The Causal Link Between Circular Economy And Economic Growth In EU-25

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The causal link between circular economy and economic growth in EU-25

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Abstract

Actively promoting circular economy (CE) is one of the key means of global sustainable development. The purpose of this study is to analyze the causal relationship between CE and economic growth using data from EU-25 countries from 2010 to 2018. The selected CE indicators included municipal waste recycling rate, CE-related investment, municipal waste generation per capita, circularity rate, and trade in recyclable raw materials. Panel cointegration techniques affirmed the long-term equilibrium relationship between CE indicators and GDP. Panel vector error correction model results confirmed that in terms of short-run causality, an increase in material recycling led to a decrease in waste generation, an increase in waste generation led to an increase in CE-related investment, and economic growth led to circular economy growth, but not vice versa. This implies that encouraging CE-related innovation investments and promoting material recycling to stimulate the secondary raw material market can help achieve zero waste goals. Looking at the long-term causality, the GDP and CE indicators constituted a causal loop, which implies that there is co-evolution between them, although the circular economy is still in its infancy. This co-evolutionary sustainable economic growth can bring welfare to future generations.

Keywords: Recycling; Circular economy; Economic growth; Causality; Panel model

Acronyms and nomenclature			
ARDL	Autoregressive distributed lag model	R&D	The expenditure of R&D
CE	Circular Economy	RbW	Recycling of bio-waste
CUR	Circularity rate	ReP	Recycling rate of e-products
C2C	Cradle to cradle	RecyFact	Recycling factor
EC	Energy consumption	ResoFacts	Resource consumption factors
EE	Environmental employment	ReW	Recycling rate of e-waste
ELEC	Electricity consumption	RMW	Recycling rate of municipal waste
ETax	Environmental Taxes	RP	Resource productivity
GDP	Gross Domestic Product	RpW	Recycling rate of packaging waste
GMWp	Municipal waste generation per capita	S_Innov	Market share of environment-related innovative products
GPP	National Green Procurement Plans	S_REC	Share of renewable energy in electricity
HE	Heating Energy	TMR	Trade in recyclable raw materials
INV	CE-related investment	VAR	Vector Autoregression model
LF	Labor force-related variables	VECM	Vector error correction model
LU	Luxembourg.	YCG	Per capita GDP growth
MSWG	Municipal solid waste generation	≅/≈/≠	Negative/positive/no influence
PAT	Recycling-related patents	↔/→/~	Bidirectional/Unidirectional/No causality
REC	Renewable Energy Consumption		

1. Introduction

The 2021 Circularity Gap Report (CGR 2021) has shown that our world is getting less circular. The world economy Circular Gap from 9.1% in 2018 to 8.6% in 2020. The Report signal that large-scale unsustainable influences, processes, and behaviors have occurred in our ongoing linear economy. This results in the production of greenhouse gases (GHGs) from resources extraction to final use accounting for about 70 percent of the total GHGs. If the circular strategy proposed in the Report is adopted, it is expected to reduce global GHG emissions and raw material usage by 39% and 28%, respectively. In 2021, the European Commission released its new Circular Economy Action Plan (CEAP 2021). It fits in a list of EU strategic documents that have a significant impact on standardization, including the new Biodiversity, Farm-to-Table, Industrial, Sustainable Chemicals, and Sustainable Product Initiative strategies. The Commission's vice-president, Frans Timmemans pointed out that the European economy is still largely linear, with only 12% of materials being recycled and returned to the economy. He said "To achieve climate-neutrality by 2050, to preserve our natural environment, and to strengthen our economic competitiveness, requires a fully circular economy". Understanding how a circular economy affects economic growth is an important issue in moving towards more circularity.

Promoting a circular economy requires an innovative business model that closes the loop throughout the life cycle of products, materials, and resources to achieve sustainability and profitability, while being attractive to customers and suppliers. Therefore, strengthening the CE can achieve mutual benefits in three aspects, that is, increasing company profits, reducing customer costs, and environmental sustainability (Korhonen et al. 2018). McKinsey calculated that by 2030, in Europe alone, the circular economy would create a net benefit of 1.8 trillion Euros due to the technology revolution (McKinsey & Company 2015). The social outcomes created by this economic model are expected to improve the lives of Europeans, such as improving the quality of life and the environment, creating local green jobs, and increasing household income by almost €3000 (Ellen MacArthur Foundation 2015).

To understand the current state of the EU's promotion of a circular economy, we collected six CE related data for preliminary analysis, including municipal waste recycling rate (RMW), CE-related investment (INV), municipal waste generation per capita (GMWp), circularity rate (CUR), trade in recyclable raw materials (TRM), and real GDP. The second row of Table 1 is the average value of each variable in the EU-27 as a whole from 2010 to 2017, the next row is the value of each variable in 2018 (Eurostat 2021; World Bank 2021). The last row of Table 1 shows the percentage increased for each variable in 2018. Of them, CE-related investment and waste recycling rate increased the most, materials recycling volume and its recycling rate increased slightly, and waste generation increased the least. The growth of circular economy indicators and GDP imply that European countries were making efforts to promote efficient resource management and sustainable economic growth.

Table 1: The comparison between the average value of each indicator from 2010 to 2017 and the corresponding value in 2018 for the EU-27 as a whole

	GMWp kg	TRM Million tonne	CUR %	RMW %	INV Billion euro	GDP Billion us dollar
			Eurostat, 2021			World Bank, 2021
2010-2017	489	80.15	11.03	42.63	114.17	13360.35
2018	496	84.10	11.50	47.20	130.80	4500.41
Growth %	1.43	4.93	4.31	10.73	14.56	8.53

Most recent studies indicate that a circular economy is conducive to economic development. However, there are few quantitative articles that comprehensively explore the nexus between circular economy and economic growth. To fill this gap, this study uses a panel vector error-correcting econometric model (VECM) to examine whether the causal relationship between the circular economy and economic growth is beneficial, inhibitory, neutral, or feedback. Given the short annual data cycles of circular economy indicators, analysis using cross-country panel data can improve the validity of the model.

After introducing the literature gap and the objectives of this paper in the first section, the literature review in the second section discusses topics that are critical to this study. The third section proposes the research framework and research methods. The next section contains descriptive statistics of the connected data, empirical evidence, and discussion. The last section proposes conclusions, policy implications, and research limitations.

