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# Energy Consumption under Circular Economy Conditions in the EU Countries

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**Abstract:** Due to industrialization, urbanization, and rapid population increases, the worldwide energy demand is increasing daily. The need for energy meets limitations, and searching for new energy sources is crucial, particularly for European countries. Energy crises occur temporarily due to different circumstances and cause oil price fluctuations. The present study aims to identify circular economy (CE) determinants that conditionally increase/decrease energy use to remain sustainable. It focuses on the linkage between energy consumption and circular economy in the European Union (EU) member states. In the econometric panel model specifications, two alternative endogenous variables are considered, i.e., total energy consumption and energy consumption from renewable sources. The results demonstrate that the selected CE indicators decreased the former and increased the latter. The data covered the period from 2010–2019. The significance of this study relies upon identifying the current level of CE implementation in the EU countries in the context of reducing total energy consumption and increasing the share of energy from renewable sources.

**Keywords:** circular economy; energy consumption; European Union; panel model

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## 1. Introduction

The concept of a linear economy belongs to mainstream economics and has played a leading role in the industrial revolution for the last 150 years [1]. The linear economy is the extraction of raw materials, producing and consuming the products, and depositing them as waste materials [2]. Therefore, the linear economy model is defined as take–make–use–destroy [3]. Recently, researchers proposed the CE concept [4–8]. The Ellen MacArthur Foundation defines a CE as "restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." The CE has been discussed widely among researchers, industrialists, ecologists, economists, and environmentalists. Researchers are exploring the different aspects of resource efficiency in economies and relate the waste material to environmental sustainability. The CE is based on the '3R' principles: Reduce, Reuse, and Recycle [9–15]. The CE's main features are low exploitation, high usage, and low pollution. The CE model is based on manufacturing and consumption, then sharing, reducing, reusing, remanufacturing, repairing, refurbishing, and recycling existing materials and products for as long as possible [16,17]. The CE has received significant attention from researchers and politicians due to rapid population growth, climate change due to global warming, decreased soil fertility, and biodiversity.

The most significant challenges to human society, such as climate change and global warming, are fundamentally tied to energy consumption and greenhouse gas (GHG) emissions. Most of this rise has occurred in emerging nations, where population growth, urbanization, and economic expansion have been the key determinants.

Controlling energy usage requires strong energy policies. Countries have used various energy strategies, including energy rules for buildings, subsidies, and energy labeling.

Making those rules necessary, focusing on net-zero energy buildings, and raising public awareness of new technology are all ways to improve their chances of success. However, growing nations, such as China, India, and Iran, continue to experience a significant rise in GHG emissions and energy consumption, primarily due to the lack of a firm, effective strategy [18]. Some researchers elaborated on the linkages between energy consumption and GHG emissions, evidencing a positive correlation between fossil fuels and GHG emissions. Ref. [19] found that transportation is responsible for 28.5% of $CO_2$ emissions in the EU.

Ref. [20] analyzed the impact of the EU energy policy on uncoupling GHG emissions from economic growth between 1996 and 2017. The key contributors to emission mitigation were identified using five variables from the Log-Mean Divisia Index (LMDI). Regardless of the method used to assess GHG emissions, the results showed that GHG emissions and economic growth can be separated in almost all nations, apart from Greece, Croatia, Italy, and Portugal. According to LMDI data, essential factors in reducing GHG emissions are the energy structure, intensity, and carbon intensity, while economic activity and population size cause increase in GHG emissions. Thus, the limitations of decoupling come from the faster development of developing countries both in the EU and outside of the EU. Therefore, implementing CE principles and solutions could reduce GHG emissions and keep the desired growth rates. Another study on linkages between CE and emissions reduction in 29 European countries [21] showed that progress toward a CE will significantly improve environmental quality by reducing $CO_2$ emissions.

The CE can be defined as restorative and regenerative by nature, according to [22], and aims to keep goods, components, and materials at their highest utility and value, distinguishing between technological and biological cycles. The central concept of the CE is the R system, first developed as a 3R framework (‘Reduce,’ ‘Reuse,’ and ‘Recycle’) and then developed into a 4R framework when ‘Recover’ was adopted by the EU Waste Framework Directive in 2008 as the fourth R [23]. The hierarchy of the Rs is central in the 4R system [24]: the first R (‘Reduce’) is considered a priority for the second R, and so on. This hierarchical relationship is closely related to the concept of “cascade,” which means the use of raw materials according to a priority dependent on the possible value added [25].

The substantial demand for consumer goods, housing, transport, and packaging further increases the need for raw materials. The studies on single industries’ contributions to CE show more definite solutions. For example, [18] demonstrated the importance of concrete policy in the residential section, showing that success derives from the enhancement of making them mandatory, targeting net-zero energy buildings, and increasing public awareness of new technologies. On the other hand, [26] discussed the linkage between policy adoption and energy consumption in the transportation sector. The examples show a need to redesign economic and social policies to reduce global environmental footprints. Nevertheless, it has been estimated that 60–65% of ecological damage costs are related to resource processing, and only 35–40% are related to energy-related products [27]. Therefore, there is a need to emphasize supportive policies for the CE.

The CE is playing a pivotal role in economic growth worldwide. More than 40 nations are currently investing and promoting strategies and policies in the CE sector. About 2 trillion USD of products, such as agriculture and forestry, bioenergy, food, biotechnology, and green chemistry, were exported in 2014, 13% of world trade [28,29]. Under the Horizon 2020 program, the EU’s CE strategy aimed to transform the European economy to reduce environmental problems. Instead, the focus was on reducing solid waste through recycling and GHG emissions.

Energy security is essential in developed and developing countries, affirming different sectors’ current and future energy needs. While global energy use continues to increase, and in 2021, the value was double that in 1980, it has slowed down in the EU. In 2006, the energy consumption in the EU gained its maximum value of 41,445 Mtoe. By 2020, the final energy consumption decreased from its peak level by 10.5% (https://ec.europa.eu/eurostat, accessed on 1 July 2022). Was this due to a broad application of sustainable economic growth and the CE approach, or was it instead the result of the COVID-19 pandemic in 2020? Both explanations played an essential role in the reduction. Ref. [30] found diversified changes in electricity use across regions during COVID-19.

Being a relatively new concept, the circular economy is undoubtedly contributing to the positive change toward sustainability. Progress has already been made, but the issue is how far the global economy is from achieving the goal. Theoretically, it can be considered a game between now and tomorrow. Based on this, [31] considered using a portfolio theory to select the right proportion of resources and to distinguish between three manifestations of linearity and circularity: fully linear, fully circular, and imperfectly circular. They showed that increasing the circularity of resources does not necessarily mean that resources will be used more efficiently. The combination of resource users that minimizes resource use is not necessarily the combination that maximizes eco-efficiency. The idea that the circular economy results in an infinite eco-efficiency of resource use is only valid in the unlikely case of perfect circularity. Therefore, there is a need to distinguish between the theoretical concept of perfect circularity and the practical case of the imperfectly circular use of resources.

