\hat{\varnothing}_i)} \quad (11)$$

$\hat{\varnothing}_i$  in Equation (10), ordinary least squares estimation of  $\varnothing_i$  in Equation (9) and  $\hat{\sigma}_i$  is the estimated standard error. Furthermore,  $\hat{w}_i$  is the estimated long term variance of  $\Delta v_{i,t}$ .  $SE(\hat{\varnothing}_i)$  in Equation (11) is the estimated standard error of  $\hat{\varnothing}_i$  (see Westerlund and Edgerton [26] for detailed information about the cointegration test).

Then, dealing with the presence of cross-sectional dependence and slope heterogeneity across units, the Augmented Mean Group (AMG) estimator of Eberhardt and Teal [40] has been used.

When all variables are integrated of the first order, the AMG estimator can be used to determine each cross-section's coefficient and the panel cointegrating coefficients. Based on Eberhardt and Bond [41], this estimator can be implemented in the case of an endogeneity resulting from the error terms. The following model was adopted:

$$y_{it} = \beta_i^l x_{it} + u_{it} \quad (12)$$

$$u_{it} = \alpha_i + \lambda_i^l f_t + \varepsilon_{it} \quad (i = 1 \dots N, \quad t = 1 \dots T) \quad (13)$$

$$x_{mit} = \pi_{mi} + \delta_{mi}^l g_{mt} + \rho_{1mi} f_{1mt} + \dots + \rho_{nmi} f_{nmt} + v_{it} \quad (m = 1 \dots k) \quad (14)$$

$$f_t = \tau' f_{t-1} + \varepsilon_{it} \text{ ve } g_t = \Psi' g_{t-1} + \Omega_{it} \quad (15)$$

$x_{it}$  in Equation (12) denotes the vector of observable covariates and  $u_{it}$  indicates the unobservable variables,  $\alpha_i$  in Equation (13) represents combined group specification effects,  $f_t$  denotes the common factors and  $\lambda_i$  indicates the country specific factor loadings.  $f_t$  in Equation (14) shows the unobservable common factors,  $g_t$  represents the relative specification factor weights (see Eberhardt and Bond [41] for detailed information about AMG estimator method).

Finally, potential directions of causality have been studied by using Granger causality test for heterogeneous panels recently introduced by Dumitrescu-Hurlin (2012) [27]. The test can be used in both cases when  $T > N$  and  $N > T$ .

### 3. Results

To perform the panel data analysis, one important aspect is to investigate cross-sectional dependency and homogeneity. In this context, cross-sectional dependency in the panel was analyzed based on Breusch and Pagan LM test [35], Pesaran CD test [36] and Pesaran et al.,  $LM_{adj.}$  test [37] and results are reported in Table 3. These tests have indicated that among series there is a cross section dependence. Furthermore, the presence of a unit root and the existence of cointegration relationship between variables was tested by applying a second-generation panel unit root and cointegration tests.

**Table 3.** Cross-sectional dependence tests.

Test	Test Statistic	Probability Value
Breusch-Pagan LM	602.3	0.0000
Pesaran et al. $LM_{adj.}$	13.31	0.0000
Pesaran CD *	10.31	0.0000

\* Two-sided test. Source: own processing.

Using Pesaran and Yamagata homogeneity tests [38], the homogeneity of slope coefficients of the cointegration equation were inspected and results are included in Table 4. Based on our results, the null hypothesis of homogeneous slope coefficients was rejected, coefficients were found to be heterogeneous and therefore heterogeneous panel techniques needed to be employed.

**Table 4.** Pesaran and Yamagata [38] slope homogeneity test.

Test	Test Statistic	Probability Value
$\tilde{\Delta}$	14.307	0.000
$\tilde{\Delta}_{adj.}$	16.707	0.000

Source: own processing.

To address the issue of series stationarity the Im, Pesaran and Shin (IPS [42] panel unit root test was carried out. Results are displayed in Table 5 and indicated that variables became stationary at first difference.

Furthermore, considering the cross-section dependence and structural breaks, the panel cointegration test proposed by Westerlund and Edgerton [26] has been applied to investigate the long run relationship among variables. The results presented in Table 6 revealed a significant cointegration relationship among the variables, the null hypothesis of no cointegration being rejected at three models. Our findings also suggest that structural breaks occur during the global financial crisis and Eurozone sovereign debt crisis.

**Table 5.** Im, Pesaran and Shin (IPS) [42] panel unit root test.

Variables	Constant		Constant + Trend	
	Zt–Bar	Probability Value	Zt–Bar	Probability Value
CO	−2.757	0.203	−0.501	0.308
d (CO)	−7.990	0.000	−5.663	0.000
RECYCY	−0.667	0.252	1.212	0.887
d (RECYCY)	−2.798	0.003	1.156	0.000
RENENG	−1.266	0.103	1.529	0.937
d (RENENG)	−3.233	0.001	−0.907	0.000

Source: own processing.

