Circular economy in plastic waste - Analysis of resource and energy productivity

(versão final após defesa)

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Resumo

A economia circular destaca-se nos países da União Europeia, através da implementação de medidas que pretendem alterar a degração ambiental sentida ao longo dos últimos séculos, permitindo atingir um bem estar ambiental, social e económico. Considerando este propósito, este estudo analisa a transição para uma economia circular com foco no plástico, considerando a produtividade dos recursos e energética como soluções ambientalmente sustentáveis. O sucesso na implementação da produtividade nestes setores, poderão nutrir benefícios através de uma melhor gestão dos resíduos, menores níveis de poluição, escassez dos recursos e uma promoção do crescimento económico. Este estudo utilizada uma abordagem de dados em painel para 20 países da União Europeia, com um horizonte temporal de 15 anos, mais especificamente, de 2004 a 2018. Para esta análise foi utilizado o modelo ARDL, através do estimador Driscoll-Kray, de forma a analisar os efeitos de curto e longo prazo. Após a análise, as principais conclusões confirmam uma relação positiva entre a reciclagem e recuperação de resíduos plásticos com a produtividade dos recursos. Outros resultados de destaque, implicam uma elevada taxação no setor energético, fraco investimento em pesquisa e desenvolvimento e fracas oportunidades de emprego. Suscitando que, aumentar a produtividade revela ser um bom contributo circular, contudo a capacidade de adaptação a alternativas mais sustentáveis decorre de forma lenta. Como robustez foi efetuada a conceção de dois modelos de consumo do material e energia, de forma a validar as escolhas das variáveis em estudo. A análise destas variáveis avalia a intensidade da utilização do material e energia, consolidando a eficência da sua utilização, os resultados apresentam-se distintos dos modelos de produtividade pela diferente forma de interpretação, contudo apoiam que o aumento da produtividade beneficia a transição circular. Estes resultados revelam que as medidas de implementação de uma economia circular são viáveis e refletem os efeitos desejados, contudo, deverão ser tomadas medidas governamentais e não governamentais que incidam na aceleração da transição circular sem repercurtir efeitos indesejados ao meio envolvente.

Palavras-Chave

Economia circular; resíduos plásticos; produtividade dos recursos; produtividade energética; União Europeia

Resumo Alargado

A necessidade de transição de uma economia linear para uma economia circular, é um dos principais desafios colocados a países desenvolvidos e em desenvolvimento. A União Europeia, destaca-se através da implementação de medidas que incidem sobre gestão e prevenção residual, eficiência em termos de recursos, energia renovável, entre os demais objetivos. É crucial perceber que existe uma quantidade abrupta de poluidores, que colocam em causa o desenvolvimento sustentável do planeta. Investigar sobre a forma mais rápida e eficaz de atingir a economia circular, viabiliza um menor impacto ambiental e garante um aumento de qualidade de vida.

Alguns dos estudos que abordam a economia circular, relatam a importância da dissociação entre o consumo de recursos e o crescimento económico. Estes estudos defendem que o crescimento económico deve ser dissociado do consumo de recursos naturais, principalmente os não-renováveis, permitindo uma reutilização dos mesmos, aumentando o seu valor. Uma melhoria a nível industrial, que permita uma menor utilização de recursos nos processos de reciclagem e recuperação de resíduos, que consuma energia renovável, emita menos emissões de gases para a atmosfera e contribua para o crescimento económico, revela ser um com caminho para alcançar a economia circular.

O conceito de economia circular, foi introduzido na literatura por Pearce & Turner, (1990), que através da degradação da matéria e da energia, explicaram a transformação de um sistema linear para um sistema circular. Estes economistas e ambientalistas, chegaram a um consenso que, quanto mais tempo um produto se manter na economia, mais valor agregado terá, levando a um menor desperdício. Este conceito tem sido indagado por diversos estudos, através de uma abordagem DEA (Data Envelopment Analyses), com o principal objetivo de medir a eficiência dos níveis de produção sobre um aumento dos inputs.

Este estudo tem como objetivo a análise da contribuição da produtividade dos recursos e da energia para a transição circular, com foco nos resíduos de plástico, dado que ao longo dos séculos vêm gerado externalidades negativas ao meio envolvente. Para isso, foram utilizados dados anuais de 2004 a 2018, para um conjunto de 20 países da União Europeia. As variáveis produtividade dos recursos (RP) e produtividade energética (EP), foram destacadas neste estudo como principais indicadores, por impulsionarem a minimização de recursos naturais e contribuirem para atingir os mesmos níveis de produção com um menor consumo.

A incoporação das restantes variáveis, incide sobre os resultados esperados no processo de transição circular, consoante as medidas anunciadas pela European Commission. Os Gases de efeito estufa (GHG), Resíduos plásticos (WASTE) e Energia fóssil (ENF) devem diminuir o seu impacto. As demais, devem nutrir um impulso positivo, das quais: Reciclagem de plásticos (RECY), Recuperação de plásticos (RECO), Energia renovável consumida (ENR), Receitas fiscais ambietais (TAX), Despesa interna bruta em pesquisa e desenvolvimento (RD), Taxa de empregabilidade (EMP) e Índice de produção industrial (IPI). Desta forma, realizou-se a conversão de todas as variáveis, nos seus logaritmos naturais e respetivas diferenças.

Em primeiro lugar, foi analisada a matriz das correlações, onde é possivel verificar a não existência de problemas de colineariedade entre as variáveis. Segue-se a análise de dois tipos de raízes unitárias (primeira e segunda geração), onde é percebida a ordem de integração das séries. Dado não existirem variáveis com ordem de integração superior a um, considera-se adequada a utilização do modelo ARDL. Sucedem-se os testes de diagnóstico, dos quais: teste de Hausman (avaliando se o melhor modelo a aplicar é efeitos fixos ou aleatórios), cross-section dependence, heterocedasticidade e autocorrelação. Após a análise destes testes, verificou-se que estamos perante um modelo de efeitos fixos, a existência de cross-section dependence, heterocedasticidade e autocorrelação, revelando assim o estimador Driscoll-Kraay como o mais apropriado.

A metodologia aplicada avalia as variáveis em curto e longo prazo, o que permite de forma concisa avaliar a existência de mudanças nas variáveis, em dois momentos diferentes. Permite ainda a utilização de variáveis com ordem de integração I(0) e I(1), assim como a introdução de variáveis dummy. Desta forma, foi efetuado um modelo ARDL, que destaca como variáveis dependentes a produtividade dos recursos e da energia.

Os resultados obtidos comprovam que a reciclagem e recuperação de resíduos, a energia renovável e o crescimento económico, impulsionam a economia circular através de uma minimização dos recursos e da energia. A influência positiva por parte da energia fóssil, revela a existência de dependência dos combutiveis fósseis na União Europeia. Os resíduos plásticos e os gases de efeito estufa influenciam negativamente o modelo, dado refletirem saídas indesejáveis, necessitando assim de medidas que prevaleçam a sua diminuição. Por sua vez, as receitas fiscais ambientais, aplicadas à energia denotam elevada tributação no setor energético, de acordo com a sua influência negativa. O investimento em pesquisa e desenvolvimento revela um impacto negativo, que remete a um fraco investimento nos setores dos recursos e da energia. Por fim, espera-se que a transição circular beneficie da criação de emprego, dada uma influência negativa no setor dos recursos e positiva no setor energético, prevendo-se que a crise e as medidas de austeridade, no período de estudo, influenciaram estes resultados.