In the current study, we concentrate on energy consumption across the European Union's countries, taking them as a leading regional group. The research question is whether circular economy indicators can help to decrease total energy consumption and increase energy use from renewable sources. Based on the literature [32,33] arguing that renewable energy sources cannot replace conventional ones and have limited logistical growth paths, we assume that both will be used in the future. Therefore, we checked whether introducing the circular economy idea of nothing being left behind [34] over the last decade has helped to reduce total energy consumption and increase the proportion of energy use from renewable sources.

This study uses a panel regression approach to examine the relationships between CE indicators and energy consumption in 24 EU countries (excluding Bulgaria, Cyprus, and Malta, where data were incomplete). It aims to identify the CE factors that can increase/decrease aggregate energy consumption (EC) and energy from renewable sources (RENC), ensuring sustainable development. We concentrated on CE indicators, and the data covered the period from 2010–2019. The paper's novelty lies in the comparison of several model specifications and the common factors across the countries being found. Further, we identified developed and underdeveloped areas of the CE in the analyzed countries. To our best knowledge, this is the first regional analysis of relationships between CE and aggregated and disaggregated energy use in European countries. The significance of this study lies in the identification of the current level of CE implementation in the EU countries in the context of reducing energy consumption, which corresponds to the following Sustainable Development Goals: SDG-7 (affordable and clean energy), SDG-9 (industry, innovation, and infrastructure), SDG-11 (sustainable cities and communities), SDG-12 (responsible production and consumption), and SDG-13 (climate action).

The rest of the paper is organized as follows: Section 2 reports a review of the relevant literature. Section 3 provides the materials and methods. Section 4 presents the empirical results and checks their robustness. Section 5 discusses the results and conclusions, and formulates future research plans.

## 2. Literature Review

A large plethora of literature is available on the CE in different countries, including the EU. Researchers are concerned about the future requirements and roles of CE drivers, such as climate change, food security, and resource depletion [35,36]. Some studies have highlighted the adverse effects of reliance on natural resources, such as Dutch disease [37], motivating the search for a new natural resource curse or blessing for the economy. As a strategy, there is a need to develop the energy market, access to energy, energy supply, energy stability, energy independence, climate change, and pollution reduction. Compared with CE, the omnipresent model of the linear economy does not count for other considerations, such as the effect on social wealth, including human resources, and the conservation of finite resources [38].

Europe has defined principles and frameworks for a shared environmental policy. It is not generally referred to as a CE, but the trends align closely with the CE's ideals. All aspects, including production, use, waste management, and environmental policies, are covered. Ref. [39] appealed to labor, business, and civil society leaders to promote resource efficiency and move to a CE.

Ref. [40] analyzed the influences of climate change in the last century due to the increased use of natural resources, global environmental destruction, and human-induced climate change. The research community and the decision-makers have debated and challenged the linear fossil-based economy model [41,42]. According to [1], a CE should primarily use energy from renewable sources to minimize its reliance on fossil fuels and improve its ability to respond to the negative consequences of oil consumption.

According to [43], significant environmental and sustainability factors must be taken into account when considering sustainable household consumption, including water, materials, energy consumption, pollutant emissions, waste disposal, and land-use patterns caused by household activities, products, and services. The CE often achieves sustainability, but narrowly focuses on the economic and environmental dimensions [16]. It envisions the implementation of a more resource-effective and efficient economic system by intentionally narrowing, slowing, and closing materials and energy flow [1,44].

Ref. [45] analyzed the framework for evaluating the CE model's sustainability in light of environmental considerations using a data set from 2007 to 2016 for 27 EU nations. The study's objective was to present the economic aspects of the long-term growth of a CE. Three statistical hypotheses were validated by a panel data model using the Mankiw–Romer–Weil economic growth model based on the resource productivity, environmental employment, recycling rate, and environmental innovation. The findings showed that resource productivity, environmental employment, recycling rate, and environmental innovation influenced the extended Mankiw–Romer–Weil model. The econometric model described in line with the objectives of environmental conservation and sustainable economic growth requires investment in recycling infrastructure and cutting-edge resources.

The increasing percentage of renewable and recyclable resources, including renewable energy, is necessary for the CE, according to [46]. The authors of [1] used the phrase "replace fossil fuels with renewable energy" to illustrate how the CE works. "The implementation of CE will radically change economic activity away from dependence on nonrenewable and emissions-intensive carbon fluxes towards more sustainable production and consumption" is the expectation [47].

According to [48], it is crucial for CE business models to "maximize material and energy efficiency, create value from waste, or apply biomimicry principles to migrate from nonrenewable to renewable resources." The CE includes the ideas of "designing out waste, substituting renewable materials for nonrenewable ones, and restoring natural systems," in addition to concentrating on creating such technologies and models that maintain the material in circulation [49].

Ref. [50] analyzed the energy efficiency scores of 28 chosen EU states and the energy recovery from waste. The study used inputs including the final energy consumption, labor, capital, and population density, and outputs including the gross domestic product (GDP), nitrogen oxide (NOx), sulfur oxide (SOx), and greenhouse gas (GHG) emissions for the years of 2008, 2010, 2012, 2014, and 2016. The efficiencies were evaluated using data envelopment analysis (DEA). The results indicated that most countries retained their efficiency scores, slightly improving in just a very small number, and that the scores of most nations were declining after 2012. Based on these efficiency scores, the study suggests advancing toward waste-to-energy with two key goals: sufficient and sustainable energy production and efficient treatment of municipal solid waste (MSW).

Using data from 2000 to 2016, [51] examined a set of decisive criteria for a CE in Europe. The study used panel unit root tests, panel cointegration tests, and vector autoregression

(VAR) models for cluster analysis. As the researchers incorporated all of the relevant factors of the circularity of the investigated countries, the explanatory variables chosen were all statistically significant for the general panel and the three different resource productivity (RP) growth rate groups. All groups were affected similarly by environmental tax revenues in the percentage of GDP (ET), gross value added by industry sectors in the percentage of total GDP (IND), population density (POP), and gross value added by services sectors in the percentage of total GDP (SERV), though to varying degrees. The conclusions for these factors were consistent across all groups. The researchers observed that POP and SERV enhanced RP, while ET and IND reduced RP. Taxes were commonly linked to the so-called "deadweight loss" that impacted all nations in the same direction (although affecting more high-growth countries). More service-based nations demonstrated greater efficiency because they used fewer resources. Additionally, efficiency was increased by higher population densities. Depending on the rate of expansion of the countries considered, other factors, such as gross domestic expenditure on R&D (GERD), the recycling rate in percentage (RECY), and the ratio of gross inland renewable energy consumption to the gross inland total energy consumption (REN), had varying effects (positive or negative) on the RP. Countries with poor growth were negatively impacted by RECY and REN, while strong-growth countries were positively impacted. In contrast, GERD had a favorable influence on low-growth countries, but a negative one on high-growth ones, as though R&D spending had a quicker return on investment for initially underdeveloped economies.

Ref. [52] compared the specific effects and results of the CE and its value sources. A sample of 25 European nations was used for the panel data study, covering data from 2010 to 2019. According to the findings, the CE significantly impacted the achievement of sustainable development (SD), which benefits the economy, environment, and society. The outcomes demonstrated that each CE value source affected the three SD dimensions differently. While recycling had little impact and repair raised GHG emissions, renewable energies and reuse had positive environmental impacts. However, repair was the only CE source that had a positive economic effect on a national scale. Finally, employment was decreased by recycling, repair, and renewable energy. Decision-makers should use impact analysis to develop appropriate, effective, and targeted policies based on the unique goals of each nation.