**Table 6.** Westerlund and Edgerton [26] panel cointegration test with multiple structural breaks.

Model	$Z_{\varphi}$ (N)	Probability Value	$Z_{\tau}$ (N)	Probability Value
No shift	−2.018	0.022	−1.687	0.046
Level shift	−2.347	0.009	−3.126	0.001
Regime shift	−2.391	0.008	2.588	0.005

Country	Structural breaks	
	Level shift	Regime shift
Austria	2008	2011
Belgium	2008	2010
Bulgaria	2008	2008
Croatia	2008	2008
Cyprus	2011	2012
Czechia	2008	2008
Denmark	2006	2007
Estonia	2009	2009
Finland	2009	2009
France	2013	2013
Germany	2008	2012
Greece	2006	2008
Hungary	2011	2011
Ireland	2008	2008
Italy	2008	2008
Latvia	2013	2013
Lithuania	2008	2008
Luxembourg	2009	2009
Malta	2014	2014
Netherlands	2009	2010
Poland	2005	2009
Portugal	2005	2006
Romania	2008	2008
Slovakia	2005	2005
Slovenia	2008	2015
Spain	2008	2008
Sweden	2011	2011

Source: own processing.

The long-run coefficients were estimated by employing the Augmented Mean Group estimator (AMG), developed by Eberhardt and Teal [40] and are reported in Table 7. Referring to overall panel, the findings revealed a long-run negative relationship between renewable energy use and CO<sub>2</sub> emissions and no statistically significant long-run relationship between recycling rate of municipal waste and CO<sub>2</sub> emissions. Both recycling and renewable energy use tend to drive a decline in CO<sub>2</sub> emissions in the long term, so improvements in recycling and renewable energy use are expected to make a significant contribution to environment sustainability. These results are similar to those reported by Sun

et al. [16], Abdel-Shafy and Mansour [17], de la Barrera and Hooda [18], Turner et al. [19] indicating that recycling helps in saving carbon emissions through different processes.

**Table 7.** Estimation of cointegrating coefficients.

Country	RECYC	RENENG
	Coefficients	Coefficients
Austria	0.2619074	−0.1370404
Belgium	−0.9632962 *	−1.327302
Bulgaria	0.1861442	−1.707382
Croatia	−0.0137206	−0.627371 ***
Cyprus	−0.2629339 *	−0.3020184
Czechia	−0.2094755	−1.249691
Denmark	0.3685708	0.4873273
Estonia	−0.0572621	0.0564618
Finland	−0.8736393 *	−0.2626224
France	−3.602233	3.600411
Germany	−5.952555	−0.3278314
Greece	1.628655 ***	0.3690342
Hungary	−0.3571574 *	−0.8296546 ***
Ireland	0.0712733	−1.837451
Italy	2.322387	3.658701
Latvia	0.139688	−0.4157306
Lithuania	0.0267099	0.4833972
Luxembourg	0.3369808 ***	−0.9513458 ***
Malta	0.0310063	−0.2267532 **
Netherlands	2.83384	−9.669656
Poland	−0.9788892 *	−8.180569
Portugal	0.7036087	0.3792934
Romania	−0.4314038	−1.550044
Slovakia	−0.0130721	−0.2990781
Slovenia	−0.001741	−0.3093451
Spain	0.794273	−15.92366 **
Sweden	−0.0000376	−2.029158 **
Panel	−0.1486064	−1.449225 *

\*\*\*, \*\*, and \* indicates it is respectively significant at 1%, 5%, and 10%. Source: own processing.

Referring to the relationship between renewable energy and CO<sub>2</sub> emissions, similar findings were reported by Lu [20], Zoundi [21], and Lee [22] that support the idea that rapid growth in the use of renewable energy will contribute to the progress in reducing carbon emissions.

However, the individual cointegration coefficients indicate that recycling process helps countries like Belgium, Cyprus, Finland, Hungary, and Poland to decrease the CO<sub>2</sub> emissions, but this process is attributed to an increase in CO<sub>2</sub> emissions in countries like Greece and Luxembourg. Furthermore, recycling had a negative effect on the CO<sub>2</sub> emissions in most of the remaining countries in the sample, but it was statistically insignificant. On the other side, renewable energy leads to a decrease in CO<sub>2</sub> emissions in countries like Croatia, Hungary, Luxembourg, Malta, Spain, and Sweden.

Differences between countries' results can be explained by different approaches and actions related to municipal waste recycling as well as renewable energy taken by individuals, corporations, and states. Due to the complex issues, it cannot be asserted that there is one single kind of individual or corporate action or societal discourse or law which leads to these effects.

The causal interaction among CO<sub>2</sub> emissions, recycling rate, and renewable energy use was explored through Dumitrescu and Hurlin [27] causality test. The results reported in Table 8 disclose no significant short-run interactions among the variables. Contrary to our results, Lu [20] found a bidirectional causal relationship between renewable en-

ergy consumption and CO<sub>2</sub> emissions, and Lee [22] reported a negative and significant relationship between variables in the short term.