2. Literature review

The "take-make-waste" approach in the global production and consumption sectors contributed to around half of global carbon dioxide emissions in 2019, and the resulting waste is causing damage to the environment and human health. And a circular economy that promotes waste elimination and the continued safe use of natural resources could generate economic benefits of up to $4.5 trillion by 2030 (World Economic Forum 2019). CE aims to model human industrial following natural processes through a Cradle-to-Cradle (C2C) design philosophy. This way there will be no waste as all materials are considered recyclable and useful nutrients. Therefore, the CE strategy is seen as a key way to achieve both resource decoupling and impact decoupling. This two types of decoupling are one of the necessary conditions for sustainability.

In 2018, the European Commission proposed using four aspects of production and consumption, waste management, secondary raw materials, and competitiveness and innovation to measure progress in resource use and circular economy. Each aspect contains some quantitative indicators of circular economy, such as resource productivity (RP), recycling rate of e-products (ReP), municipal solid waste generation (MSWG), and municipal waste generation per capita (GMWp) in the production and consumption aspect; the recycling rate from municipal waste, bio-waste, e-waste, and packaging waste (RMW, RbW, ReW, and RpW) in the waste management aspect; CE-related private investment (INV) and recycling-related patents (PAT) in the competitiveness and innovation aspect; as well as trade volume of recyclable raw materials (TRM) and circularity rate (CUR) in secondary raw materials aspect. Table 2 Panel A shows the literature that uses these indicators and GDP-related variables to construct a linear econometric model to study the impact of circular economy on economic growth, namely the CE–growth nexus study. The empirical results presented that indicators RMW (including ReW, RpW, and RbW), CUR, TRM, INV, PAT, ReP, or RP had a positive impact on the growth of GDP per capita (Busu and Trica 2019; Busu 2019; Trica et al. 2019; Hysa et al. 2020; and Sverko Grdic et al. 2020), indicators CUR, RP, and TRM positively influenced RMW (Tantau et al. 2018), as well as recycling factor (RecyFact) and resource consumption factor (ResoFact) positively influenced RP (Pineiro-Villaverde and García-Álvarez 2020). In addition to the above research, there are some literatures discussing this issue from different angles. Siminică et al. (2020) pointed out that the implementation of the "National Green Procurement Plan" had a positive impact on the EU economy. Sulich and Sołoducho-Pelc (2022) studied the creation of Green Jobs market in the circular economy. They found RbW, INV, and PAT can enhance a number of Green Jobs in the EU-28. About causality, Magazzino et al. (2020) found a bidirectional Granger causality between MSWG and economic growth in Switzerland. Gardiner and Hajek (2020) revealed bidirectional causalities between GMWp and economic growth and between GMWp, heating energy, and R&D intensity indicators using panel VECM in EU countries. Based on the findings, they propose policies, such as fees, incentives, and eco-innovations, to strengthen the circular economy and reduce waste generation.

Regarding energy resources and economic growth nexus, many historical literatures use panel VECM to analyze the causal relationship between them (i.e., energy−growth causality). One of its extensions is the study of CE−growth causality, because CE is highly related to resource consumption, efficiency, and conservation. Panel B of Table 2 shows the literature on the energy-growth and CE-growth nexus. In order to understand the impact of the effective use of energy resources in the EU on the economy in recent years, we only selected literature whose research data period exceeds 2015. For the Central and Eastern European countries, Bercu et al. (2019) found a long-run bidirectional causality between electricity consumption and economic growth and Manta et al. (2020) found no causality between total energy consumption and growth. For clean energy, Smolović et al. (2020) found a long-run bidirectional causality between renewable energy consumption and growth in new EU-13 and a long-run unidirectional causality from growth to renewable in traditional EU-15. Simionescu et al. (2019) found no causality between share of renewable energy in electricity and growth in EU-27. Busu (2020) found a long-run unidirectional causality from renewable energy consumption to growth and a bidirectional causality between resource productivity and growth in EU-28. One of the possible reasons for the inconsistent research results is that the proxy variables used for energy in the literature are different.

To the best of our knowledge, there are few articles using quantitative indicators of the four aspects of circular economy to construct an econometric model to comprehensively analyze their causal relationship with economic growth. That is, whether the growth of circular economy will lead to economic growth, reverse growth, co-evolution, or neutrality. Our study aims to fill this gap, using a panel VECM to investigate the causal relationship between CE and economic growth in EU countries.

Table 2: Literature survey

Panel A: GDP-CE nexus

Author	Period	Country/Region	Methodology	Depend var.	Independent var. and results
Busu and Trica (2019)	2010–2017	EU-27	Pooled regression	YCG	CUR, RMW, TRM, ETax, and LF (All≈YCG)
Busu (2019)	2008–2017	EU-27	Pooled regression	YCG	RMW, S_INNOV, REC, and LF (All≈YCG)
Trica et al. (2019)	2007–2016	EU-27	Pooled regression	YCG	RP, EE, ReP, S_Innov (All≈YCG)
Hysa et al. (2020)	2000-2017	EU-28	Panel regression	GDP per capita	ETax, RMW, and INV≈GDP, TRM≠GDP
Sverko Grdic et al. (2020	2008-2016	EU-28	Pooled regression	GDP per capita	INV, GMWp, RMW, RpW, RbW, and ReW≈GDP
Tantau et al. (2018)	2010–2014	EU-28	Panel regression	RMW	CUR, RP, TRM, ETax, RD, (All≈RMW except ETax≅RMW)
Pineiro-Villaverde and García-Álvarez (2020)	2001-2018	EU-28	Pooled regression	RP	RecyFact≈RP, ResoFacts≈RP
Siminică et al. (2020)	2007–2018	EU-28	Panel unrestricted VAR	GDP, CE, CO_2	GPP (GPP≠CO_2; GPP≈GDP/CE)
Sulich and Sołoducho-Pelc (2022)	2009-2019	EU-28	Pooled regression	Green Jobs	RbW, PAT, INV≈Green Jobs
Magazzino et al. (2020)	1990-2017	Switzerland	Granger test	GDP per capita, MSWG	GDP↔MSWG
Gardiner and Hajek (2020)	2000–2018	EU-28	Panel VECM	GDP, GMWp, HE, and R&D intensity	GMWp↔GDP, GMWp↔HE↔R&D intensity

Panel B: Energy−GDP causality

Author	Period	Country/Region	Methodology	Results
Bercu et al. (2019)	1995–2017	14 Central and Eastern European countries	Panel VECM	ELEC↔GDP
Manta et al. (2020)	2000-2017	10 Central and Eastern European Countries	Panel VECM	EC~GDP
Smolović et al. (2020)	2004-2018	New EU-13 and traditional EU-15	Panel ARDL	REC↔GDP (EU-13), GDP→REC (EU-15)
Simionescu et al. (2019)	2007-2017	European Union (EU-28, except LU)	Panel Granger causality	S_REC~GDP
Busu (2020)	2004-2017	European Union (EU-28)	Panel VECM	5-type REC→GDP, RP↔GDP

Note: The abbreviations are in the abbreviation table.