In the CE framework in Europe's chosen nations, [53] extensively analyzed national municipal waste management systems, including waste-to-energy (WtE), as a significant component. According to the study's findings, all EU member states should switch from the antiquated practice of disposing of waste to a more intelligent waste treatment strategy that incorporates the CE concept into their waste policies. One way to create a CE that minimizes waste and resource consumption is by converting waste into energy. This would allow the preservation of the value of goods, materials, and resources in the market for as long as feasible. Researchers are exploring which municipal waste management strategies are used in particular nations, how those countries are approaching the CE, and what role WtE technology might play in this situation. The authors considered Estonia, Greece, Italy, Latvia, Lithuania, Norway, Poland, Slovenia, Spain, and the United Kingdom to represent a broad European context.

## 3. Materials and Methods

### *3.1. Data Sources and Descriptive Statistics*

This section is divided into two subsections related to the data sources' description and methodology.

Based on the literature review, it was possible to indicate the variables that characterized CE indicators. Consequently, the study was based on the secondary panel data source, consisting of annual observations of the EU-24 from 2010 to 2019. The availability of data determined the dataset. The panel data set was fully balanced and comprised 240 observations. The data set was downloaded from Eurostat, except for EC and RENC, which were taken from British Petroleum (BP-2019). The list of countries used in the study, due to data accessibility, is given in Table 1.

**Table 1.** The list of selected countries.

| Country | Code | Country | Code | Country | Code | Country | Code |
|---|---|---|---|---|---|---|---|
| Austria | AUT | Finland | FIN | Italy | ITA | Portugal | PRT |
| Belgium | BEL | France | FRA | Latvia | LVA | Romania | ROU |
| Croatia | HRV | Germany | DEU | Lithuania | LTU | Slovak Republic | SVK |
| Czech Republic | CZE | Greece | GRC | Luxembourg | LUX | Slovenia | SVN |
| Denmark | DNK | Hungary | HUN | Netherlands | NLD | Spain | ESP |
| Estonia | EST | Ireland | IRL | Poland | POL | Sweden | SWE |

The details of the used variables are given in Table 2. The summary statistics of all variables are given in Table A1 in Appendix A.

**Table 2.** Description of the variables used in the study.

| Variable | Name | Definition | Unit | Eurostat Codes |
|---|---|---|---|---|
| Y1 | EC | Aggregate energy consumption | Mtoe | BP |
| Y2 | RENC | Renewable energy consumption | Mtoe | BP |
| X1 | RGDP | Real GDP per capita at market prices in 2015 | Chain-linked volumes (2010), Euros per capita | SDG_08_10 |
| X2 | RGDPpc | Real GDP per capita at market prices in 2015 | Percentage (%) | SDG_08_10 |
| X3 | RP | Gross domestic product divided by domestic material consumption | Euros per kilogram, chain-linked volumes (2015) | SDG_12_20 |
| X4 | RRMW | Recycling rate of municipal waste | Percentage (%) | cei_wm011 |
| X5 | RBW | Recycling of biowaste | Kilograms per capita | cei_wm030 |
| X6 | CMUR | Ratio of the circular use of materials to the overall material use | Percentage (%) | cei_srm030 |
| X7 | TRM | Imports intra-EU27 (from 2020) | Tons | cei_srm020 |
| X8 | ETAXM | Environmental taxes by economic activity (NACE Rev. 2) | Million euro | env_ac_taxind2 |
| X9 | ETAXP | Environmental tax revenue (% of GDP) | Percentage of GDP | T2020_RT320 |
| X10 | RLP | Productivity per person employed in relation to the EU average | Percentage (%) | NAMA_10_LP_ULC |
| X11 | GHGpc | Greenhouse gas emissions per capita | Tons of $CO_2$ equivalent per capita. | T2020_RD300 |
| X12 | GHGIEC | Greenhouse gas emissions intensity of energy consumption | Index, 2000 = 100 | sdg_13_20 |
| X13 | DMCpc | Domestic material consumption per capita | Tons per capita | T2020_RL110 |
| X14 | SRECFC | Share of renewable energy sources in gross final energy consumption | Percentage (%) | SDG_07_40 |
| X15 | FECHpc | Final energy consumption in households per capita | Kilogram of oil equivalent (KGOE) | SDG_07_20 |
| X16 | PECpc | Primary energy consumption per capita | Kilograms of oil equivalent per capita | sdg_07_10 |
| X17 | FECpc | Final energy consumption per capita | Kilograms of oil equivalent per capita | sdg_07_11 |
| X18 | IRDEB | Intramural R&D expenditure (GERD)—Business | Euros per inhabitant | rd_e_gerdtot |
| X19 | IRDEG | Intramural R&D expenditure (GERD)—Government | Euros per inhabitant | rd_e_gerdtot |

The selected CE variables are shown in Figure A1 in Appendix A. Leading countries can be indicated according to CMUR, RP, RRMW, and RENC. The Netherlands leads in the ratio of the CMUR and the RP. At the same time, Germany leads in the RRMW and RENC.

### *3.2. Methodology*

An econometric panel model is a valuable tool for solving problems on an international scale; however, finding a suitable model for panel data requires testing and model comparisons. It is possible to develop and select a statistically and economically reasonable model, starting from the most straightforward construction using the more advanced ones. The current study is based on the panel unit root testing, Pooled Ordinary Least Square (POLS), Fixed-Effect (FE), and Random-Effect (RE) models.

#### 3.2.1. Panel Model Specification

a. Panel Unit Root Testing

When analyzing panel data with long-time dimensions, empirical researchers must address panel unit roots and panel cointegration. Owing to concerns about the spurious regression problem, testing for panel unit roots is critical. When regressing two non-stationary variables in levels, spurious regression produces a "false positive" result. As panel data have a temporal dimension, the nature of false regression differs from that of time-series data.

A difference is established between homogeneous panels, which presume common unit root patterns for all cross-section units, and heterogeneous panels in panel unit roots, which assume potentially different unit root structures for different cross-sectional units in that unit roots characterize some cross-section units and others are stationary. The Levin–Lin–Chu (LLC) test proposed by [54], Breitung, and Hadri unit root tests are suitable for homogeneous panels. The Im–Pesaran–Shin (IPS) test proposed by [55], ADF-Fisher (ADFF) test, and PP-Fisher (PPF) test are panel unit root tests for heterogeneous panels [56]. The $p$-values for individual cross-section units are combined into an overall $p$-value for the panel in Fisher-type tests for panel unit roots. This study presents the results of LLC, IPS, ADFF, and PPF panel unit root tests with and without trends at the levels and the first differences. They are collected in Table A2.