Abstract

The massive increase in plastic waste, gas emissions as well as the overexploitation of natural resources have a negative influence on the ecosystem. The European Union, as a pioneer in the circular economy, is confronting this problem by implementing strategies to change this trend. Decreasing the use of resources and energy in industry while being able to sustainably manage plastic waste, use renewable energy, increase jobs and contribute to economic development can accelerate the circular process. This investigation analyses the transition to a circular economy through resource and energy productivity in relation to EU countries between 2004 and 2018. The method applied is the Autoregressive Distributed Lag (ARDL) Model, with the help of the Estimator Driscool Kraay. The results obtained confirm a positive relationship between recycling and valorisation of plastic and resource productivity. However, high energy taxation, low investment in research and development, and fewer job opportunities stand out as barriers to circular development.

Keywords

Circular economy; Plastic waste; Resource productivity; Energy productivity; European Union

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Tables List

Acronyms List

GRP	Gabinete de Relações Públicas
UBI	Universidade da Beira Interior
ARDL	Autoregressive-Distributed Lag model
CAP	Capital Invested by the Government
CE	Circular Economy
DEA	Data Envelopment Analysis
DMC	Domestic Material Consumption
EC	European Commission
ECM	Error Correction Mechanism
EMP	Employability rate
ENF	Energy Produced by Fossil Fuels
ENR	Renewable Energy Consumption
EP	Energy Productivity
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gases
IPI	Industrial Production Index
OECD	Organization for Economic Cooperation and Development
RECO	Plastic Waste Recovery Rate
RECY	Plastic Waste Recycling Rate
RP	Resource Productivity
TAX	Environmental Tax Revenues
VIF	Variance Inflation Factor
WASTE	Generated Plastic Waste
R&D	Research and Development
LCA	Life Cycle Assessment
MEA	Multidirectional Efficiency Analysis

1.Introduction

Over the past few years, the natural ecosystem has been in constant degradation, disabling future generations to inhabit it, alternatives are needed to prevent this trend. The world has reached a point where, for example, 60 to 95% of marine debris is plastic (Schnurr et al., 2018). Europeans are responsible for the annual production of 25 million tonnes of plastic waste, of which less than 30% is collected for recycling (European Commission, 2018). Global consumption of material (biomass, fossil fuels, woods and minerals) is expected to double in the next 40 years and resource extraction and processing is responsible for half of greenhouse gas emissions and 90% of biodiversity loss (European Commission, 2020).

The European Commission thus launches in 2015 the first circular economy plan, with the purpose of promoting a reduction in the residual amount, increasing its value, through its reintroduction in the productive chain. It also hopes to minimize the use of resources, energy and polluting gas emissions, with a view to benefiting from greater competitiveness, innovation and economic stimuli that will open up job creation (European Commission, 2015). Later, in 2019, this plan was updated, giving more emphasis to the sustainability of the products, the consumer, the sectors that use most of the resources and the residual reduction (European Commission, 2020).

Empirical studies have addressed the circular economy in different ways; at the microeconomic and macroeconomic level, at the level of companies and industries, and with a focus on the environment, economic development, renewable energies and technological innovation. There is, however, scarce literature on the analysis of plastic with quantitative indicators. One such indicator is resource productivity. Within a circular economy, resource productivity improves when resources are kept in the economy for longer through a decrease in the quantity of virgin resources used. In the same way, energy productivity is an important indicator within a circular economy. An increase in energy productivity promotes a decrease in energy used, reducing the quantity of fossil fuels needed to produce an energy unit. Evaluating these indicators in favour of the circular economy contributes to the literature by providing guidance that can be useful in the implementation of future policies and measures.

This investigation aims to analyse the transition to a circular through the productivity of resources and energy, considering these indicators as environmentally sustainable solutions for a circular economy. Note that, in a circular system, the maximum economic value is extracted from a set of resources resulting in a reduction in the quantity of waste. Achieving optimum productivity within the plastics industry requires optimisation of resources and energy, which in turn will allow efficient plastic production with less waste, enabling a competitive market. Thus, increasing resource and energy productivity could allow industry to make a transition to a sustainable circular economy, resulting in the main research question: What are the main factors contributing to the circular economy? From there, other secondary questions emerge: (i) what are the effects of the recycling, recovery and generation of plastic waste on circular economy? (ii) what is the effect of the remain variables that reflect circularity measures, having the productivity of resources and energy as a proxy for the circular economy?

To answer the previous questions, the ARDL (*Autoregressive-Distributed Lag*) model was applied, using a panel data approach, focusing on the European Union, a leader in the circular transition through goals that aim to reduce plastic pollution. This method allows us to observe the established relationships through the analysis of short-term dynamics and long-term adjustments. The main conclusions reveal that the application of taxes on pollution in the energy sector increases energy capacity in industry, employability hinders the rationalisation of resources, and investment in research and development is inefficient in increasing industrial productivity in the short term. These results allow for a better understanding of the implementation of some circular measures, validating the slow capacity for change and adaptation to new sustainable conditions.

The reminder of the study is organized as follows: Section 2 is dedicated to the literature review; Section 3 provides an overview of the data and methodology; Section 4 shows the results; Section 5 is dedicated to the robustness check of the results; Sections 6 and 7 discuss the results and conclusions, respectively.

2. Literature Review

The first studies about circular economy were developed by Pearce & Turner, (1990), who, through the degradation of matter and energy, explained the transformation of a linear economic system to a circular economic one. Under the Circular Economy paradigm, both economists and environmentalists agree that the longer a product remains in the economy, it will have more added value, and less will be wasted.

There is not a consensus on what is the best definition of a circular economy. A study of Kirchherr, Reike, & Hekkert (2017, p. 229) by analysing 114 definitions of a circular economy, proposed the following: *"... economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations."*

The circular economy emerges from scientific areas, such as ecological, environmental, industrial, eco-efficiency and industrial symbiosis (Ghisellini, Cialani, & Ulgiati, 2016; Korhonen, Nuur, Feldmann, & Eshetu, 2018). The three principles of a circular economy were defined through the end-of-life processing strategies, called the 3 R's: reduce, reuse and recycle (X. Li, Deng, & Ye, 2011). Subsequently, in a comprehensive and more complete way, three more were added, namely, recover, redesign and remanufacture giving rise to the 6 R's (Jawahir & Bradley, 2016). These principles make it possible to manage waste in a sustainable way by reintroducing waste into the economy and minimizing environmental impacts.

The global production of plastic residues increased exponentially from 1950 to 2015, with total production rising from 1.5 to 322 million tons per year, respectively (European Parliament, 2018). This proliferation of plastic has generated a widespread use of disposable and single-use products (Rios, Moore, & Jones, 2007), but it was through improper disposal and management of such products that a new problem started, which is plastic pollution in the oceans such as noted, for instance, by Barnes (2019).

According to PlasticsEurope (2018) in 2017 the production of plastic at that time was divided into the following sectors: Packaging 39.7%; Building & Construction 19.8%; Automotive 10.1%; Electrical & Electronic 6.2%; Household, Leisure & Sports 4.1%; Agriculture 3.4% and Others 16.7%. Packaging is the most abundant plastic waste, the majority being of single-use and discarded in the year it is produced (UNEP, 2018). A decrease in plastic packaging waste is crucial for an increase in the circular economy. Reducing this waste through sustainable management would benefit sustainable, economic and social development (Robaina, Murillo, Rocha, & Villar, 2020).