3. Model and methodology

CE strategies are seen as a key way to decouple resource use and environmental impacts from economic growth. We selected five key quantitative indicators from four aspects of CE as a benchmark for comprehensively measuring the progress of circular economy in the EU. They are municipal waste generation per capita (GMWp) in the production and consumption aspect, municipal waste recycling rate (RMW) in the waste management aspect, trade in recyclable raw materials (TRM) and circularity rate (CUR) in the aspect of secondary raw materials, and CE-related private investments (INV) in the aspect of competitiveness and innovation. Using these indicators, we constructed econometric models to analyze the causal relationship between CE and economic growth (i.e., CE−growth causality). In recent years, the use of panel econometric models to study the causal relationship between energy resources and economic growth has achieved fruitful results in the EU (i.e., energy resources−growth causality), see Table 1 Panel B. Following previous studies and Pao and Chen (2021), this study uses panel VECM to investigate CE−growth causality through the following framework

$$L\mathrm{GDP}_{it} = \omega_0 + \omega_1 \mathrm{RMW}_{it} + \omega_2 L\mathrm{TRM}_{it} + \omega_3 L\mathrm{INV}_{it} + \omega_4 L\mathrm{GMWp}_{it} + \omega_5 \mathrm{CUR}_{it} + \varepsilon_{it} \quad (1),$$

where the subscript *i=1,…, 25* denotes an individual of European Union countries, *t* represents the timeline from 2010 to 2018, and ε_{it} is the error term. The variables LGDP, LINV, LGMWp, and LTRM are the natural logarithms of GDP, CE-related investments, generation of municipal waste per capita, and trade volume of recyclable raw materials, respectively. Two percentage-based variables, municipal waste recycling rate (RMW) and circularity rate (CUR), are not converted. The parameter ω_i is the CE-related indicator *i* elasticity of GDP.

We constructed the following equation to examine whether the three explanatory variables CUR, *L*TRM, and RMW belonging to the resource recycling system in Eq. (1) have multicollinearity.

$$\mathrm{CUR}_{it} = r_0 + r_1 L\mathrm{TRM}_{it} + r_2 \mathrm{RMW}_{it} + \varepsilon_{it} \quad (2)$$

If Eq. (2) is a goodness-of-fit model, then multicollinearity occurs in Eq. (1) and CUR should be removed from Eq. (1) as follows:

$$L\mathrm{GDP}_{it} = \omega_0 + \omega_1 \mathrm{RMW}_{it} + \omega_2 L\mathrm{TRM}_{it} + \omega_3 L\mathrm{INV}_{it} + \omega_4 L\mathrm{GMWp}_{it} + \varepsilon_{it} \quad (3)$$

In order to evaluate causality between time series variables in Eq. (3), three steps are required. First, the panel unit root test is used to assess for stationary in a time series. The null hypothesis is that there is a unit root and the alternative is stationary. Time series with unit root is nonstationary and is called integrated of order 1 or *I*(1). A stationary time series is called integrated of order 0 or *I*(0). An *I*(1) series can be changed to *I*(0) through first-order difference. Three panel unit tests, namely Fisher-type ADF (Augmented Dickey–Fuller), PP (Phillips–Perron) (Maddala and Wu 1999; Choi 2001), and LLC (Levin Lin and Chu 2002) are used to find the order of integration of *L*GDP, *L*INV, *L*GMWp, *L*TRM, RMW, and CUR.

In the second step, if the five series of *L*GDP, *L*INV, *L*GMWp, *L*TRM, and RMW in Eq. (3) are *I*(1), then the panel cointegration analysis is performed. If there exists a linear combination of the five variables that is *I*(0), then these five variables are said to be cointegrated and Eq. (3) is a cointegration equation. Cointegration equation has super-consistent OLS estimator $\widehat{\omega}_i$, which means that it is very close to the true parameter (Kao 1999). Two panel cointegration tests, Pedroni (1999) and Kao (1999), were employed. They have a common null hypothesis assumes of no cointegration. Pedroni (1999) derived seven cointegration statistics, four of which are based on the assumption of homogeneous panels, and the other three are in heterogeneous panels. Kao (1999) introduced an ADF t-statistics based on homogeneous panels. Briefly, based on Eq. (3), if (LGDP, RMW, LTRM, LINV, LGMWp) are $I(1)$ and there exist $\widehat{\omega}_i$ i=0,…,4 such that residual $\hat{\varepsilon}_{it}$ is $I(0)$, then Eq. (3) is a cointegration equation. If a cointegration equation exists between the variables, then there is long-run equilibrium relationship between them and there is causality between them in at least one direction (Engle and Granger, 1987).

When panel cointegration is present, the final step is to extract causal relationships between the variables in Eq. (3) using panel VECM as follows:

$$\begin{bmatrix} \Delta LGDP_{it} \\ \Delta RMW_{it} \\ \Delta LTRM_{it} \\ \Delta LINV_{it} \\ \Delta LGMWp_{it} \end{bmatrix} = \begin{bmatrix} \alpha_{10} \\ \alpha_{20} \\ \alpha_{30} \\ \alpha_{40} \\ \alpha_{50} \end{bmatrix} + \sum_{d=1}^{r} \begin{bmatrix} \alpha_{11d} & \alpha_{12d} & \alpha_{13d} & \alpha_{14d} & \alpha_{15d} \\ \alpha_{21d} & \alpha_{22d} & \alpha_{23d} & \alpha_{24d} & \alpha_{25d} \\ \alpha_{31d} & \alpha_{32d} & \alpha_{33d} & \alpha_{34d} & \alpha_{35d} \\ \alpha_{41d} & \alpha_{42d} & \alpha_{43d} & \alpha_{44d} & \alpha_{45d} \\ \alpha_{51d} & \alpha_{52d} & \alpha_{53d} & \alpha_{54d} & \alpha_{55d} \end{bmatrix} \begin{bmatrix} \Delta LGDP_{it-d} \\ \Delta RMW_{it-d} \\ \Delta LTRM_{it-d} \\ \Delta LINV_{it-d} \\ \Delta LGMWp_{it-d} \end{bmatrix} + \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \end{bmatrix} ECT_{it-1} +$$

$$\begin{bmatrix} u_{1it} \\ u_{2it} \\ u_{3it} \\ u_{4it} \\ u_{5it} \end{bmatrix} \qquad (4)$$