For most variables, the null hypothesis of the unit roots was rejected. These results indicate that the variables were stationary at levels. There were some differences in some test results, but we assumed that all variables were stationary after a short time series.

b. Pooled Model

The simplest model for panel data is the POLS model [57]. It refers to the homogenous population and takes the form:

$$y_{it} = \beta_0 + \beta' x_{it} + \varepsilon_{it}\ i = 1, \ldots, N,\ t = 1, \ldots, T, \tag{1}$$

where $y_{it}$ is the endogenous variable (EC or RENC), $\beta_0$ is a constant (equal for each unit—here, country), $x_{it}$ is a matrix of observed values of exogenous variables (here, the exogenous variables set is defined in Table 3), $\beta\prime$ is a matrix of parameter estimates, $\varepsilon_{it}$ represents the error term, =1, . . . , $N$, represents the units in the panel (here, countries), and $t$ = 1, . . . , $T$, represents the time units (here, years). Model (1) is rarely appropriate for practical use, but it is a starting point for panel model construction.

c. Fixed-Effect Model

The FE model controls the cross-sectional variations in the data and allows a separate intercept for each cross-section [63] The model takes the following form:

$$i = 1, \ldots, N,\ t = 1, \ldots, T,,\ i = 1, \ldots, N,\ t = 1, \ldots, T, \tag{2}$$

where $\alpha_i$ is a vector of individual effects for each unit (here, each country); the remaining symbols are the same as those in the model (1).

**Table 3.** Summary of previous studies on the impact of the circular economy on economic growth in the European Union.

| No. | Authors | Sample | Dependent Variables | Independent Variables |
|---|---|---|---|---|
| 1 | [58] | 2010–2017 | GDP per capita growth (%) | CMUR (%); RRMW (Tons); TRM (Imports intra-EU27 (from 2020)); ETAXM (Euros); RLP (%); RP (Euros/kg) |
| 2 | [59] | 2000–2017 | GDP per capita growth (%) | ETAXP (% of GDP); RRMW; TRM (imports intra-EU27 (from 2020)); INV |
| 3 | [60] | 2008–2016 | GDP per capita (Euros) | GMWpc (kilograms per capita); RRMW (%); RRPTP (%); RREW (%); RBW (kilograms per capita); VAFC (million euros); PAT (number) |
| 4 | [61] | 2010–2014 | RRMW (%) | CMUR (%); ETAXM (in million Euros); RP (Euros per kg); TRM (imports intra-EU27 (from 2020)); GERD (in million Euros) |
| 5 | [62] | 2001–2018 | RP (Euros per kilogram, chain-linked volumes (2015)) | RRMW (%); CMUR (%); RRCDW (%); DMCpc (tons per capita); SRECFC (%); FECHpc (KGOE); PECpc (in kilograms of oil equivalent per capita); FECpc (in kilograms of oil equivalent per capita); IRDEB (Euros per inhabitant); IRDEG (Euros per inhabitant); GHGpc (tons of $CO_2$ equivalent per capita); GHGIEC (Index, 2000 = 100) |

Note: INV: innovation; RRPTP: recycling rate of packaging waste by type of packaging; VAFC: private investments, jobs, and gross value added related to circular economy sectors. For all variable descriptions, see Table 2.

The FE model assumes no covariance between the cross-sectional variations and independent variables. More specifically, the FE model uses N-1 dummy variables for cross-sections, where N is the number of panels in the data. The FE model can be compared with both the POLS and RE models using the standard F test and HT.

The current study uses the robust FE model, assuming that the residuals are heteroscedastic. The robust FE provides aid to the estimator to tackle the heteroscedasticity issue.

d. Random-Effect Model

The RE model is also a panel regression model, which, in contrast to the FE model, does not allow separate intercepts of each panel [63]. In the RE approach, individual differences between units are random, i.e., they are included in the error term. The model takes the following form

$$y_{it} = \mu + \beta \prime x_{it} + v_{it},\ i = 1, \ldots, N,\ t = 1, \ldots, T, \tag{3}$$

where $\mu$ is a common constant and error term $v_{it}$ is a sum of the independent error terms across all observations $\varepsilon_{it}$ and random individual effects $\alpha_i$, which are constant over time, but differ across the panel units (countries)

$$v_{it} = \varepsilon_{it} + \alpha_i,\ i = 1, \ldots, N,\ t = 1, \ldots, T, \tag{4}$$

The RE model uses a single intercept, an average of all intercepts. It is appropriate when a random sample is selected from a large population [64]. Particularly with samples with a large number of cross-sectional units, RE models can have a higher degree of freedom and a higher level of estimation efficiency (lower standard errors and greater statistical significance) [65]. The RE model can be compared with both the pooling and FE models using the BPLM test and HT.

#### 3.2.2. Panel Diagnostic

a. Hausman Test

It is not easy to decide between the FE and RE models. Therefore, [66] provided a test to choose the appropriate model for data to make this decision easy. Researchers usually use the HT to check the endogeneity bias in panel data. In [66], the authors described that rejecting the null hypothesis $H_0$ implies that the FE and RE are different. Therefore, FE should be preferred over RE. The test checks the following null hypothesis:

$$H_0: \; E(v_{it}/X_{it}) = 0 \;\; i = 1, \ldots, N, \; t = 1, \ldots, T, \tag{5}$$

The hypothesis means that the error term is uncorrelated with independent variables. In other words, the independent variables do not vary for the cross-section, so the RE is appropriate. Hence, accepting the hypothesis means that the RE is proper, whereas rejections of the hypothesis indicate that a FE model is best for the data.

b. Breusch and Pagan Lagrangian Multiplier Test

The current study used the BPLM test [67] to analyze whether POLS or RE models were better in the panel data set. The null hypothesis of the BPLM test is that the POLS regression model is appropriate, and the alternative hypothesis is that the RE model is appropriate. Suppose the $p$-value is small enough to reject the null hypothesis. As a result, the RE model would be recommended over the POLS model, as there would be a significant RE.

The BPLM test can be used as $T \rightarrow \infty$ in a fixed case. The formula for the test is as follows:

$$LM_{BP} = T \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \hat{\rho}_{ij}^2, \tag{6}$$

c. Cross-Sectional Dependence Test

Pesaran's cross-sectional independence test was used to analyze the cross-sectional dependence in the panel data set [68]. The residuals were examined for cross-sectional dependence using the Pesaran (cross-sectional dependence) $CD$ test. The $CD$ test may cause the results to be biased (also called contemporaneous correlation). The null hypothesis of Pesaran's test assumes that there is no serial correlation. On the other hand, the alternative hypothesis is that a serial correlation does exist.

$$CD_{LM} = \sqrt{\frac{1}{n(n-1)}} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left( TP_{ij}^2 - 1 \right) \tag{7}$$

According to [52], $CD_{LM}$ is asymptotically distributed as $N(0, 1)$, with $T \rightarrow \infty$ coming first and $n \rightarrow \infty$ coming later, under the null hypothesis.