For a circular economy analysis, qualitative and quantitative indicators are incorporated depending on the micro, meso or macro level (companies, eco-parks and countries, respectively). At the macro level, which assesses countries, when these indicators are examined, the observed outcomes can be used to improve the efficiency of programs and policies currently applied (Huysman et al., 2015). These political applications aim to achieve a reduction in the entry of materials and energy, minimising polluting emissions, and as such increasing economic development (e.g. Alataş, Karakaya, & Sarı, 2020; Bimpizas-Pinis et al., 2021).

The EEA (2016) defined the resource productivity indicator as a good indicator for monitoring savings through the efficient use of resources. This indicator increases when there is a reduction of waste through the creation of a greater output obtained from a lower input (European Commission, 2011). Decreasing the use of natural resources is crucial to avoid resource depletion and environmental degradation. However, progress in this sector depends on the capacity that governments have in implementing material management policies (OECD, 2011).

Conforming to the European Commission (2011), to promote efficiency in the use of resources, it is necessary to reduce energy consumption at all stages of the energy chain. The same is verified by Alataş, Karakaya, & Sarı (2020), reporting that material productivity must be promoted together with energy productivity. The energy productivity indicator is useful in assessing energy efficiency (Nataly Echevarria Huaman & Xiu Jun, 2014), meeting economic, energy and environmental issues (Atalla & Bean, 2017).

In the literature, the progress of a circular economy is mainly analysed through efficiency in comparison with productivity. Energy efficiency, resource efficiency, eco-efficiency, among others, are explored in favour of the circular economy. Using different methods, the literature has adopted models like MEA (Multidirectional Efficiency Analysis) and LCA (Life Cycle Assessment), although the most used is DEA (Data Envelopment Analysis), proposed by (Charnes, Cooper, & Rhodes, 1978) with the main objective of measuring the efficiency of the production levels under an increase in inputs (Zhang & Cui, 2020).

In line with Mavi & Mavi (2019), to achieve efficiency in a country, it is necessary to implement programs that promote renewable energies, energy efficiency and residual management. These measures meet a circular transition through the promotion of sustainable practices. In Bimpizas-Pinis et al. (2021), they portray the circular economy as a new efficient paradigm due to the minimisation of material, energy, environmental impacts and an increase in economic production.

Increasing energy productivity promotes economic benefits (Atalla & Bean, 2017) and, a joint increase with renewable energy and eco-innovation relieves air pollution (Ding, Khattak, & Ahmad, 2021). In turn, an increase in efficiency in the use of resources also allows economic benefits to be obtained, improving recycling and waste recovery techniques (Ma, Hu, Chen, & Zhu, 2015). A joint increase in resource and energy efficiency will allow more robust results to be achieved in the efficiency of the circular transition (Domenech & Bahn-Walkowiak, 2019).

Pursuant to Domenech & Bahn-Walkowiak (2019), who studied the effectiveness of policy measures implemented in the EU in favour of the circular economy, the following conclusions were revealed: policy should focus on flow and resource production systems; the application of policies in favour of absolute decoupling of the use of resources and economic growth should be neglected; maximizing energy and resource efficiency reduces environmental problems; recycling and the reuse of resources increase circularity, however, these measures are insufficient if there is no substitution of primary material consumption.

In consonance with the literature, this study will fill the gap in relation to the introduction of resource and energy productivity in circular economy measures. Since productivity is associated with efficiency, one defines the quantity and the other quality, respectively. Through a short- and long-term temporal analysis, conclusions can be determined that facilitate the transition from a linear to a circular economy.

2.1. The circular economy in the European Union: policy framework

The circular economy was a concept created to combat residual increase, atmospheric pollution and the scarcity of natural resources, as they jeopardize the sustainable development of the planet. This concept thus reached the European Union's political guidelines in 2015, through the implementation of a plan by the European Commission (European Commission, 2015), with the aim of developing a more sustainable economy, with low carbon content, and a greater competitiveness and resource efficiency. This plan aims to enhance and protect companies against the scarcity of resources, price volatility, innovation in production and consumption, job creation, energy savings and the reduction of environmental impact.

Due to an increase in pollution caused by plastics, in 2018, Europe created the first "European Strategy for Plastics in the Circular Economy" that aims to achieve objectives such as: "The recyclability of all packaging before 2030, reduced consumption of single-use plastics and restrictions on the use of microplastics" (European Commission, 2018). The EU is distinguished for being a pioneer of the circular economy. As such it is deemed to be the appropriate focus of analysis for the present study.

3.Methodology

3.1. Data

This study uses annual data from 2004 to 2018 for 20 countries from the European Union, namely: Germany, Austria, Belgium, Czech Republic, Denmark, Slovakia, Spain, Estonia, Finland, France, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Poland, Portugal, the United Kingdom and Sweden. Considering a difficulty, the inclusion of all EU countries, due to the lack of data for some countries and years.

In recent years, the literature has focused on new ways to reduce the use of resources and energy to increase circular practices (e.g. (J. Li, Zhang, Ali, & Khan, 2020; Robaina et al., 2020)). As such, both resource productivity and energy productivity are considered as dependent variables in this study. Table 1 shows the variables under study, their descriptions and data source.

Table 1. Variables description

Variable	Description	Source
RP	Resource Productivity - This indicator is defined as the ratio between Gross Domestic Product (GDP) and Domestic Material Consumption (DMC). DMC measures the total amount of materials directly used by an economy. It is defined as the annual quantity of raw materials extracted from the domestic territory of the local economy, plus all physical imports minus all physical exports. (Euro per kilogram, chain linked volumes (2010)).	Eurostat
EP	Energy Productivity – the ratio between GDP and gross available energy. It measures the productivity of energy consumption and provides a picture of the degree of decoupling of energy use from growth in GDP. (Euro per kilogram of oil equivalent (KGOE)).	Eurostat
RECY	Plastic waste recycling rate - is defined by the total amount of recycled packaging divided by the total amount of packaging generated by the domestic sector (%)	Eurostat
RECO	Plastic waste recovery rate - defined by the total amount of packaging recovered divided by the total amount of packaging generated by the domestic sector (%)	Eurostat
WASTE	Generated plastic waste - defined by the total amount of plastic packaging waste generated by the domestic sector (Tonnes).	Eurostat
ENF	Energy produced by fossil fuels - represents the total amount of fossil fuels that serve the entire energy sector, including supply, transformation and final consumption (% of gross final energy production).	Eurostat
ENR	Renewable energy consumption - it measures the proportion of renewable energy consumption in the final gross energy, defining itself as the energy used by the final consumers plus all the losses of the network and the self-consumption of the factories (% of gross final energy consumption).	Eurostat
TAX	Environmental tax revenues - expresses total tax revenue in the category of environmental taxes including taxes on energy, transportation and the sum of taxes on pollution and resources (%).	Eurostat
RD	Gross domestic expenditure on R&D- demonstrates investment in research and experimental development (R&D) is used as a representative variable of innovation and technology (% of GDP).	Eurostat
EMP	Employability rate - expressed by the ratio between the employed population and the population of working age. This variable covers workers aged between 15 and 64 years (%).	Eurostat
GHG	Greenhouse gases – this variable expresses the emissions of greenhouse gases emitted into the atmosphere (Mtoe).	EEA
IPI	Industrial Production Index - is used as a form of representation of economic growth, and industrial output. Measured in an index based on the reference period (2015=100) under annual data.	OECD
DMC	Domestic material consumption- The indicator is defined as the total amount of material directly used in an economy and equals direct material input (DMI) minus exports (Tonnes per capita).	Eurostat
EC	Energy Consumption – energy balance of the final energy consumption of the entire economy (Thousand tonnes of oil equivalent).	Eurostat