Where Δ is the first-order difference operator, d is the lag length, and u is the error term. The first-order difference after taking the logarithm of a series (e.g., Δ*L*GDP) approximates its growth rate. The joint-Wald test for the lag periods of the first-order difference of each explanatory series is to find the short-run causality from the independent variable to the dependent variable. The error correction term (*ECT* or $\hat{\varepsilon}_{it}$) is the residual resulting from the cointegration Eq. (3) as follows:

$$\mathrm{ECT}_{it} = L\mathrm{GDP}_{it} - \widehat{\omega_0} - \widehat{\omega_1}\mathrm{RMW}_{it} - \widehat{\omega_2}L\mathrm{TRM}_{it} - \widehat{\omega_3}L\mathrm{INV}_{it} - \widehat{\omega_4}L\mathrm{GMWp}_{it} \quad (5)$$

A t-test of the coefficient λ_j of the lagged ECT term is used to find long-run unidirectional causality from the independent variables to the dependent variable. The λ_j is expected to be between -1 and 0, indicating the degree of correction to the previous imbalance.

4. Results and discussions

4.1 Descriptive statistics

The annual data in our study from 2010 to 2018 were obtained from Eurostat 2021 and the World Development Indicators 2021 (WDI 2021) for the EU 25 countries (except for Malta and Ireland due to insufficient data) (EU-25). Five CE indicators, namely per capita municipal waste generation (GMWp; measured in Kg), municipal waste recycling rate (%) (RMW), trade in recyclable raw materials (TRM; measured in ton), circularity rate (%) (CUR), and CE-related investments (INV; measured in million euro) are all in Eurostat database. Real GDP (measured in million Constant 2015 US$) is in the WDI database.

The summary statistics of the above 6 variables in the EU-25 data set from 2010 to 2018 were presented in Table 3. The variables 8-year CAGR and 5-year CAGR respectively represent the average annual growth rate of a variable in 2010-2018 and 2013-2018 for the EU-25 as a whole. The coefficient of variation (CV) is the ratio of the standard deviation to the mean, and it can be used to compare the volatility of different attribute variables. Fig. 1 shows the annual mean trend of each variable for EU-25 as a whole from

2010 to 2018. Fig. 2 is a dot plot of each time series in each country. The results show that the rising trends of *L*GMWp, *L*INV, and RMW were similar to *L*GDP, indicating that they were positively correlated with real GDP. The two indicators in the secondary raw materials dimension, *L*TRM and CUR, had different trends from country to country.

For the real GDP, INV, and TRM variables, their first to third largest CV values indicated that the EU has national differences in the three indicators of economic growth, CE-related investment, and material recycling. For the time series of RMW and GMWp, RMW had the second smallest CV value and the second highest 8-year average growth rate, GMWp had the smallest CV value and the second lowest 8-year average growth rate. Based on the CV value and annual average growth rate, the EU as a whole attached great importance to waste recycling and resource management. For the two indicators in the aspect of secondary raw materials, TRM and CUR, the mean of their 8-year average growth rate ((0.284+1.264)/2) was less than 1% and the 5-year average growth rate was the lowest, indicating that the EU should actively understand the main barriers that hinder an effective secondary raw materials market, which will make the circular economy more effective.

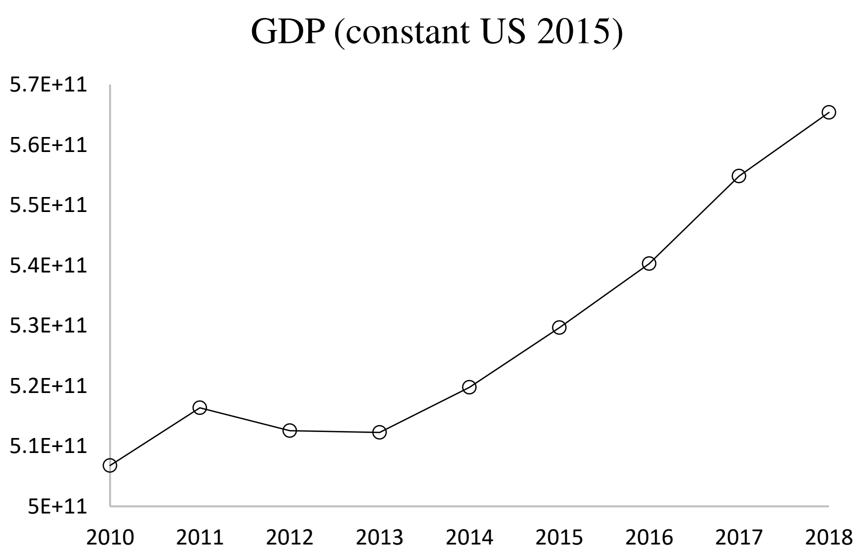
In addition, by comparing the average growth rate of 8-year and 5-year, it can be seen that the growth rate of waste recycling rate was the most stable. The 8-year average growth rate of CE-related investment was the highest, but the 5-year average growth rate was only 0.46 times the 8-year average growth rate, implying that it is imperative to introduce policies to attract investment. The 5-year average growth rate of per capita waste generation was 2.37 times the 8-year average growth rate, while the corresponding GDP was only 1.45 times, implying that C2C concept should be actively promoted. Regarding

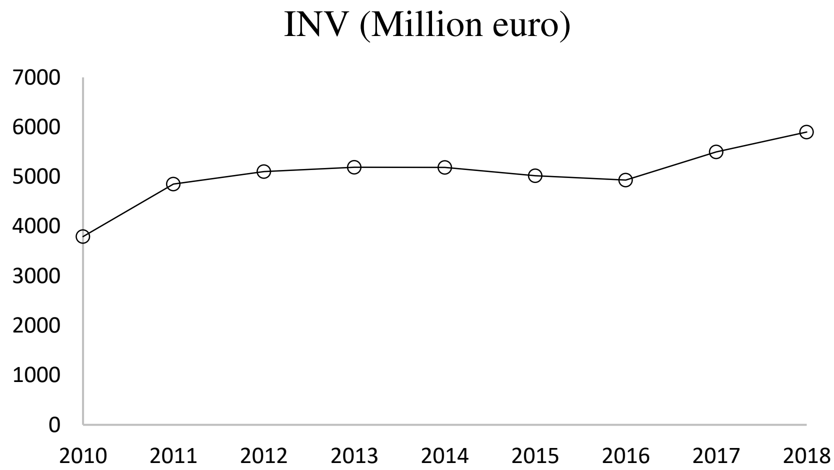
CUR and TRM, we discuss the mean of their annual average growth rates, because they are both indicators in the aspect of secondary raw materials. Although their 5-year average growth rate (1.216%) was higher than the 8-year average growth rate (0.774%), they were still the lowest among all indicators. Overall, the primary task of promoting a resource-efficient circular economy is to use C2C design concepts to overcome the obstacles to creating a secondary raw materials market.