Ref. [69] advised using the subsequent $CD$ test statistic:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left( \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \right) \tag{8}$$

where $CD$ represents the cross-sectional dependence, $N$ denotes the cross-sections in the panel data, $T$ is the time horizon, and $\hat{\rho}_{ij}$ is the cross-sectional correlation of error between $i$ and $j$.

d. Autocorrelation Test

The current study uses the Wooldridge test [70] to detect autocorrelation in the panel data model. The null hypothesis of Wooldridge's test assumes that there is no first-order autocorrelation. On the other hand, the alternative hypothesis is that autocorrelation exists.

e. Heteroscedasticity Test

The modified Wald test was applied to analyze the group-wise heteroscedasticity in the residuals of the FE panel model. Owing to the massive differences between cross-sectional countries, this presumption may be violated, raising the distributions' variance. As a result, the OLS estimate is biased [64]. When the assumption of normality is not satisfied, the modified Wald statistic is still valid, at least in asymptotic terms [71]. The modified Wald test null hypothesis assumes that residuals are homoscedastic, and the alternative hypothesis is that the residuals are heteroscedastic.

## 4. Results

This study focuses on identifying the CE indicators that affect (positively or negatively) energy consumption in 24 countries of the EU. We selected five modeling approaches that covered different CE aspects based on the literature review. In particular, we considered publications [58–62]. In these papers, the dependent variables were usually the GDP per capita, the RRMW, and the RP. However, from other empirical studies, it is evident that the EC is closely related to the GDP per capita [72,73]. Therefore, we added GDP per capita to each defined specification. Using alternative models describing EC and RENC allows for model comparison and finds the most appropriate model. The hypothetical models are summarized in Table 3.

The empirical study entailed two stages. Firstly, we compared alternative model specifications describing EC and RENC indicators, and secondly, we extracted and interpreted those significant CE indicators across most of the model's specifications. Finally, linking the CE factors to SDGs was possible.

We employed the panel data methodology from the panel unit roots test and the construction of the panel model. As the variables exhibited no unit roots, we decided to start with a POLS model with FE and RE estimators. The panel diagnostics indicated that the RE estimator was appropriate. However, panel heterogeneity was observed. Therefore, we used the robust FE model based on the robust standard error proposed by [74]. The results of the model comparison are presented in Table 4. It is worth mentioning that the robust FE model automatically adjusted the issue of heteroscedasticity and serial correlation.

**Table 4.** Comparison of robust Fixed-Effect models for aggregate and renewable energy consumption.

| | EC | | | | | RENC | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Exogenous Variable** | **Model 1a** | **Model 2a** | **Model 3a** | **Model 4a** | **Model 5a** | **Model 1b** | **Model 2b** | **Model 3b** | **Model 4b** | **Model 5b** |
| RGDPpc | − | − | | | − | − | − | | | + |
| RGDP | | | | + | | | | | + | |
| ETAXM | + | − | | + | | + | − | | + | |
| ETAXP | | | | | + | | | | | − |
| RP | + | + | + | + | + | − | + | − | + | + |
| RLP | + | − | | − | + | − | − | | − | − |
| RRMW | − | − | − | − | − | − | − | − | − | − |
| CMUR | − | − | + | − | + | − | − | − | − | − |
| TRM | − | − | | − | − | − | − | | + | + |
| GMWpc | | − | | − | | | − | | − | |
| RBW | | − | | | | | − | | | |
| DMCpc | | | − | + | + | | | − | − | + |
| PECpc | | | + | − | + | | | − | − | − |
| FECpc | | | − | − | − | | | − | − | − |
| SRECFC | | | − | − | − | | | + | + | + |
| FECHpc | | | − | − | − | | | − | − | + |
| GHGpc | | | − | − | − | | | − | − | − |
| GHGIEC | | | − | − | − | | | − | − | − |
| IRDEB | | | − | − | − | | | − | − | − |
| IRDEG | | | + | + | + | | | − | − | − |
| Model diagnostics | | | | | | | | | | |
| $R^2$ within the groups | 0.496 | 0.344 | 0.421 | 0.597 | 0.4775 | 0.3756 | 0.2851 | 0.4164 | 0.5698 | 0.4912 |
| $R^2$ between the groups | 0.7216 | 0.006 | 0.0535 | 0.5216 | 0.0010 | 0.2817 | 0.1768 | 0.1123 | 0.1384 | 0.0247 |
| $R^2$ overall | 0.7004 | 0.004 | 0.0499 | 0.5019 | 0.0014 | 0.2854 | 0.1326 | 0.1206 | 0.1531 | 0.0148 |
| BIC | 1086.24 | 1129.28 | 1146.65 | 1002.16 | 1144.25 | 955.48 | 998.92 | 966.63 | 915.37 | 955.65 |

Note: + indicates significant variables and − indicates insignificant variables in the models.

Taking Table 4, based on the $R^2$ indicators and Bayesian Information Criterion (BIC), we selected the best model specifications, i.e., model 4, which was best for EC (Model 4a) and RENC (Model 4b) descriptions. The detailed results of models 4a and 4b are presented in Table 5.

**Table 5.** Empirical results for model 4a for EC and 4b for RENC.

| | EC | | | | RENC | | | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Coef.** | **St. Err.** | ***t*-Value** | ***p*-Value** | **Coef.** | **St. Err.** | ***t*-Value** | ***p*-Value** |
| RGDP | 0.000 | 0.000 | 1.83 | 0.080 | 0.000 | 0.000 | −1.93 | 0.066 |
| TRM | 0.000 | 0.000 | 0.76 | 0.455 | 0.000 | 0.000 | −1.77 | 0.090 |
| RLP | 0.068 | 0.063 | 1.08 | 0.291 | 0.045 | 0.035 | 1.26 | 0.219 |
| RP | −6.879 | 2.173 | −3.17 | 0.004 | 2.342 | 1.164 | 2.01 | 0.056 |
| ETAXM | −0.001 | 0.000 | −7.82 | 0.000 | 0.000 | 0.000 | 3.6 | 0.002 |
| RRMW | 0.004 | 0.025 | 0.18 | 0.861 | 0.000 | 0.016 | 0.000 | 0.996 |
| CMUR | −0.174 | 0.154 | −1.13 | 0.270 | −0.236 | 0.188 | −1.26 | 0.221 |
| DMCpc | −0.344 | 0.157 | −2.19 | 0.039 | −0.051 | 0.132 | −0.38 | 0.704 |
| SRECFC | −0.003 | 0.082 | −0.04 | 0.969 | 0.127 | 0.068 | 1.86 | 0.075 |
| FECHpc | 0.011 | 0.007 | 1.56 | 0.132 | −0.003 | 0.003 | −1.03 | 0.315 |
| PECpc | 3.003 | 2.164 | 1.39 | 0.178 | 1.361 | 2.316 | 0.59 | 0.563 |
| FECpc | 1.431 | 1.636 | 0.88 | 0.391 | 1.325 | 0.873 | 1.52 | 0.143 |
| IRDEB | 0.004 | 0.006 | 0.6 | 0.555 | 0.02 | 0.013 | 1.5 | 0.147 |
| IRDEG | 0.029 | 0.016 | 1.81 | 0.084 | 0.046 | 0.041 | 1.13 | 0.270 |
| GHGpc | 0.207 | 0.589 | 0.35 | 0.728 | −0.02 | 0.417 | −0.05 | 0.963 |
| GHGIEC | −0.044 | 0.063 | −0.7 | 0.492 | 0.014 | 0.05 | 0.27 | 0.791 |
| Constant | 50.803 | 8.603 | 5.91 | 0.000 | −12.538 | 9.309 | −1.35 | 0.191 |
| Model diagnostics for parameter significance | | | | | | | | |
| F-TEST | *F-TEST = 39.668, Prob > F = 0.000* | | | | *F-TEST = 8.817, Prob > F = 0.000* | | | |

In this paper, we asked whether CE indicators decreased the total EC in EU countries by reducing waste, extending the life cycle of products, and making more intelligent use of raw materials. On the other hand, these factors should encourage and increase the RENC.

