# The Effects of Environmental Innovations on CO2 Emissions: Empirical Evidence from Europe

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**Abstract**

Environmental innovations are key enablers of transition towards greener economies. Despite their importance, empirical studies examining the effect of green technologies on $CO_2$ emissions are still limited. Using an autoregressive distributed-lag model (ARDL), we analyze the impact of environmental innovations, the consumption of renewable energies, GDP per capita, and degree of economic openness on $CO_2$ emissions for 15 European countries over 23 years. Our results indicate that, in the long-term, environmental innovations tend to lower $CO_2$ emissions, whereas in the short-term the observed effect is the opposite, suggesting the existence of a rebound effect. This study recommends introducing new policies that combine tools of environmental economics with those of ecological economy to integrate economic incentives with regulatory changes and encourage individuals to consume differently by favouring products and/or services with a less negative impact on the environment.



**Keywords:** Environmental innovations; $CO_2$ emissions; Rebound effect; Europe; ARDL model.

**JEL Classification:** Q53; Q55

## 1. Introduction

The current trajectory of global economic development is not without consequence on our planet. Ecological deregulation, unlimited exploitation of natural resources, and growing inequalities are at the heart of contemporary problems. According to a recent report[1], anthropogenic emissions of greenhouse gas as a result of human activities are responsible for almost 95% of global warming. In the absence of a reinforcement of the international action in favor of the climate, the rise of the average global temperature could reach 2 degrees Celsius resulting in even more natural disasters (floods, droughts, degradation of the agricultural yields, accelerated melting mountain glaciers and polar ice caps, rising sea levels, etc.) and irreversible effects on ecosystems. The European Union (EU) is not immune to these effects and by ratifying the Paris Agreement, they committed themselves to 40% increase in their greenhouse gas emissions by 2030. More recently, the European Commission (EC) developed a plan to attain an economy that is a climate-neutral in 30 years (EC, 2018).

The stylized facts[2] show that in the EU[3], $CO_2$ emissions tend to decrease (-26%) over the period 1991-2014 while at the same time patent filings in 'technologies related to the environment' have continued to grow. For example, over the period 1991-2014, patent filings in these technologies increased by 209%. The leaders in this field are Germany, France, and the United Kingdom (with 3707, 1430, and 988 patents respectively, filed in 2014). These patents focus on technologies for combating climate change related to transport and the production, transmission, and distribution of energy.

Experts and scholars admit that the transition to a green economy is critical and cannot be achieved without innovation (Aghion et al., 2009). In recent decades, there is remarkable agreement among experts and economists on the importance of green technological progress (or eco-innovation) as an effective instrument for achieving sustainability goals, improving energy efficiency, reduce the negative consequences of resources use, and decrease pollution and other environmental risks (Kemp and Pearson, 2007). Today, eco-innovation is considered a real strategic tool for firms, enabling them to monitor the impacts of their actions, and avoid reputational damage and associated costs. Given the importance of green innovation in shaping environmental sustainability, this study seeks to provide answers to two central questions. First, is there a causal relationship between $CO_2$ emissions on the one hand and green technologies on the other. Second, if so, what is the nature of this impact?

Recent studies showcase the role of technological innovation in achieving environmental sustainability goals (Amri et al, 2018). Technological innovation makes a positive impact on the ecosystem due to using green energy and lowering fossil fuels' consumption (Jordaan et al., 2017). Moreover, these technologies could help countries to improve the efficiency of their production processes (Gozgor, 2017). Also, there is an increase in the adoption of greener production methods and more sustainable and environmentally friendly products and services (Yu and Du, 2019).

Existing literature on energy and the environment has largely been dominated by analyzing the association between economic development, energy demand, and carbon emissions, with an underlying focus on testing the Environmental Kuznets Curve (EKC) (Belaïd and Youssef, 2017; Bélaïd and Abderrahmani, 2013; Grossman and Krueger, 1991). Further, existing works have also examined the link between economic growth, energy demand, and environmental

[1] IPCC. (2018). Global warming of 1.5 Degrees. Retrieved from https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf
[2] Source: OECD, author's calculation
[3] EU-15 in 2004

pollution (Belaïd and Zrelli, 2019; Belaïd and Youssef, 2017; Apergis and Payne, 2014). Recently, a new research stream has emerged that focuses on the role technological innovation in lowering $CO_2$ emissions (Erdoğan et al., 2020; Nguyen et al., 2020; Chen and Lei, 2018).