The remaining variables reflect an influence, directly or indirectly, from which the following results are expected to be obtained:

(i) Residual management practices (recycling and recovery) contribute to the conservation of materials for a long time, consolidating a mitigation of the consumption of resources and energy, thus hoping to achieve a positive contribution in maximizing the productivities under study (Domenech & Bahn-Walkowiak, 2019);

(ii) The circular transition requires sustainable practices, playing an important role in the elimination of gases in the atmosphere and waste in landfills. However, the contribution of the variables GHG and WASTE, although with some reductions, is still considered to be negative, an impulse caused by economic development and dependence on fossil fuels (Mavi & Mavi, 2019; Pérez, González-Araya, & Iriarte, 2017);

(iii) The consumption of renewable energy is clean energy, and a positive contribution is expected, as it reduces the use of energy from fossil fuels, boosting economic growth and energy productivity. Similarly, the energy provided by fossil fuels expects a positive contribution, given the dependence that still exists in the EU on energy produced by fossil fuels (Martins, Felgueiras, & Smitková, 2018);

(iv) The variable environmental tax revenue covers both sectors under study. The contribution related to resource productivity is expected to be negative, due to the increase in the rate, which leads to a decrease in production (Guo, Izumi, & Tsai, 2019). On the other hand, in relation to energy productivity, a positive contribution is expected, since the introduction of taxes in the energy sector will lead to an adjustment of the energy used, increasing its productivity (He, Sun, Niu, Long, & Li, 2020);

(v) The regarding investment in research and development (RD), a positive contribution is expected, as it is a variable that represents innovation and technology, according to Mavi & Mavi (2019), this investment improves energy and environmental efficiency, this increase allows the achieving economic development as well as better use of energy;

(vi) The EMP variable, being representative of the workforce, should contribute negatively to resource productivity, due to the crisis and the austerity measures that occurred in the period under study (Busu, 2019; Robaina et al., 2020);

(vii) IPI as a proxy of economic growth, plays an important role in the development of the circular economy, although it can cause environmental damage by accelerating gas emissions, a positive boost is expected in maximizing resources and energy (Busu, 2019).

The Table 2 is presented, related to descriptive statistics, where all variables were converted to natural logarithms.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
LRP	300	0.3282531	0.5887904	-0.805868	1.364713
LRECY	300	3.465913	0.346051	2.351375	4.309456
LRECO	300	4.027112	0.4542027	2.493206	4.60517
LWASTE	300	12.56809	1.409289	9.937309	14.98979
LGHG	300	4.397237	0.3133266	3.718438	5.052417
LIPI	300	4.56551	0.1669219	3.987607	4.900858
LEMP	300	4.183154	0.0864095	3.939638	4.348987
LRD	300	0.4081571	0.5348328	-0.9162908	1.316408
LENF	300	4.287931	0.2357438	3.410818	4.577285
LENR	300	2.606674	0.8095612	-0.1064722	4.000968
LTAX	300	1.913242	0.2118883	1.463255	2.463853
LEP	300	1.834155	0.4522491	0.923465	2.922193

Notes: All variables converted to natural logarithms

This matrix is based on Pearson's correlation coefficient that studies the linear relationship between two continuous variables, ranging between (-1) and 1. A value greater than 0, indicates a positive relationship between the variables.

Table 3 shows a positive linear relationship (0.8095) between the variables LRP and LEP, revealing a direct proportional relationship, given that when the value of the LRP increases, the LEP will also increase.

Table 3. Correlation Matrix

	LRP	LRECY	LRECO	LWASTE	LGHG	LIPI	LEMP	LRD	LENF	LENR	LTAX	LEP
LRP	1.0000											
LRECY	0.2024	1.0000										
LRECO	0.5731	0.5384	1.0000									
LWASTE	0.4231	0.0333	0.1047	1.0000								
LGHG	0.4439	-0.2480	0.1510	0.4329	1.0000							
LIPI	0.3348	0.0330	0.3404	0.2195	0.2100	1.0000						
LEMP	0.1318	0.1106	0.2890	-0.0690	-0.0538	0.3604	1.0000					
LRD	0.4870	0.1138	0.5591	0.2586	0.3590	0.3476	0.5763	1.0000				
LENF	-0.0536	-0.0624	-0.0606	0.1081	0.1452	-0.2300	-0.2808	-0.3547	1.0000			
LENR	-0.2963	0.0632	0.0581	-0.1671	-0.2536	0.2333	0.3158	0.2140	-0.5868	1.0000		
LTAX	-0.4342	-0.2319	-0.3097	-0.3554	-0.2698	-0.2203	-0.0871	-0.4433	0.3414	0.0658	1.0000	
LEP	0.8095	0.0580	0.4669	0.3854	0.5825	0.2874	0.3070	0.4950	0.0373	-0.0969	-0.1836	1.0000

To strengthen the results of the correlation matrix, the average VIF and VIF tests were performed, which can be seen in tables 6 and A1, respectively. Revealing values below 10, these values are within the acceptance range, indicating that there are no problems related to collinearity

3.2 Method

This section begins with the analysis of the cross-sectional dependence tests (Table 4). A sequence of tests was performed. Firstly the CD-test introduced by Pesaran (2004). This test is appropriate for panel data models that may have substantial cross-sectional dependence in the errors caused by the presence of common shocks and unobservable components, which ultimately become an integral part of the error term.

Subsequently, first and second-generation unit roots were tested (Table A.3), namely Maddala and ADF-fisher (Maddala & Wu, 1999) and CIPS (Pesaran, 2007b). The CIPS test, given its robustness, is favoured. The ADF-FISHER test is performed to confirm the results of the CIPS test. Being more powerful, it can study the unit root processes individually, testing the level of stationarity of the variable and integration order, and it works in the presence of cross-sectional dependence (De Hoyos & Sarafidis, 2006).

The Table 5 following is a battery of diagnostic tests carried out in order to better understand the characteristics of the series under analysis. The Hausman test, proposed by Hausman (1978), where the null hypothesis is that the preferred model is random effects, confronting the presence of fixed effects with random effects. The Pesaran Test of cross-sectional dependence, proposed by Pesaran (2004) where the null hypothesis rejects the cross-sectional dependency in the model. The Wooldridge test, proposed by Wooldridge (2002), evaluates the presence of autocorrelation, and the null hypothesis is no first-order autocorrelation. A modified Wald test, proposed by Greene (2000), which assesses heteroscedasticity and its null hypothesis in the presence of homoscedasticity.

The Driscool-Kraay estimator proposed by Driscoll & Kraay (1998), proves to be appropriate estimator ARDL, better adjusting the data, of which there can be balanced and unbalanced panels. This allows the presence of cross-sectional dependence, fixed effects, autocorrelation and heteroscedasticity, obtaining more robust results (Hoechle, 2007).