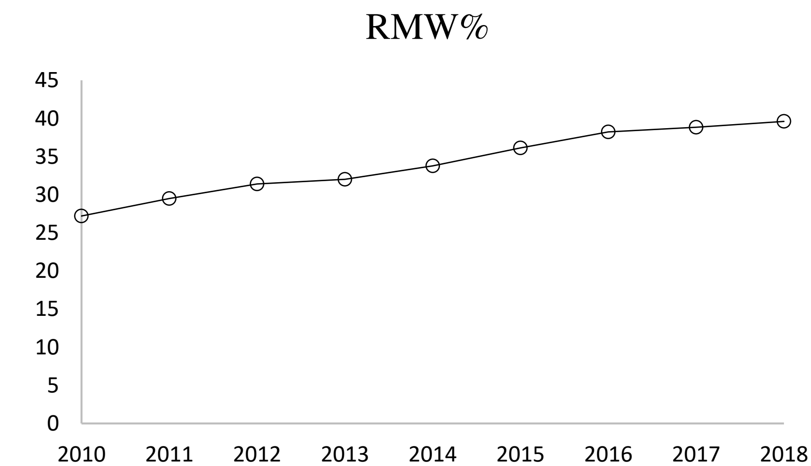
Table 3: The descriptive statistics of EU-25 as a whole for actual data, 2010–2018.

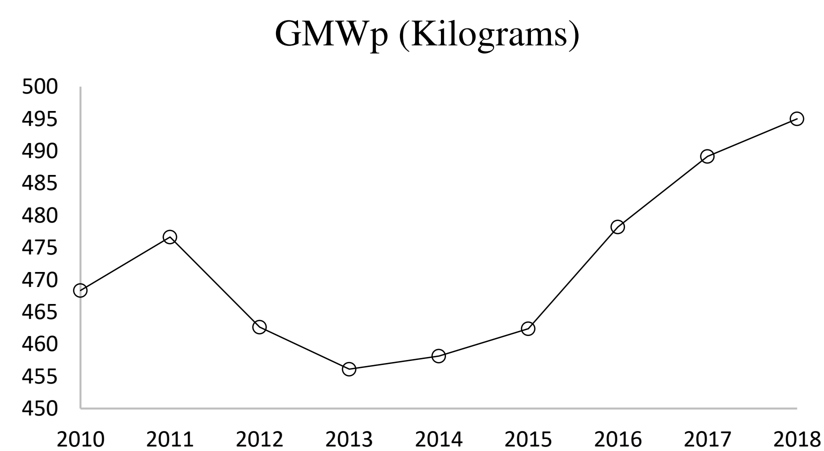
	GDP	INV	TRM	CUR	RMW	GMWp
	Constant US 2015 (billion)	Million euro	Million tonne	%	%	kg
Mean	528.639	5058.239	3.189	8.756	34.109	471.866
SD	818.394	7643.364	3.990	6.277	15.587	127.364
%CV	154.812	151.107	125.137	71.687	45.698	26.991
8-year %CAGR	1.377	5.678	0.284	1.264	4.808	0.695
5-year %CAGR	1.992	2.593	1.695	0.738	4.350	1.650

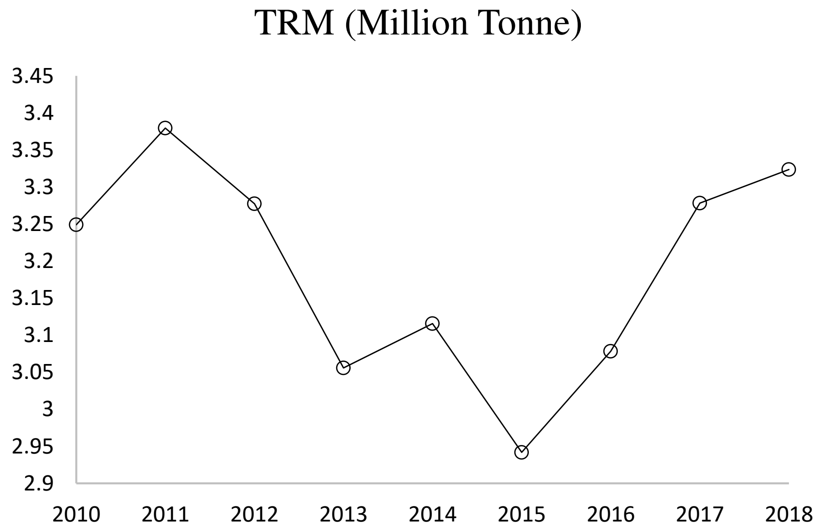
Note: SD is the standard deviations, %CV is the coefficient of variation. The 5-year %CAGR and 8-year %CAGR are the percentage-based compound annual growth rate for 2013–2018 and 2010-2018, respectively.




INV (Million euro)
0
1000
2000
3000
4000
5000
6000
7000
2010
2011
2012
2013
2014
2015
2016
2017
2018


RMW%
0
5
10
15
20
25
30
35
40
45
2010
2011
2012
2013
2014
2015
2016
2017
2018


GMWp (Kilograms)
450
455
460
465
470
475
480
485
490
495
500
2010
2011
2012
2013
2014
2015
2016
2017
2018



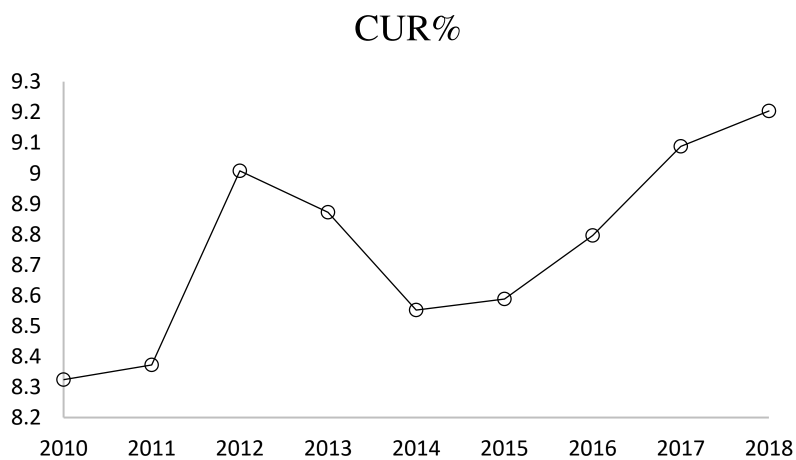


Fig. 1 Annual average trend of 25 EU countries for each variable (2010–2018).