**Table 8.** Dumitrescu and Hurlin [27] panel granger causality test.

Null Hypothesis	W-Stat.	Zbar-Stat.	Probability Value
DRECYC $\nrightarrow$ DCO	1.22055	−0.14722	0.8830
DCO $\nrightarrow$ DRECYC	1.37483	0.20133	0.8404
DRENENG $\nrightarrow$ DCO	1.43638	0.34040	0.7336
DCO $\nrightarrow$ DRENENG	1.29835	0.02854	0.9772

Source: own processing.

There are several possibilities to explain these results. Of course, no significant short-term interaction does not mean that there is no interaction at all. One might argue that more time is needed for the environment as well as for actors to grasp the advantages of recycling and renewable energy. Especially unintended side effects are not easy to deal with and might not disappear within a short period of time. However, there are also critical interpretations possible if it comes to low hanging fruits and rebound effects. As mentioned above, some recycling processes could be seen as low hanging fruits, which means that the first positive results are relatively easy to grasp. This could be a motivator for further steps, but also a sedative. Going one step further, there are possible rebound effects, for example, renewable energy could lead to (more) energy waste because there might be fewer reasons seen for saving energy.

#### 4. Conclusions

Climate change effects can be seen everywhere, and our responsibility is to find the best solutions to identify and limit all factors that cause this phenomenon. Since CO<sub>2</sub> emissions are considered a key driver of climate change, it is important for researchers, activists, and policymakers to identify the sources of these emissions and to investigate how these emissions can be reduced.

In this context, our study specifically focused on the long-term and short-term correlations between municipal waste recycling, renewable energy usage and CO<sub>2</sub> emissions. Results prove a long running cointegration between both recycling and renewable energy use and CO<sub>2</sub> emissions for most of the countries examined. Both recycling and renewable energy use tend to drive a decline in CO<sub>2</sub> emissions in the long term, so improvements in recycling and renewable energy use are expected to make a significant contribution to environment sustainability.

Global energy consumption is steadily increasing, having a negative effect on carbon emissions. In this context, various policies and strategies must focus on the renewable energy sector to increase the share of energy from renewable sources in the final energy consumption. To lower overall emissions, the EU set mandatory targets for the share of renewable energy in the gross final energy consumption. For our analyzed countries, the results indicate that renewable energy does not cause direct carbon reduction therefore more efforts need to be done to reduce emissions. Raising targets for renewable energy use and promoting energy efficiency measures may only be a few initiatives that can improve carbon emissions.

Our results can be important in shaping different public policies. Firstly, the production and consumption of renewable energy must be stimulated using support mechanisms like tax incentives, feed-in-tariffs, renewable investment subsidies, green certificates, etc. Secondly, more attention should be paid to stimulating the production of energy from renewable sources like solar, wind, and geothermal instead of biomass or hydropower, due to the fact that it has a bigger carbon footprint per unit of energy than the first category.

### *Limitations and Recommendations for Future Research*

The current research was focused on developed countries of European Union, where specific recycling targets have been set out under EU waste legislation. Even though there are some differences across EU countries related to recycling target achievement, different programs were developed in all countries and sustained efforts are made to achieve them. Compared to this category of countries, developing countries present with rapid development of urban areas, uncontrolled waste, lack of recycling regulations, and lack of people's environmental awareness. Further analyses should be carried out for developing countries since these countries are facing serious development challenges and enormous problems regarding waste management. It is important in these areas to monitor the recycling rates and the contribution of this process to the reduction of carbon emissions. Establishing global standards that encourage recycling can be a solution for developing countries to pay much attention on the recycling process. International cooperation between national agencies of developed and developing countries to supply policy advice, technical assistance and support for the transition to a circular economy can be the key to success for this category of countries.

Also, the current study took into consideration the amount of municipal waste being recycled but future research can include all types of recyclable waste.

Even then there are controversial debates related to nuclear energy sustainability; it can be admitted that this energy source has one of the lowest environmental impacts compared to other energy sources and no GHG emissions are emitted from electricity production. In these circumstances, extended research is necessary to analyze the overall impact of renewable and nuclear energy production and consumption on carbon emissions. Many countries consider it necessary to phase out nuclear capacity for security reasons, but maybe more research is needed to encounter the real benefits and disadvantages of this energy production. Combining renewable energy and nuclear source production can be the key for many countries to achieve their GHG reduction targets, but decisions related to this subject must be done on relevant studies.

Carrying out an in-depth analysis of the relation between major categories of renewable energy sources and CO<sub>2</sub> emissions is also necessary in a future study. Even electricity produced from renewable energy sources is associated with low carbon emissions and there are major differences related to the amount of CO<sub>2</sub> emitted for each type of energy source. The carbon footprint of different renewable energy sources must be carefully analyzed, hydroelectric power, for example, can generate significant amounts of carbon emissions depending on the reservoir characteristics (size, sedimentation, etc.).

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