To explore the claim that green innovation policies enhance environmental quality through stimulating renewable energy production, this study provides empirical evidence focusing on 15 EU countries. Contributions of this study are at least twofold. First, new evidence is put forward on the role played by technological innovation to shape the carbon emissions trend in the case of EU countries. These countries offer an interesting case to study this claim for two reasons. The first reason is that these countries are net importers of fossil fuels and environmental quality is a major challenge for them. The second reason is that most of the EU countries have set ambitious targets for reducing $CO_2$ emissions, and investment in innovation is at the heart of European energy and environmental policies. Nonetheless, studies exploring the role of green innovations in shaping environmental quality are rather limited (Du et al., 2019). This study contributes to the ongoing debate on the drivers of environmental sustainability by exploring the effects of green innovations on improving the environmental quality in the EU countries.

In a recent study, Töbelmann and Wendler (2020) developed a Generalized Method of Moments (GMM) to explore the environmental innovation impact on carbon emissions in the EU-27 countries during the period 1992-2014. Our study is different in several respects using a different empirical approach and focusing on 15 EU countries. While Töbelmann and Wendler (2020) use a GMM approach to examine mainly the long-run impact of innovation on carbon emissions, our study uses an ARDL model to explore both the short and the long-run impacts of environmental innovations, the consumption of renewable energies, GDP per capita, and degree of economic openness on the environmental quality. Compared to other methods of co-integration, ARDL has many advantages: (i) it provides valid results on whether the variables are I(0) or I(1) or mutually co-integrated and provides very consistent and efficient results in large or small samples; (ii) it allows for capturing the data generation process from a general modeling framework by including a sufficient number of lags; and (iii) it is most appropriate technique in the case of a small sample size, which is the case of our study (Pesaran et al., 2001). Furthermore, and in contrast to the Töbelmann and Wendler (2020) study, we chose to focus on a panel of 15 countries for two main reasons: (i) these 15 countries are the richest and invest the most in green innovations, and (ii) for the other EU countries, data on green innovations are generally missing, and even when they are found, they are of poor quality. Since studies on this subject are rare, our study provides new insights that enrich our knowledge on the impact of environmental innovation and inform policies on the role that innovation could play in reducing greenhouse gas emissions.

The rest of this study proceeds as follows. Section 2 is devoted to reviewing the literature on the drivers of $CO_2$ emissions. The following section presents the data and methodology. Section 4 discusses the results and section 5 draws the conclusions and provides some policy implications.

## 2. Key Determinants of Carbon Emissions

Since the pioneering work of Grossman and Krueger (1991), who introduced EKC[4], a growing body of work on the drivers of $CO_2$ emissions has developed in recent decades (Lean and Smyth, 2010; Yang et al., 2015; Perman and Stern, 2003; Stokey, 1998). In this context, the

[4] An inverted U-shaped relationship has been suggested between the pollution indicators and income per capita.

degree of economic openness (Hu et al., 2018; Piaggio et al., 2017; Grossman and Krueger, 1991), the rate of urbanization (Wang et al., 2019), the structure of the productive apparatus (Du et al., 2019), the level of wealth ( Esteve and Tamarit, 2012; Dinda and Coondoo, 2006; Kuznet, 1955), technological innovation (Yii and Geetha, 2017), and the energy structure (Cheng et al., 2018) are the main variables usually used to explain $CO_2$ emissions. More recently, the work of Zhang et al. (2016) recognizes the critical role of green technologies in reducing $CO_2$ emissions. However, this research is still limited and far from reaching a consensus. Indeed, some studies (Acemoglu and Gancia, 2012; Jaffe et al., 2002) admit that the effects of green technologies (positive or negative) on $CO_2$ emissions depend on the country's wealth and the time of the impact (short vs. long-term). The existence of short-term rebound effects[5] (Braungardt et al., 2016) is particularly noticeable in technologies e.g. fuel (Belaid et al., 2019; Font et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007), and this contributes to the debate on the effect of green technologies on $CO_2$ emissions. Similarly, the findings of Weina et al. (2016) in the Italy-wide study points to the extent to which environmental innovations increase environmental productivity, but do not reduce $CO_2$ emissions.

These various studies on the determinants of $CO_2$ emissions highlight the important work that remains to be done to untangle the spectrum of the sustainability process, particularly when it comes to environmental innovations. From policy perspectives, the results of such analysis would constitute a strategic tool to better guide public policies aimed at achieving climate objectives. This is one of the major contributions of our study. This original contribution stems from the multidimensional analysis and investigating some of the nuances that are often overlooked in the current economic and policy debate. Despite the growing emphasis on the localized nature of environmental innovations, our understanding of its effects on environmental quality enhancement remains limited. Indeed, environmental innovations are the subject of little research, both in terms of empirical work on the geography of innovation and on the analysis of the determinants of $CO_2$ emissions (Du et al., 2019; Autant-Bernard et al., 2010). In this context, the specificities of environmental innovations are poorly studied, even less so when it comes to studying the impact of environmental innovations on carbon emissions.

This article examines the effects of green technologies on carbon emissions in EU countries. Based on the work of Du et al. (2019), we use $CO_2$ emissions as a proxy for carbon emissions performance. The explanatory variables are based on the literature findings including environmental innovations and three control variables namely the consumption of renewable energy, GDP per capita, and degree of economic openness.