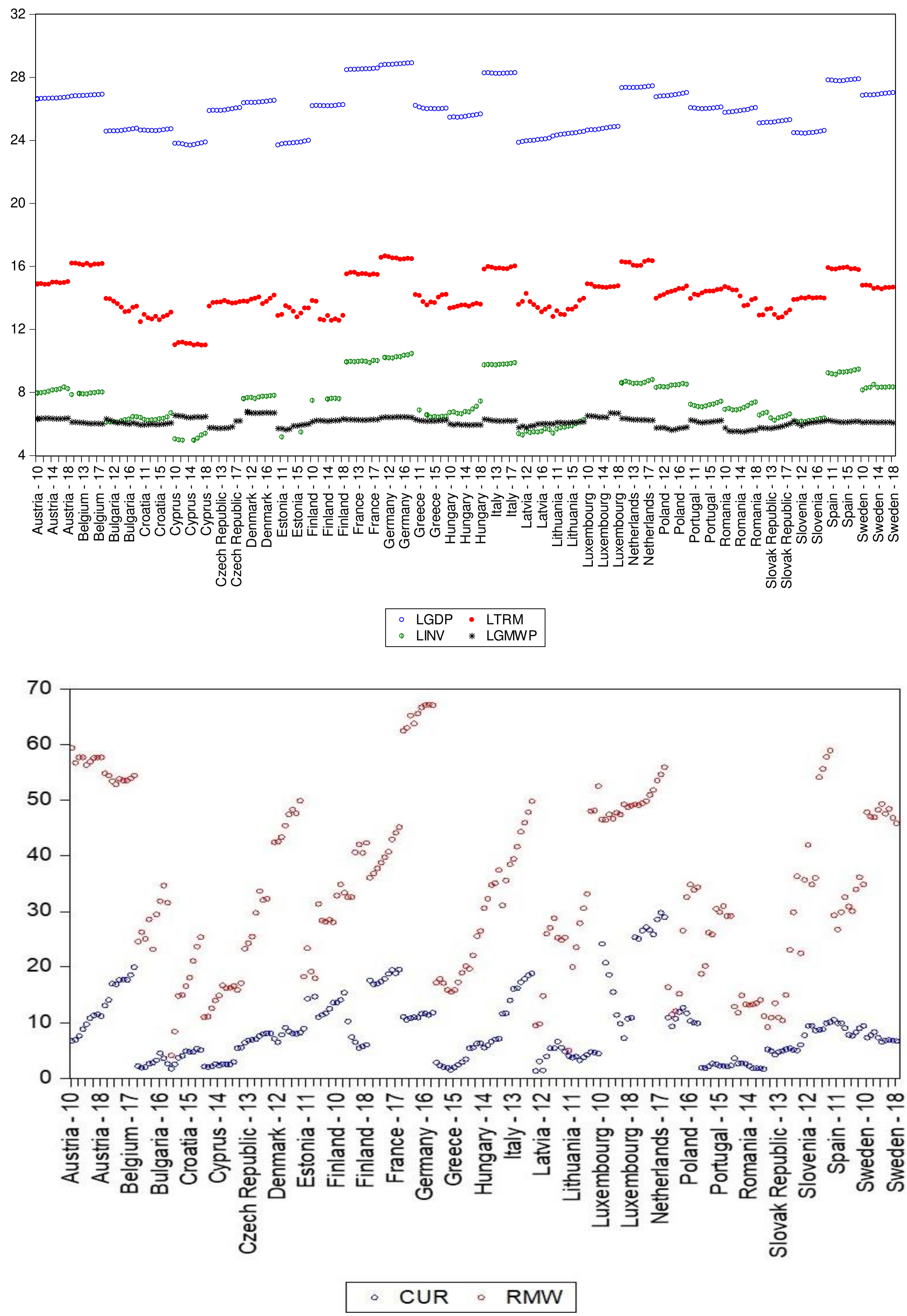


Fig. 2 Dot plots of *L*GDP versus the CE indicators for EU-25 (2010–2018).

4.2 Long-run estimates

In order to avoid spurious regression occurring in Eqs. (1-3), first, the integration order of each series must be determined by panel unit root test. Three panel unit tests, ADF, PP, and LLC, were used. Their results shown in Table 4 revealed that all the series *L*GDP, *L*INV, *L*GMWp, *L*TRM, RMW, and CUR in Eq. (1) were integrated of order one or *I*(1).

In the second step, we performed panel cointegration test using Pedroni and Kao procedures. Table 5 shows that CUR, *L*TRM, and RMW in Eq. (2) and *L*GDP, *L*INV, *L*GMWp, *L*TRM, and RMW in Eq. (3) was panel cointegrated. It indicated that there was long-run equilibrium relationship between CUR, TRM, and RMW and between GDP, INV, GMWp, TRM, and RMW, and their respective OLS estimators were consider to be super-consistent.

Table 4: Unit root test for EU-25 panel data, 2010–2018.

Var.	Indivdual unit root		Common unit root
	ADF	PP	LLC
LGDP	22.428	21.997	4.689
RMW	59.795	60.597	-3.366***
LTRM	21.592	24.668	2.021
LINV	34.741	44.673	0.323
LGMWp	38.180	46.384	-0.150
CUR	62.688	57.093	-7.394***
ΔLGDP	70.340*	71.714*	-8.260***
ΔRMW	145.028***	179.826***	-14.617***
ΔLTRM	226.215***	228.751***	-14.188***
ΔLINV	90.004***	119.480***	-9.314***
ΔLGMWp	188.118**	196.412***	-13.451***
ΔCUR	106.882***	127.775***	-11.594***

Note: *, **, and *** denote p-val.<0.1 , p-val.<0.05, and p-val.<0.01, respectively.

Table 5: Panel cointegration tests results for Eqs. (2-3), 2010–2018.