Model 4a showed that EC in the EU can be significantly described using RGDP (+), RP (−), ETAXM (−), DMCpc (−), and IRDEG (+), where the signs of the coefficients are presented in parentheses. The significance level was assumed to be 0.1 due to the relatively short time series, and other variables were not significant in the model. The general picture is that the assumption can be confirmed in light of the data. A positive linkage between real GDP (RGDP) has been established, as reported in many papers [75,76].

Additionally, a positive relationship could be seen between R&D expenditure by the government and EC. As reported in the literature, R&D expenditures represent innovations in the economy, increasing economic growth and making it more sustainable [77]. However, CE indicators, such as RP, DMCpc, and ETAXM, decrease the total EC, which is produced from nonrenewable and renewable sources.

Model 4b, which describes the RENC, revealed positive relationships between the RENC and the following variables: RGDP, TRM, RP, ETAXM, and SRECFC. These findings also support the hypothesis that a CE provides technological, financial, and institutional incentives for increasing energy production from renewable sources.

## 5. Discussion and Conclusions

The EU countries are developing the CE concept and are relatively advanced in introducing that idea into practice toward SDGs. However, the level of CE development differs between individual countries. We compared five model specifications for the total and RENC, including RGDP and CE indicators. This paper analyzed EU countries' data from 2010 to 2019 based on a balanced panel.

We confirmed the research question that CE indicators decreased the total EC in EU countries; on the contrary, these factors increased the RENC. We found that the panel RE estimator in many specifications was relatively sufficient. However, due to heteroscedasticity, we decided to employ a robust FE estimation that reduced its effects. Based on the statistical procedure, we could select the best model specification out of the five alternatives.

The CE indicators, such as RP, ETAXM, and DMCpc, significantly reduced the total EC. The RENC expanded due to RP, ETAXM, SRECFC, and TRM. These results show that the EU economy is transforming by increasing the reuse of recycled materials and decreasing waste. The impact of environmental tax revenues and GERD was similarly confirmed by [51]. However, it is still in the process leading to achieving the SDGs, particularly in the areas of affordable and clean energy (7), industry, innovations, and infrastructure (9), sustainable cities and communities (11), responsible consumption and production (12), and climate action (13). Is the speed of the process satisfactory for avoiding the negative consequences of global warming and climate change? This question is still open. It requires continuous monitoring by economists, social scientists, engineers, biologists, and other researchers.

Insignificant CE indicators demonstrated that potential variables were still not very much used in energy-use reduction. These were primarily RRMW and CMUR. This means that, apart from the increased recycling and use of municipal waste, its use does not reduce EC. A low impact of recycling was also confirmed in [52]. IRDEB is another insignificant variable, and it represents R&D expenditures in the business sector, which do not play as significant a role as they could. Additionally, greenhouse gas emissions and intensity (GHGpc, and GHGIEC) still have no impact on EC reduction. Similarly, the above variables do not increase RENC. These variables allow for identifying the underdeveloped areas that require future focus.

As the panel models reported heterogeneity, we employed a robust method for parameter estimation. However, the EU member countries are diversified in terms of total energy use and sustainability. It may be reasonable to distinguish homogenous subgroups of countries, but it also requires a more extended time series in the panel data. This is a direction for future investigation.

A general framework from the SDGs is essential, but not wholly satisfactory, as detailed regulation, social awareness, and individual attitudes toward acting for future generations can speed up or slow down the entire process. Increasing the CE share in the entire economy requires many institutional solutions, both formal and informal. Institutional solutions can also be analyzed and compared from particular country and EU perspectives.

The concept of the circular economy is relatively new, and countries are adopting it into industrial sectors at different speeds, as it requires some technical adjustments and investments. Other countries have introduced not only new institutional rules, but also new materials, and industrial technologies are continuously being improved. For example, Germany and the Netherlands can be considered leaders in green energy and municipal waste reuse. However, the other countries are not as advanced in the CE. Therefore, a continuous monitoring process is necessary. Keeping in mind that not all consumed energy will originate from renewable sources, adding new data can reveal new results and show the speed and direction in which the entire application of the CE is approaching. In further research, comparing countries attempting to gain sustainability from global and regional perspectives will be necessary.

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## Appendix A

**Table A1.** Summary statistics of the circular economy for the EU in 2010–2019.

| | EC | RENC | CMUR | DMCpc | ETAXM | ETAXP | FECHpc | FECpc | GHGIEC | GHGpc | GMWpc | IRDEB | IRDEG | RBW | PECpc | RGDPp | RGDPpc | TRM | SRECFC | RRMW | RP | RLP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean** | 60.60 | 4.86 | 9.13 | 16.88 | 12,268.53 | 2.62 | 594.28 | 2.42 | 89.00 | 9.54 | 478.19 | 336.21 | 56.98 | 65.27 | 3.27 | 28,717.59 | 1.84 | 17,01536.00 | 21.09 | 35.23 | 1.70 | 99.70 |
| **Med** | 27.81 | 2.28 | 7.6 | 15.67 | 5345.02 | 2.51 | 596 | 2.08 | 87.95 | 8.45 | 466 | 166 | 37.55 | 60 | 2.95 | 21,826.05 | 1.67 | 630,787 | 18.03 | 34.45 | 1.25 | 100 |
| **Max** | 329.22 | 50.57 | 30 | 37.34 | 61,119 | 4.14 | 1084 | 8.54 | 124.5 | 26.6 | 931 | 1151.9 | 350.6 | 196 | 9.09 | 97,853.71 | 19.35 | 10,792,542 | 55.78 | 67.2 | 4.97 | 120.56 |
| **Min** | 3.43 | 0.038 | 1.2 | 7.95 | 431.6 | 1.41 | 252 | 1.09 | 63.2 | 5.2 | 247 | 8.5 | 2.4 | 2 | 1.51 | 6871.97 | −11.13 | 17,383 | 2.852 | 4 | 0.29 | 76.58 |
| **SD.** | 78.86 | 8.05 | 6.40 | 6.21 | 16,837.50 | 0.65 | 184.51 | 1.30 | 9.81 | 3.77 | 134.63 | 332.45 | 62.34 | 50.26 | 1.38 | 19,614.15 | 2.65 | 2,351,216.0 | 11.25 | 14.97 | 1.07 | 5.59 |
| **Skew** | 2.01 | 3.27 | 1.13 | 0.83 | 1.90 | 0.49 | 0.14 | 2.64 | 0.59 | 1.81 | 0.91 | 0.80 | 2.85 | 0.69 | 1.73 | 1.65 | 0.56 | 1.96 | 0.81 | 0.12 | 0.90 | −0.46 |
| **Kurt** | 6.38 | 15.17 | 3.99 | 3.32 | 5.31 | 2.33 | 2.59 | 10.71 | 3.90 | 7.21 | 4.10 | 2.22 | 11.80 | 2.53 | 6.42 | 6.28 | 12.61 | 6.48 | 3.36 | 2.22 | 3.03 | 7.06 |
| **JB** | 276.78 | 1911.74 | 61.04 | 28.88 | 197.92 | 14.26 | 2.49 | 872.82 | 22.07 | 307.90 | 45.10 | 31.93 | 1099.44 | 21.02 | 236.26 | 216.95 | 936.46 | 275.39 | 27.85 | 6.64 | 32.11 | 173.76 |
| **Prob** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.29 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 | 0.00 |

Note: Max = maximum; Min = minimum; S.D. = standard deviation; Skew = skewness; Kurt = Kurtosis; JB = Jarque–Berra; Prob = probability; N*T = 240 observations.