Following the main objective, the analysis of the impact of circularity measures, considering the productivity of resources and energy as a proxy for circular economy, an autoregressive distributed lag (ARDL) was used, proposed by Pesaran, Shin, & Smith (2001). The ARDL model allows the analysis of short and long-term relationships between variables with order of integration between zero or one, I (0) or I (1), respectively. It also allows the correction of possible outliers with the introduction of dummy variables and achieves robust results with small samples. The models are specified as follows:

$$\Delta LRP_{it} = \alpha_{1t} + \sum_{n=0}^{k} \beta_{1\,2it}\, \Delta LRECO_{it-n} + \sum_{n=0}^{k} \beta_{1\,3it}\, \Delta LGHG_{it-n} + \sum_{n=0}^{k} \beta_{1\,4it}\, \Delta LEMP_{it-n} + \sum_{n=0}^{k} \beta_{1\,5it}\, \Delta LRD_{it-n} + \delta_{1\,6it} LRP_{it-1} + \delta_{1\,7it} LRECY_{it-1} + \delta_{1\,8it} LWASTE_{it-1} + \delta_{1\,9it} LIPI_{it-1} + \delta_{1\,10it} LEMP_{it-1} + \delta_{1\,11it} LENR_{it-1} + \alpha_{2t} TREND + \varepsilon_{1it} \tag{1}$$

$$\Delta LEP_{it} = \alpha_{1t} + \sum_{n=0}^{k} \beta_{1\,2it}\, \Delta LGHG_{it-n} + \sum_{n=0}^{k} \beta_{1\,3it}\, \Delta LIPI_{it-n} + \sum_{n=0}^{k} \beta_{1\,4it}\, \Delta LEMP_{it-n} + \sum_{n=0}^{k} \beta_{1\,5it}\, \Delta LENF_{it-n} + \sum_{n=0}^{k} \beta_{1\,6it}\, \Delta LTAX_{it-n} + \delta_{1\,7it} LEP_{it-1} + \delta_{1\,8it} LGHG_{it-1} + \delta_{1\,9it} LIPI_{it-1} + \delta_{1\,10it} LRD_{it-1} + \delta_{1\,11it} LENF_{it-1} + \delta_{1\,12it} LENR_{it-1} + \delta_{1\,13it} LTAX_{it-1} + \varepsilon_{1it} \tag{2}$$

where ΔLRP_{it} and ΔLEP_{it} are the dependent variables in equations (1) and (2), respectively. The "Δ" is operator stands for the first differences, "L" is the natural logarithm of the variables, $\beta keit$, k= 1, 2 and e=1,.., m is the short-run coefficients, $\delta keit$, k= 1 and e=1,.., m indicates the long-run coefficients, α_{1t} reveals the constant and ε_{1it} is the error term.

4. Results

Estimates are distorted in size when the cross-sectional dependence is ignored (Pesaran, 2007a). In Table 4, cross-sectional dependence is analysed, through the CD-test proposed by (Pesaran, 2004).

Table 4. Individual cross section dependence

Variable	CD-test	Variable	CD-test
LRP	33.21***	ΔLRP	8.58***
LRECY	28.63***	ΔLRECY	1.95*
LRECO	30.46***	ΔLRECO	-0.91
LWASTE	30.23***	ΔLWASTE	5.81***
LGHG	36.58***	ΔLGHG	23.28***
LIPI	14.40***	ΔLIPI	40.38***
LEMP	24.76***	ΔLEMP	23.74***
LRD	17.81***	ΔLRD	7.07***
LENF	32.80***	ΔLENF	5.38***
LENR	49.38***	ΔLENR	11.41***
LTAX	7.46***	ΔLTAX	9.55***
LEP	45.40***	ΔLEP	13.18***

Note: *** and *, corresponds 1% and 10% significance level respectively; a) constant and trend; b) constant; c) none. Δ means first differences; CD test has N~(0,1) distribution, under the H0: cross-section Independence

The results of the CD-test (see Table 4) demonstrate the presence of cross-sectional dependence for all variables, except DLRECO. To identify the order of integration of these variables, the ADF-Fisher test (individual unit root process) is performed, for the other variables that reject the null hypothesis, the second-generation unit root tests are performed. The unit root tests can be seen in the Table A.3.

Table 5 below presents a battery of tests, starting with: (i) Hausman test (Hausman, 1978), including the sigmamore and sigmaless options (Fuinhas, Marques, & Couto, 2015) comparing the fixed effects (FE) with the random effects (RE); (ii) Pesaran (Pesaran, 2004), which investigates the transversal dependence for the model; (iii) Wooldridge test (Wooldridge, 2002), indicates the first order serial correlation test; and (iv) Modified Wald test (Greene, 2000), measuring the presence of heteroscedasticity in the model.

Table 5. Diagnostic Tests

	ΔLRP	ΔLEP
Hausman	60.90***	81.40***
Hausman, Sigmamore	52.21***	67.90***
Hausman, Sigmaless	60.71***	85.55***
Pesaran	3.440***	6.390***
Wooldridge test	44.547***	66.497***
Modified Wald test	618.31***	272.17***

Note: *** denotes statistical significance at 1%; Δ means first differences; the results of the Hausman, Pesaran, Wooldridge test and Modified Wald test, are based on chi-squared distribution, standard normal distribution, F distribution and chi-squared distribution, respectively. The null hypothesis of the Hausman, Pesaran, Wooldridge test and Modified Wald test is random effects, cross-sectional independence, no first-order autocorrelation and homoscedasticity, respectively

The results of the diagnostic tests reveal the presence of fixed effects in all specifications (sigmamore and sigmaless). The results demonstrate the rejection of the null hypothesis in the Pesaran test, which indicates the presence of cross-sectional dependence on the model. The data have first-order autocorrelation using the Wooldridge test. The presence of heteroscedasticity is confirmed.

According to the results obtained in the pre-tests, the Driscoll-Kraay estimator is the most suitable. Following an estimation of two ARDL models, resource productivity (RP) and energy productivity (EP) stand out as dependent variables. All the results obtained and estimations are included in Table 6.

Table 6. ARDL Estimations

	ΔLRP	ΔLEP
ΔLRECO	0.033233**	
ΔLGHG	-0.1516986***	-0.7629156***
ΔLIPI		0.2757668***
ΔLEMP	-1.360204***	0.4924203
ΔLRD	-0.1426319**	
ΔLENF		0.4307995**
ΔLTAX		-0.1196514*
LRP(-1)	-0.3389931***	
LEP(-1)		-0.3344338***
LRECY(-1)	0.0524811***	
LWASTE(-1)	-0.1094203*	
LGHG(-1)		-0.341954**
LIPI(-1)	0.1504217***	0.1786259***
LEMP(-1)	-0.583315***	
LRD(-1)		-0.0366985**
LENF(-1)		0.18293*
LENR(-1)	0.060429***	0.0188527**
LTAX(-1)		-0.0759916***
TREND	0.0055812**	
C	2.887183***	0.6366321***
ECM	-0.3389931***	-0.3344338***
OBS	280	280
F-OBS	122.87***	3799.44***
R^2	0.3932	0.6104
VIF_{MEAN}	1.40	1.82

Note: ***, **,*, corresponds 1%, 5%, 10% significance level respectively; a) constant and trend; b) constant; c) none. Δ means first differences; VIF_{MEAN} means values of the variance inflation statistic.

The analysis of the values obtained in the ECM (error correction mechanism) reveal confidence in the adequacy of the econometric technique due to the negative values and a significance level of 1%. This demonstrates that the results corroborate the understanding about the presence of long memory in the data. And it reveals the existence of differences in the equilibrium trajectory of the different types of productivity. The ECM value for resource productivity indicates that almost 34% of the balance is corrected in one year, while for energy productivity, the correction is almost 33%. The VIF test was also performed, which was presented under its average value, and later, its individual values are attached, proving that the variables do not exceed the expected values (Table A.5).