Pedroni test			
Within dimensions		Between dimensions	
Panel $\nu-$ statistic	-1.421 (2)	Group $\rho-$ statistic	4.094 (2)
	-1.368 (3)		5.280 (3)
Panel $\rho-$ statistic	2.129 (2)	Group PP $-$ statistic	-4.347***(2)
	3.322 (3)		-8.678***(3)
Panel PP $-$ statistic	-2.878**(2)	Group ADF $-$ statistic	-3.481***(2)
	-6.771***(3)		-5.917***(3)
Panel ADF $-$ stat.	-2.747**(2)		
	-4.656***(3)		
Kao test			
ADF $-$ stat.	-2.803**(2)		
	-2.742**(3)		

Notes: ** and *** are the same as in Table 4. The (2) and (3) represent Eq. (2) and Eq. (3), respectively.

The two panel cointegration equations (Eqs. 6-8) shown in Table 6 have R^2 values greater than 98% and normally distributed errors based on the Jarque-Bera test statistics (JB, 1980). Through the unit root test, we get that their residual series are integrated of order zero. Therefore, all OLS estimators in Eqs. (6-8) are super-consistent and there is multicollinearity in Eq. (7) because of its best fit. Remove the CUR series from Eq. (6) to get Eq. (8). Eq. (8) was used to construct VECM as shown in Eq. (4) to find the causal relationship between economic growth and circular economy. The error correction term (ECT) in VECM is the residual series of Eq. (8).

The estimated coefficients of Eq. (7) provided that for every 1 percentage point increase in RMW and one percent increase in TRM, the average CUR increased by about 0.058 and 0.009 (=0.869/100) percentage points, respectively. The positive influence of waste recycling rate (RMW) and material recycling volumes (TRM) on circularity rate (CUR) is similar to that of Tantau et al. (2018) for EU-28. The estimated coefficients in Eq. (8) provided that for every 1 percent increase in INV and GMWp, the average

GDP increased by 0.280% and 0.126%, respectively, a 1 percentage point increase in RMW increased average GDP by 0.200%, and a 1 percent increase in TRM resulted in a decrease in average GDP by 0.039%. The negative influence of TRM on GDP can be understood from the annual average trend of TRM in Fig 1.

In summary, a 1 percentage point increase in the waste recycling rate and a 1% increase in CE-related investment corresponded to 0.200% and 0.280% increase in GDP, respectively. This revealed that waste recycling and investment played a key role in economic growth. In fact, Table 3 also shows that the 8-year and 5-year average growth rates of RMW and INV were the two highest. In addition, a 1% increase in materials recycling corresponded to 0.039% decrease in GDP. The negative influence of materials recycling on GDP can be understood from the annual average trend of TRM in Fig 1. Based on the fact that the 8-year average growth rates of both materials recycling and materials recycling rate were the lowest, and their 5-year average growth rates were relatively low, the EU should actively understand the main obstacles hindering the efficiency of the secondary raw materials market, which will make the circular economy more effective. Increasing the use of recycled materials can not only enhance economic resilience, but is also one of the main goals of the EU Circular Economy Action Plan (CEAP 2021), which makes goods sold on the EU market clean, circular, and sustainable.

Table 6: Panel cointegration equations (Eqs. 6-8), 2010–2018.

	Equation	**%R²**	**JB-Stat.**
(6)	LGDP = 23.537+0.002RMW-0.039LTRM+0.279LINV+0.158LGMWp+0.003CUR	99.992	2.378
	(0.218)*** (0.000)*** (0.011)*** (0.016)*** (0.031)*** (0.002)*		[0.305]
(7)	CUR = -5.586+0.058RMW +0.869LTRM	98.006	3.503
	(2.633)** (0.009)*** (0.190)***		[0.174]
(8)	LGDP = 23.743+0.002RMW-0.039LTRM +0.280LINV+0.126LGMWp	99.993	2.120
	(0.172)*** (0.000)*** (0.011)*** (0.016)*** (0.023)***		[0.347]

Notes: JB-stat. is the Jarque-Bera test statistic. The standard error and *p*-value are placed in parentheses and brackets, respectively. *, ** and *** are the same as in Table 4.

4.3 Results and discussion of causality

Table 7 provides the estimated results of the panel VECM shown in Eq. (4). The ECT series are the residuals of Eq. (8). The short-run causality and long-run causality were tested using Wald F-statistics and Student's t-statistics, respectively.

Regarding short-run causality, Eq. (9a) reveals that no CE indicator had a statistically significant effect on economic growth. According to the results of Eqs. (9b-9c), LGDP had a significant positive statistical effect on RMW and LTRM, but the CE-related indicators in the independent variables were insignificant. In Eq. (9d) with the dependent variable INV, LGDP and LGMWp were positive statistically significant, while RMW and LTRM were insignificant. In Eq. (9e) with the dependent variable LGMWp, LGDP and LTRM were positive and negative statistically significant, respectively, while LINV and RMW were insignificant.

The estimated coefficients λ_j of lagged error correction term (ECT_{t-1}) in Eqs. (9a-9e) were negative statistically significant at the 1% level, revealing the long-run bidirectional causality between GDP, RMW, TRM, INV, and GMWp, and each series responded to previous period's deviation from the long-run equilibrium. The adjustment coefficient λ_j measures the mean reversion speed of series j over a period of one year. The 62.2% and 44.3% adjustment speeds of INV and GMWp towards equilibrium were quite fast, while GDP, RMW, and TRM were relatively slow.

In summary, from a long-run perspective, there was a causal loop between any two of the five variables (including GDP and four CE indicators) shown in Fig. 3, indicating that there was a close and stable causal relationship between CE and economic growth. In the short-run, 1) the existence of a negative unidirectional causality from TRM to GMWP implied that increased material recycling helped reduce waste generation; 2) the existence of a positive unidirectional causality from GMWp to INV implied that the increase in waste generation stimulated CE-related investments in order to effectively convert waste into gold for more sustainable development; and 3) the existence of a unidirectional causality from GDP to CE indicators without feedback, indicated that economic growth promoted circular economy, but not vice versa. This may be because the circular economy is still in its infancy. A recent ABI research report estimated that with sustainability efforts and upcoming legislation taking effect, by 2030, the world will achieve circularity of more than 10.5% (ABIresearch 2021).

Table 7: Panel causality test results, 2010–2018.