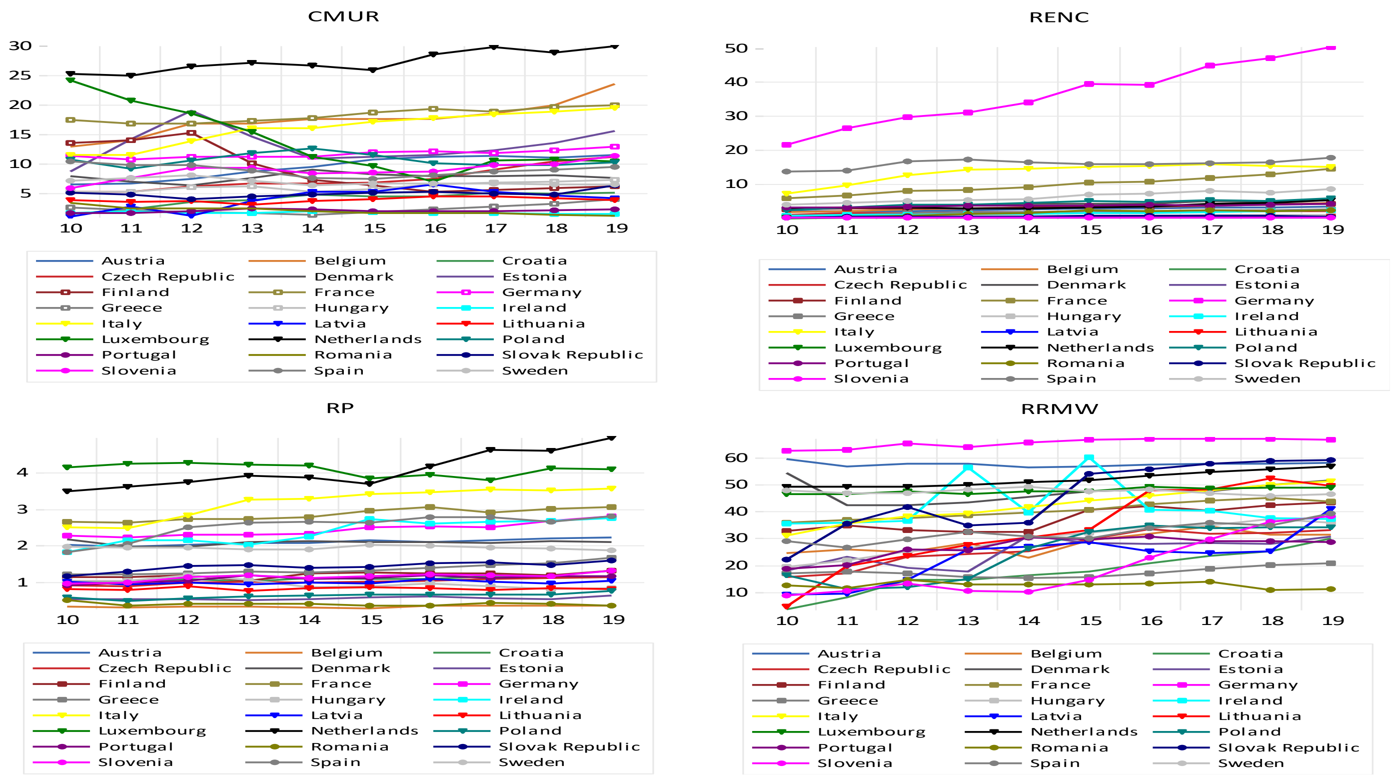


**Figure A1.** Graphical trends of the circular economy indicators for the EU in 2010–2019.

**Table A2.** Cross-sectional independent unit root tests.

| | Var | EC | | | | RENC | | | | DMCpc | | | | CMUR | | | | EXTAM | | | | EXTAP | | | | FECHPC | | | | FECPC | | | | GHGIEC | | | | GHGPC | | | | GMWPC | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Test** | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF |
| Intercept at level | Stat | −7.8 | −4.8 | 107.9 | 123.9 | −2.6 | 1.7 | 57.0 | 80.0 | −10.5 | −2.9 | 87.2 | 65.0 | −5.0 | −0.4 | 61.41 | 57.29 | −1.9 | 2.1 | 53.3 | 46.0 | −9.2 | −3.1 | 95.3 | 88.7 | −9.8 | −4.2 | 98.5 | 136.2 | −11.1 | −4.6 | 115.1 | 94.6 | −3.7 | 1.9 | 44.1 | 63.0 | −7.2 | −2.2 | 75.8 | 90.5 | −3.5 | −0.7 | 63.9 | 81.3 |
| | *p*-value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.96 | 0.17 | 0.00 | 0.0 | 0.0 | 0.0 | 0.1 | 0.00 | 0.32 | 0.09 | 0.168 | 0.0 | 1.0 | 0.3 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.6 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.1 | 0.0 |
| | Result | S | S | S | S | S | NS | NS | S | S | S | S | S | S | NS | NS | NS | S | NS | NS | NS | S | S | S | S | S | S | S | S | S | S | S | S | S | NS | NS | S | S | S | S | S | S | NS | S | S |
| | I order | I(0) | I(0) | I(0) | I(0) | I(0) | | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | | | | I(0) | | | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | | I(0) | I(0) |
| Intercept and trend at level | Stat | −9.6 | −1.2 | 73.9 | 91.4 | −7.8 | −0.7 | 67.0 | 100.1 | −17.6 | −3.3 | 112.7 | 123.4 | −7.6 | −0.3 | 58.43 | 69.28 | −9.9 | −1.1 | 90.4 | 88.1 | −10.0 | −0.5 | 70.5 | 66.6 | −11.4 | −1.4 | 77.2 | 152.8 | −29.0 | −4.2 | 111.1 | 110.7 | −7.2 | −0.4 | 61.7 | 125.7 | −9.7 | −0.8 | 65.5 | 64.2 | −14.0 | −1.9 | 83.6 | 130.3 |
| | *p*-value | 0.00 | 0.11 | 0.01 | 0.00 | 0.00 | 0.24 | 0.04 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.39 | 0.14 | 0.02 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.4 | 0.1 | 0.0 | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Result | S | NS | S | S | S | | S | S | S | S | S | S | S | NS | NS | S | S | NS | S | S | S | NS | S | S | S | S | S | S | S | S | S | S | S | NS | S | S | S | NS | S | S | S | S | S | S |
| | I order | I(0) | | I(0) | I(0) | I(0) | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | | | I(0) | I(0) | | I(0) | I(0) | I(0) | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) |
| Intercept at difference | Stat | −12.4 | −6.0 | 130.0 | 150.0 | −11.1 | −5.6 | 128.7 | 176.7 | −18.8 | −8.8 | 172.8 | 191.9 | −10.1 | −4.3 | 105.45 | 140.23 | −11.6 | −5.5 | 130.2 | 143.6 | −12.0 | −4.5 | 113.8 | 114.1 | −14.3 | −7.0 | 149.6 | 238.9 | −21.4 | −7.3 | 140.8 | 144.2 | −9.9 | −5.0 | 118.2 | 180.0 | −9.1 | −3.9 | 98.2 | 105.6 | −18.3 | −8.5 | 150.0 | 157.6 |
| | *p*-value | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Result | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S |
| | I order | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) |
| Intercept and trend at difference | Stat | −15.6 | −1.8 | 90.8 | 126.7 | −10.9 | −1.9 | 98.7 | 175.5 | −17.6 | −2.6 | 113.0 | 180.3 | −76.1 | −7.9 | 143.90 | 114.20 | −14.3 | −2.6 | 115.4 | 162.9 | −12.7 | −2.1 | 101.9 | 183.3 | −13.1 | −1.7 | 89.9 | 181.5 | −11.3 | −0.9 | 74.5 | 107.3 | −12.8 | −1.9 | 97.7 | 153.9 | −8.6 | −0.7 | 66.4 | 86.8 | −16.8 | −1.8 | 87.9 | 161.2 |
| | *p*-value | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Result | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | NS | S | S | S | S | S | S | S | NS | S | S | S | S | S | S |
| | I order | | I(1) | | | | | | | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) |