Overall, the results confirm the role of several drivers in resource productivity (RP) and energy productivity (EP). These drivers show positive and negative effects, both in the short and long term. The results that stand out for their positive effects are RECY, RECO, IPI, ENF and ENR, positively boosting both models (RP and EP). Although the positive impact of ENF on energy productivity, both in the short and long term, implies the continuation of the overexploitation of fossil fuels, the results indicate that this source of energy contributes to an increase in energy productivity.

The variables WASTE and GHG stand out for their negative effects in both models, both in the short and long term. The impact of plastic waste generated through the domestic sector (WASTE) and greenhouse gas emissions (GHG) are defined as undesirable outputs. Reflecting the future need to implement policies and measures that encourage the reduction of WASTE and GHG, to have a positive effect on the productivity of energy resources.

The TAX results reveal a negative influence in relation to energy productivity, implying a high tax rate applied to the energy sector. Regarding research and development (RD), the negative values obtained in both models reveal a weak investment in the energy sector, determined by its long-term relationship. In the resource sector, as it is a negative short-term relationship, investment can only benefit in the long term, to the detriment of the time it takes for the investment to materialize.

The employability rate reveals a negative contribution to the RP model. This result is reflected in crisis and austerity measures (Busu, 2019; Robaina et al., 2020). Regarding energy productivity, the contribution is positive; human labour does not spend energy on power tools, reflecting a greater use of available energy.

The TREND variable was applied to stabilize the oscillations caused by external factors, to the detriment of the dependent variables. Its positive influence on the RP model, represents a good stabilisation capacity.

Table 7. Elasticities

	ΔLRP	ΔLEP
LRECY(-1)	0.1548146***	
LWASTE(-1)	-0.3227803*	
LGHG(-1)		-1.022486***
LIPI(-1)	0.443731***	0.5341143***
LEMP(-1)	-1.720729***	
LRD(-1)		-0.1097334***
LENF(-1)		0.5469843**
LENR(-1)	0.1782602***	0.0563719**
LTAX(-1)		-0.2272248***

Note: ***, **,*, corresponds 1%, 5%, 10% significance level respectively; a) constant and trend; b) constant; c) none. Δ means first differences

Finally, the elasticities that come from long-term relationships indicate, in percentage terms, their influence on the dependent variable. Presenting significance levels of 1%, they prove, for example, that the increase of 1% in LRECY (-1) reflects the increase of 0.15% in ΔLRP.

5. Complementary Analysis

The main objective of this investigation is the analysis of circular measures considering the productivity of resources and energy as proxies of circular economy. To validate the robustness of the models obtained previously, an analysis of household material consumption (DMC) and energy consumption (EC) in the circular context was performed. The selection of these variables allows analysing the intensity of material and energy use in order to perceive the efficiency of its use, thus it will be possible to verify the existence of a reduction in waste, since everything produced is consumed.

Following the methodology applied in section 3, diagnostic tests were for the resource and energy consumption model (Table 8). The Hausman test reveals the presence of fixed effects. This is followed by the presence of cross-section dependence (Pesaran, 2004), heteroscedasticity (Greene, 2000) and autocorrelation (Wooldridge, 2002). Thus, these results validate that the Driscoll-Kraay estimator is the most suitable.

Table 8. Diagnostic test

	ΔLDMC	ΔLEC
Hausman	80.24***	88.45***
Hausman, Sigmamore	60.50***	79.04***
Hausman, Sigmaless	73.34***	105.85***
Pesaran	1.667*	10.609***
Wooldridge test	57.920***	78.551***
Modified Wald test	523.67***	99.16***

Note: *** and *, denotes statistical significance at 1% and 10%, respectively; Δ means first differences; the results of the Hausman, Pesaran, Wooldridge test and Modified Wald test, are based on chi-squared distribution, standard normal distribution, F distribution and chi-squared distribution, respectively. The null hypothesis of the Hausman, Pesaran, Wooldridge test and Modified Wald test is random effects, cross-sectional independence, no first-order autocorrelation and homoscedasticity, respectively.

The use of the ARDL methodology allowed us to estimate two distinct models. The results obtained are presented in the table below (Table 9) and demonstrate that the consumption of resources and energy are harmful to the environment, thus boosting the importance of productivity in both sectors.

Table 9. Estimations

	ΔLDMC	ΔLEC
ΔLGHG	0.3627993***	0.4419902***
ΔLRECO	-0.0430119***	-0.0214724***
ΔLEMP	2.065596***	
ΔLRD	0.1020739**	
ΔLIPI	0.2023061***	0.0689097*
ΔLENF	-0.3491058***	-0.1798403***
LDMC(-1)	-0.0536904***	0.0285859*
LEC(-1)	0.5035424***	-0.4208766***
LRD(-1)		-0.0283536**
LRECY(-1)	-0.0536904***	
LWASTE(-1)		-0.0275096**
LENR(-1)	-0.0367003**	-0.0186115**
LRECO(-1)	0.5878564***	
LEMP(-1)		0.310518***
C	-6.2841***	3.269809***
ECM	-0.0536904***	-0.4208766***
OBS	280	280
F-OBS	141.51***	292.07***
R2	0.6128	0.6487
VIF_{MEAN}	1.39	4.10

Note: ***, **,*, corresponds 1%, 5%, 10% significance level respectively; a) constant and trend; b) constant; c) none. Δ means first differences; VIF_{MEAN} means values of the variance inflation statistic.

Through the results obtained, one can see the difficulty of transitioning to a circular economy, when pollutants such as GHG are positively related to material and energy consumption.

The plastic waste recovery (RECO) negatively drives both models in the short term, which implies that the consumption of materials and energy decreases when the plastic is recovered, this suggests that, in the domestic sector, the reuse of plastic for other purposes boosts the circularity of plastics, reducing their consumption. In turn, a positive long-term impact on the consumption of materials should be highlighted. This impulse verifies the ineffectiveness of the prolonged reuse of plastic, which in the long term will imply the release of monetary units for the consumption of other goods, increasing consumption of materials.

The recycling of plastics (RECY) reveals a negative long-term impulse in the material consumption model, this implies that plastic recycling reduces the consumption of materials, thus contributing to an increase in the circularity of plastics as suggested by the circular economy.

Regarding plastic waste, these only denote a long-term negative impulse in energy consumption, although not maintaining any type of relationship in the energy productivity model, the residual increase of plastic represents a negative externality to the environment through the increase in emissions of gases and fossil fuel consumption, the longer it persists in the environment, the greater its degradation, requiring greater energy consumption to be extracted from the environment.

The employability rate (EMP) denotes a negative impact on the productivity of resources and a positive impact on the consumption of materials, these results suggest that the production capacity has a direct impact on the consumption of material that does not exist in terms of productivity, that is, productivity does not increase if the production capacity of the industry is the same.

Investment in research and development (RD) has a positive impact on the consumption of materials and a negative impact on the productivity of resources, this is because the investment is research, not having a direct effect on productivity, but on consumption, that is, changing a product increases its consumption but not productivity.

The consumption of renewable energy (ENR) reveals a long-term negative impact on consumption models and positive on productivity, these results state that the implementation of renewable energy will increase productivity, but reduce the consumption of materials and energy, as it is a smaller green energy will be the resources needed to produce the same energy capacity, leading to lower consumption.