Dependent var.	**Independent variable** **Short-run *F*-stat.**					**Long-run *t*-stat.**	**%R^2**
	ΔLGDP	ΔRMW	ΔLTRM	ΔLINV	ΔLGMWp	ECT_{t-1} [Coff. λ_j]	
(9a)ΔLGDP		0.823(+)	2.354(-)	0.334(+)	0.538(+)	-4.824 [-0.205]***	**75.779**
(9b)ΔRMW	4.577(+)**		0.635 (+)	----	1.674(-)	-3.799 [-0.189]***	**45.079**
(9c)ΔLTRM	8.661(+)**	0.027(+)		----	0.431(+)	-4.236 [-0.225]***	**58.264**
(9d)ΔINV	7.015(+)**	0.111(-)	1.236(-)		15.127(+)***	-7.284 [-0.622]***	**62.685**
(9e)ΔLGMWP	9.531(+)**	0.008(-)	7.868(-)**	1.724(+)		-7.228 [-0.443]***	**57.923**

Notes: +/–: the sign of the sum of the coefficients of each lagged explanatory variable. The coefficients of lagged ECT are in brackets. ** and *** are the same as in Table 4.

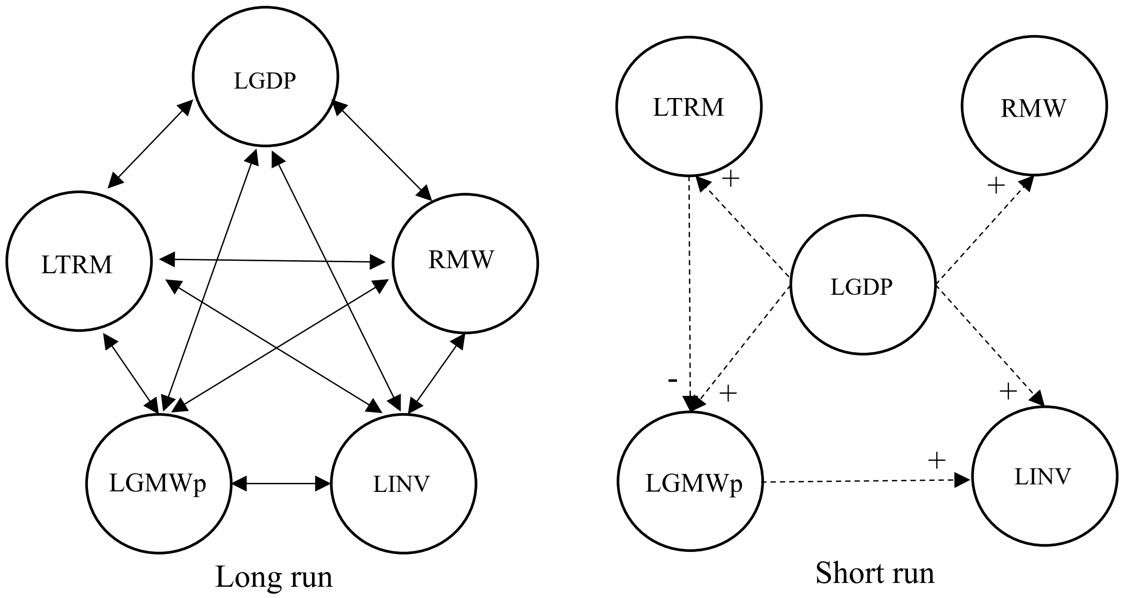


Fig. 3 Causal relationships between CE indicators and economic growth

5. Conclusions, policy implications, and research limitations

This research uses panel data from the 25 EU countries from 2010 to 2018 to innovatively explore the causality between circular economy and economic growth (CE-growth causality). The purpose is to introduce policies to achieve a comprehensive decoupling of resources environment as a whole from economic growth. It is actually an extension of the research on the nexus between energy consumption and economic growth nexus (energy-growth causality). The summary statistics of this study showed that the 8-year and 5-year average growth rates of the waste recycling rate and CE-related investment were the highest, while the material recycling volumes and its rate were very low. The result of the long-term equilibrium relationship between the CE indicators and GDP revealed that the two indicators of waste recycling rate and CE-related investment had a positive effect on GDP, while the material recycling indicator had a negative effect. The comprehensive results reveal that it is imperative to introduce policies to encourage CE-related investment and stimulate the secondary raw materials markets. The EU should actively understand the main obstacles hindering the efficiency of the secondary raw materials market, which will make the circular economy more effective. Increasing the use of secondary raw materials is also one of the important goals of the EU’s CEAP, which makes goods sold on the EU market clean, circular, and sustainable.

Regarding causality, the estimated results of the panel VECM showed that in the short-run, the increased in material recycling leaded to a decrease in waste generation and the increase in waste generation leaded to an increase in CE-related investment, indicating that EU countries are committed to achieving zero waste environmental benefits through investment in resource efficiency, which should be the effect of the EU's active implementation of its waste policy. The key target of EU waste policy is to improve waste management and stimulate innovation in recycling (European Commission website). Furthermore, economic growth promoted a circular economy in the short-run, but not vice versa. In the long-run, GDP and CE indicators constituted a causal loop. The findings revealed that the active and effective use of resources had no significant impact on economic growth in the short-term, but there was a close feedback relationship in the long-term, even though the circular economy is still in its infancy. A recent ABI research report pointed out that with sustainability efforts and upcoming legislation taking effect, by 2030, the world will achieve circularity of more than 10.5% (ABI research, 2021).

The research results imply that multilateral policies that can promote economic growth while expanding the circular economy should be introduced. Based on the Cradle-to-Cradle design concept, the two key elements of the policy should include encouraging CE-related research and innovation investment to stimulate the secondary raw materials market and improve materials recycling efficiency, as well as formulating laws to implement the EU Waste Policy and the European Green Deal. This can improve resource efficiency, achieve zero waste, and use fewer natural resources to create more value. Such sustainable economic growth can bring welfare to future generations.

The limitations of this study in terms of sample size and research methods can be resolved in future studies. Regarding the sample size, due to the short sample period of the CE indicators series (2010-2018), this study uses country-based panel data to meet the sample required for the study. The future will be better, because the general rule of quantitative research is that "the larger the sample, the more accurate the results". In addition, if the sample size is large enough, more quantitative CE indicators, such as patents or environmental tax rates, can be included in the research model to strengthen the research results. For individual countries with different attributes, individual-based VECM can also be used to explore the impact of a circular economy on economic growth. Furthermore, the dynamic interaction between energy intensity or resource productivity and circular economy can be studied in the future. These efforts can strengthen the development of circular economy policies to achieve sustainability goals.

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Statements & Declaration

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Chen and Pao provided conceptualization and first draft preparation; Chen and Pao completed methods, data, and analysis development; Chen and Pao reviewed and edited.

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Data and materials are available upon request.