| | Var | IRDEB | | | | IRDEG | | | | PECPC | | | | RBW | | | | RGDPP2015 | | | | RGDPPC2015 | | | | RLP | | | | RP | | | | RRMW | | | | SRECFC | | | | TRM | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Test** | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF | LLC | IPS | ADFF | PPF |
| Intercept at Level | Stat | 2.7 | 3.7 | 44.0 | 27.4 | −1.9 | 1.7 | 41.0 | 55.6 | −7.3 | −2.6 | 81.3 | 106.7 | 0.8 | 3.2 | 27.5 | 27.5 | 6.1 | 7.2 | 14.5 | 16.0 | −12.3 | −5.7 | 119.3 | 97.1 | 1.4 | 4.7 | 29.7 | 34.8 | −3.6 | −0.1 | 58.4 | 105.4 | −5.0 | −1.1 | 65.7 | 62.1 | −3.5 | 1.7 | 40.5 | 34.6 | −4.8 | −1.1 | 62.7 | 60.1 |
| | *p*-value | 1.0 | 1.0 | 0.6 | 1.0 | 0.0 | 1.0 | 0.8 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 1.0 | 1.0 | 0.9 | 0.0 | 0.5 | 0.1 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 1.0 | 0.8 | 0.9 | 0.0 | 0.1 | 0.1 | 0.1 |
| | Result | NS | NS | NS | NS | S | NS | NS | NS | S | S | S | S | NS | NS | NS | NS | NS | NS | NS | NS | S | S | S | S | NS | NS | NS | NS | S | NS | NS | S | S | NS | S | S | S | NS | NS | NS | S | NS | S | NS |
| | I order | | | | | I(0) | | | | I(0) | I(0) | I(0) | I(0) | | | | | | | | | I(0) | I(0) | I(0) | I(0) | | | | | I(0) | | | I(0) | I(0) | | I(0) | I(0) | | | | | I(0) | | I(0) | |
| Intercept and trend at level | Stat | −3.9 | 1.0 | 40.9 | 38.9 | −4.1 | 1.2 | 36.6 | 54.0 | −9.6 | −0.9 | 63.7 | 73.8 | −7.0 | −0.3 | 57.5 | 76.3 | −18.3 | −1.7 | 92.2 | 61.7 | −17.5 | −3.6 | 127.3 | 116.5 | −7.3 | 0.0 | 60.2 | 39.3 | −11.3 | −1.8 | 90.1 | 141.0 | −14.7 | −2.2 | 93.0 | 104.6 | −7.2 | −0.4 | 59.7 | 59.2 | −9.3 | −1.1 | 72.4 | 58.1 |
| | *p*-value | 0.0 | 0.8 | 0.8 | 0.8 | 0.0 | 0.9 | 0.9 | 0.3 | 0.0 | 0.2 | 0.1 | 0.0 | 0.0 | 0.4 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.5 | 0.1 | 0.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.1 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 |
| | Result | S | NS | NS | NS | S | NS | NS | NS | S | NS | S | S | S | NS | NS | S | S | S | S | NS | S | S | S | S | S | NS | NS | NS | S | S | S | S | S | S | S | S | S | NS | NS | NS | S | NS | S | NS |
| | I order | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) | I(0) |
| Intercept at difference | Stat | −5.5 | −2.0 | 78.7 | 114.9 | −11.6 | −4.6 | 114.7 | 151.8 | −10.6 | −5.0 | 116.3 | 148.8 | −15.0 | −6.4 | 139.1 | 168.3 | −9.9 | −3.1 | 88.3 | 94.8 | −20.4 | −9.8 | 187.1 | 186.0 | −11.3 | −5.0 | 117.4 | 128.7 | −16.9 | −7.9 | 162.6 | 231.9 | −15.2 | −7.9 | 160.9 | 198.7 | −12.1 | −5.1 | 115.8 | 132.9 | −19.4 | −7.8 | 154.2 | 154.6 |
| | *p*-value | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Result | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S |
| | I order | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) |
| Intercept and trend at difference | Stat | −10.7 | −1.9 | 99.1 | 146.3 | −14.6 | −2.2 | 101.9 | 167.5 | −6.6 | −0.6 | 71.1 | 135.3 | −14.8 | −2.1 | 99.5 | 189.7 | −11.5 | −1.7 | 91.2 | 144.6 | −18.7 | −2.9 | 119.1 | 143.8 | −16.6 | −2.7 | 114.4 | 158.1 | −21.6 | −2.6 | 111.5 | 190.9 | −21.4 | −3.7 | 135.7 | 210.0 | −13.4 | −1.5 | 83.4 | 146.1 | −24.7 | −2.8 | 111.8 | 139.5 |
| | *p*-value | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Result | S | S | S | S | S | S | S | S | S | NS | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S | S |
| | I order | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) |

Note: If $p < 1$, which indicates the rejection of the null hypothesis of a unit root at the 1% significant level; agg = aggregate. Unit root tests with intercept, and intercept and trend at level and at difference. S = stationary; NS = nonstationary; LLC = Levin–Lin–Chu; IPS = Im–Pesaran–Shin; ADFF = ADF-Fisher; PP-Fisher.

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