Fossil energy production (ENF) reflects a positive impact on productivity models and a negative impact on consumption models, with no point of comparison regarding the productivity of resources. When analysing productivity and energy consumption, these results suggest a greater demand for renewable energy, which in the short term has a negative effect on consumption and an increase in energy productivity given the dependence on fossil fuels in the European Union, thus revealing the need for a transition to green energy.

It appears that economic growth has a positive impulse in the consumption of resources and energy, and it can be noted that the same applies when the respective productivities are applied, thus, it is possible to achieve economic growth with the application of a circular economy. As far as renewable and fossil energy sources are concerned, both have a negative momentum, which suggests that a sustainable energy transition is needed that allows for the consumption of fewer resources and energy in the EU. The ECM obtained is statistically significant and is comprised between the values [-1, 0]. For the results obtained, the elasticities were calculated using long-term coefficients, where their results are presented in the table below (Table 10).

Table 10. Elasticities

	ΔLDMC	ΔLEC
LRECY(-1)	-0.1537941***	
LWASTE(-1)		-0.0653626**
LEMP(-1)	1.683892***	0.7377888***
LENR(-1)	-0.1051265***	-0.0442208***
LEC(-1)	1.442378***	
LRD(-1)		-0.0673681***
LDMC(-1)		0.06792**

Note: *** and **, corresponds 1% and 5% significance level respectively; a) constant and trend; b) constant; c) none. Δ means first differences

The results obtained do not provide a direct point of comparison but justify the validity of the impacts obtained previously. Thus, it is possible to observe that the 1% increase in LRECY reflects the 0.15% decrease in LDMC(-1), consolidating that the increase in recycling decreases the consumption of resources. In this way, it is possible to confirm that, if recycling reduces material consumption, it will be increasing resource productivity. With the verification of the robustness tests, it was possible to observe the impact of consumption of resources and energy compared to productivity, thus it is possible to state that the measures imposed by the EU for the circular economy are in line with the results obtained.

6. Discussion

Increasing the productivity of resources and energy turn out to be a principle of circular transition, as shown by the following relationships. A positive impact of both recycling and recovery on resource productivity is empirically validated. These forms of sustainable management promote minimisation of the resources used and are related to the material reuse achieved by the industrial sector or the domestic sector, leading to an increase in resource productivity. These results agree with (Abad-Segura, de la Fuente, González-Zamar, & Belmonte-Ureña, 2020; Pineiro-Villaverde & García-álvarez, 2020; Schroeder, Anggraeni, & Weber, 2019), who reached identical findings. Thus, the introduction of policies and population awareness of the importance of sustainable management of plastic waste, promote the productivity of resources, the main principle of the circular economy.

The introduction of two energy sources in the study, specifically, fossil and renewable energy, allow a comparative analysis of the impact of each energy source, in RP and EP. In this way, an energy transition, from fossil energy to green energy, can be perceived, as expected by the CE. The results reveal a positive relationship on the part of both energy sources, in both models. Given the following, it indicates that the two energy sources benefit the productivity of resources and energy and may be at the point of cleavage in the energy transition. According to Martins, Felgueiras, & Smitková (2018), achieving the transition to green energy will imply a positive relationship between fossil energy and renewable energy. However, the European Union is still dependent on fossil fuels. For a sustainable energy transition, it is required an investment that allows renewable energy to satisfy to peak loads such as conventional energy (Robaina-Alves, Moutinho, & MacEdo, 2015).

The IPI advocates economic growth applied to the industrial sector. The positive relationships achieved in the resource and energy productivity models suggest a positive economic boost in reduce the resources and energy used. These results are against of (Busu, 2019; Vasylieva, Lyulyov, Bilan, & Streimikiene, 2019), which indicates an increase in economic development in the face of circular practices, such as resource and energy productivity. However, another study claims that these economic benefits do not arise only by exchanging virgin material for renewable material; a set of measures is still required to reach them (Busu & Nedelcu, 2017). Given the following, it appears that the rationalization of resources and energy, benefit the impetus of the circular economy through economic development.

The workforce variable demonstrates a negative effect on resource productivity and a positive one on energy productivity. These findings are not in line with the expected objectives in the implementation of the circular economy, more specifically, the increase in job creation. One possible justification for these results comes from the crisis and the austerity measures that shook the EU, resulting in high unemployment rates. This negative relationship with resource productivity was also observed by Busu (2019). However, in the robustness models, this variable has a positive impulse, and it may be correct to say that the contribution of the employability rate to productivity does not add value if what is at issue is the same production capacity.

Gross domestic expenditure on research and development has a negative impact on both models. Regarding resource productivity, there is only a short-term relationship. These results suggest that, in the energy sector, insufficient capital is invested to promote technological development of this sector. On the other hand, the resources sector may imply that the investment has not yet had time to materialize. In line with innovation and technology, an increase in RD encourages the conversion of non-renewable energy consumption into renewable energy consumption (Ding et al., 2021). This implies that more significant investment in innovation and technology would effectively promote this energy source, benefiting environmental quality through a reduction in the quantity of polluting gases released into the atmosphere.

Plastic waste and greenhouse gas emissions show a negative relationship in both models. Considering that they are two polluting variables, they represent undesirable events, and their permanence in the environment proves to be a barrier to sustainable development (Yeh, Chen, & Lai, 2010). These results are reinforced through consumption models, where the increase in consumption causes an increase in emissions. The application of environmental charges could lead to a reduction in pollution levels if the mode of implementation considerably punishes industries that reach high levels of pollution. However, when analysing the TAX variable, which represents environmental tax revenue, a negative relationship with energy productivity is observed. This relationship is an indication that the taxation of pollution in the energy sector leads to a greater amount of energy being used, which may be being applied incorrectly. However, when looking at the detailed data in Table A.6, it appears that the energy sector is the most taxed. In agreement with (Guo et al., 2019), which denotes that the higher the tax, the lower the resource or energy productivity, suggesting a negative effect. This variable is omitted in the robustness tests due to its application being focused on production and not on consumption.

Any circular transition requires a focus on implementing measures aimed at achieving beneficial results. With this, efforts must be made that include an assertive set of measures that positively influence each other. Otherwise, a barrier to the advancement of the circular economy may be created.

7. Conclusion

This study analyses the effect of some factors on the transition to circular economy, considering resource and energy productivity as a proxy for the circular economy. Through the minimization of resources and energy, environmental impacts are reduced through less use of non-renewable natural resources, progressing towards a sustainable future. In this empirical analysis, annual data were used for the period from 2004 to 2018 for 20 European Union countries, considering recycling, recovery and plastic waste. The method applied was the ARDL model with the Driscoll Kraay estimator, which allows an individual analysis of the short- and long-term relationship between the variables.

Circular practices that promote the productivity of resources and energy are recycling, waste recovery, renewable energy and economic growth, these results meet the expectations of the circular economy. The implementation of these practices will promote a reduction in plastic production and waste, valuing it in a sustainable way and with economic benefits. There is evidence of a positive impulse towards a circular economy given the lower consumption of resources and energy used. Through improved productivity, plastics contribute positively to the circular chain. Thus, governments must take an active role in making the public aware of the benefits of sustainable plastic management, whether through the implementation of policies, fees or investments, transforming this industrial sector into a circular system.

The increase in plastic waste and emissions of greenhouse gases reflect undesirable flows, acting inefficiently in the productive capacity of the resource and energy sectors. It is assumed that a decrease in the use of fossil fuels would promote a decrease in greenhouse gases. However, the positive contribution of energy produced from fossil fuels shows that the European Union still depends on these fuels. However, note that the increase in emissions and waste may be generated through an increase in economic development (Mavi & Mavi, 2019).

It is assumed that energy sources will transition to clean and renewable energy consumption over time; however there is a long way to go. The exclusive use of renewable energy requires an investment by the industry in technology and equipment suitable for its operation. However, despite the continued use of fossil energy, a decrease is expected over the following years.

Greater industrial investment is deemed necessary to increase job creation in the resource sector, increasing productivity and improving waste management systems. Thus, introducing incentives to industries can be important, allowing companies to improve production systems while creating jobs.

The revenue obtained from environmental taxes reveals high taxation of the energy sector in comparison with the resource sector (Table A.6), affecting the levels of energy productivity. Regarding internal expenses related to research and development, these reveal a weak investment in the energy sector, induced by the negative long-term relationship. However, concerning the resource sector, as it only has a negative short-term relationship, it cannot be said with certainty whether it reproduces positive or negative effects in the long run. With this, a greater focus on the energy sector is considered pertinent, whether in terms of investment or taxation, in order to achieve more satisfactory results in the future.

The European Union meets some of the measures imposed for the transition to a circular economy. However, it still faces difficulties in implementing many others. It is worth noting that there is a need to inquire into new ways that allow this implementation to be beneficial. For future research, an individual study of each country in the European Union would be considered relevant to better understand each one's needs. In this way, policies can be adapted to the individual needs of each country, efficiently and effectively promoting the transition to a circular economy.

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Appendix

Table A.1. Variance inflation factor

	ΔLRP	ΔLEP
ΔLRECO	1.12	
ΔLGHG	1.19	2.10
ΔLIPI		2.21
ΔLEMP	1.22	1.63
ΔLRD	1.07	
ΔLENF		1.56
ΔLTAX		1.24
LRP(-1)	1.85	
LEP(-1)		1.96
LRECY(-1)	1.53	
LWASTE(-1)	1.28	
LGHG(-1)		1.86
LIPI(-1)	1.52	1.54
LRD(-1)		1.98
LEMP(-1)	1.29	
LENF(-1)		2.12
LENR(-1)	1.62	2.00
LTAX(-1)		1.69
TREND	1.74	

Table A.2. Total environmental taxes revenue by type. EU27, 2002 and 2018

	EUR million		% of total		% of GDP		% of total revenues	
	2002	2018	2002	2018	2002	2018	2002	2018
Total environmental taxes	217654	324637	100.0	100.0	2.6	2.4	6.6	6.0
Energy taxes	167281	252110	76.9	77.7	2.0	1.9	5.1	4.7
Transport taxes	42441	61878	19.5	19.1	0.5	0.5	1.3	1.1
Taxes on pollution and resources	7932	10649	3.6	3.3	0.1	0.1	0.2	0.2

Source: Eurostat

Table A.3. Unit Root Tests

	MW						CIPS						ADF-FISHER
	a)			b)			a)			b)			a)
Lag	0	1	2	0	1	2	0	1	2	0	1	2	0
LRP	44.448	43.429	39.487	46.663	54.618*	17.344	-3.309***	-1.974**	-1.164	-1.392*	-1.416*	-0.143	
ΔLRP	288.262***	182.343***	49.415	232.530***	148.333***	34.808	-8.448***	-3.498***	-1.270	-6.370***	-0.630	-1.277	
LRECY	81.063***	193.498***	79.141***	47.484	94.345***	59.900**	-2.074**	-1.610*	-0.969	-1.008	-0.034	-0.190	81.0633***
ΔLRECY	300.865***	152.646***	92.693***	217.852***	132.238***	69.673***	-6.904***	-1.775**	-1.686**	-5.251***	-0.355	1.386	300.8650***
LRECO	89.797***	193.498***	79.141***	71.360***	100.904***	184.149***	-3.462***	-3.564***	-1.624*	-0.645	1.010	2.018	89.7973***
ΔLRECO	364.771***	153.863***	246.036***	315.977***	101.249***	183.323***	-9.380***	-2.627***	-0.477	-6.933***	-1.551*	-0.401	364.7708***
LWASTE	26.593	33.649	23.196	57.832**	53.256*	54.331*	-1.168	-0.755	2.108	-0.945	0.147	1.595	
ΔLWASTE	312.644***	128.724***	86.079***	237.589***	85.514***	78.851***	-7.069***	-2.760***	-0.477	-5.211***	-0.970	0.153	
LGHG	35.085	42.859	34.835	59.657**	57.686**	18.737	-0.949	-1.598*	-0.652	-0.466	-0.468	0.721	
ΔLGHG	348.531***	177.658***	66.771***	291.073***	131.398***	47.766	-8.803***	-4.508***	-1.376*	-7.162***	-2.109**	2.963	
LIPI	26.263	29.282	26.526	28.898	72.789***	46.023	1.142	0.871	0.932	5.514	2.919	2.297	
ΔLIPI	185.768***	157.696***	104.906***	125.294***	114.803***	101.131***	-1.651**	0.856	1.710	-1.266	1.268	2.771	
LEMP	41.037	32.98	34.878	28.533	29.238	26.808	0.965	0.913	0.224	2.033	0.165	-1.651**	
ΔLEMP	87.490***	71.409***	45.331	52.571*	52.151*	45.320	-2.689***	-0.445	-1.680**	-0.837	1.564	2.663	
LRD	39.527	61.798**	46.841	39.894	46.76	38.412	0.787	0.657	0.346	1.004	0.739	2.563	
ΔLRD	227.930***	96.262***	57.411**	166.102***	61.747**	38.370	-5.199***	-1.496*	0.149	-3.164***	-0.196	1.695	
LENF	30.777	27.294	21.216	32.252	54.875*	22.014	0.157	0.275	1.492	2.24	1.365	2.012	
ΔLENF	229.238***	152.740***	65.602***	189.543***	105.867***	47.731	-6.095***	-2.103**	-0.005	-5.023***	-0.959	0.016	
LENR	94.076***	66.729***	74.214***	28.380	33.842	48.269	-2.453***	-2.500***	-1.503*	-1.205	-2.231**	-0.837	
ΔLENR	191.288***	69.684***	77.465***	198.658***	84.034***	71.130***	-6.910***	-4.562***	-2.526***	-4.858***	-0.933	0.479	
LTAX	44.430	54.789*	52.156*	32.227	68.343***	80.953***	2.051	3.185	4.225	-0.052	1.408	4.925	
ΔLTAX	161.531***	104.563***	121.642***	107.153***	67.404***	92.162***	-7.526***	-3.385***	2.375	-6.517***	-4.047***	1.815	
LEP	27.010	30.040	20.631	73.751***	54.557*	82.347***	-2.908***	-1.480*	-0.727	-0.818	1.541	1.538	
ΔLEP	345.127***	147.578***	107.885***	273.401***	101.520***	79.090***	-8.580***	-2.706***	1.010	-7.145***	-1.272	3.025	

Note: ***, **,*, corresponds to a 1%, 5%, 10% statistical significance level respectively; a) constant and trend; b) constant. Δ means first differences; MW and ADF-FISHER indicates (Maddala & Wu, 1999) unit root test and CIPS indicates (Pesaran, 2007b) unit root test; a) and b), indicates option with intercept and trend and only intercept respectively; and 0, 1, 2 identified the lag order