### *2.1 Environmental Innovations*

The patent is an indicator of technological innovation insofar as it captures the R&D activity carried out within firms (Griliches, 1990). Patents filed in environmental technologies are a relevant indicator for approximating environmental innovations. Although many studies have analyzed the effects of environmental innovations on $CO_2$ emissions, research is still limited and far from reaching a general consensus. An early study by Weina et al. (2016), across 95

[5] An illustration of the direct rebound effect is given by Herring and Sorrell (2009). For example, consumers using fuel-efficient cars may travel for longer and more often due to reducing the cost of travelling.

Italian provinces, shows that environmental technologies have no significant effect on reducing $CO_2$ emissions, although they increase environmental productivity. However, a recent study by Du et al. (2019), using a panel of 71 countries for the 1996-2012 period, demonstrates that environmental innovations make a significant contribution to lowering $CO_2$ emissions, especially in countries with high-income levels. Other studies underline the existence of a short-term rebound effect especially for environmental technologies related to energy efficiency and transportation (Font Vivanco et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007). Braungardt et al. (2016) examined the impact of energy-efficient innovations on electricity demands for residents across the 27 EU countries. They found that innovations in energy efficiency contribute to better energy efficiency, which tends to limit $CO_2$ emissions. They also claim that it is essential to combine measures to reduce the rebound effect with the policy measure to promote developing residential energy-efficiency innovations.

Recent empirical studies explored the impact of innovation on environmental quality (Fethi and Rahuma, 2019; Ganda, 2019; Hashmi and Alam, 2019; Töbelmann and Wendler, 2020). A common agreement of this literature is that innovation and technological improvement have a positive impact on environmental quality, which is frequently alluded to as the technological effect. Fethi and Rahuma (2019) document that eco-innovation plays important role in enhancing environmental quality in the top 20 refined oil-exporting countries. In the context of OECD countries, Ganda (2019) highlights that technology and general innovation investments affect environmental quality in various ways, and have the potential to reduce environmental quality. This implies that it is necessary to make innovation and technology investments compatible with the environment. Hashmi and Alam (2019) suggest that environmentally friendly patent has a positive impact on the environmental quality in the OECD countries, a 1% increase in green innovation reduces CO2 emissions by 0.017%. In the same vein, a recent study by Töbelmann and Wendler (2020) shows that environmental innovation, unlike general innovative activity, contributes to the improvement of environmental quality in the EU-27 countries. Therefore, we suggest the following:

> ***Hypothesis 1.*** Environmental innovations have a positive effect on carbon emissions in the short-term due to the possible rebound effects, whereas they have a negative effect in the long-run.

### *2.2 Renewable Energy Consumption*

Renewable energies such as wind, solar, geothermal, and waste have the advantage of being carbon neutral and non-exhaustible. The consumption of renewable energies is a real sustainable economic alternative that could limit the depletion of natural resources, reduce air pollution, ensure energy security, and finally create jobs. Prior studies suggest evidence on the links between economic growth, energy consumption and/or production (non-renewable and renewable), and carbon emissions. An early study by Bento and Moutinho (2016), over the period 1960-2011 for the case of Italy, validates the EKC hypothesis by estimating pollution model that indicates less pollution over time caused by economic growth. It also shows that the production of renewable electricity per capita reduces the level of carbon emissions per capita in the long and short-terms. Gozgor (2018a) confirms the results of this work for the US case by showing the significant and positive long-term association between economic growth and the consumption of renewable energy. These results are also confirmed for the case of developing countries (Liu et al., 2017; Kahia et al., 2016). Thus, renewable energy consumption contributes to the achievement of green growth objectives.

***Hypothesis 2.*** The consumption of renewable energy promotes the reduction of carbon emissions. A significant and negative effect is assumed in the short and long-terms.

*2.3 GDP per Capita*

Following the work of Kuznet (1955), numerous empirical studies have examined the impact of economic growth on carbon emissions to test EKC's validity. Grossman and Krueger's (1991) study empirically examined the association between the level of air quality and economic growth in many cities around the world. They demonstrate that starting from a certain income level or when a certain stage of development is reached, economic growth makes it possible to reduce environmental damage by moving from a polluting industrialized economy to a tertiary cleaner economy. This is particularly relevant to investments in cleaner technologies and the increased environmental awareness, which are the consequence of the improvement in the living conditions of individuals. Although a large body of the literature has tested EKC, consensus is yet to be attained (Ridzuan, 2019). There are mixed results on the association between income inequality and the environment, with reports of positive, negative, and no significant relationship[6]. Berthe and Elie (2015) claim that this heterogeneity in the findings is largely related to the endogenous variables mobilized and no clear trend has been identified for carbon emissions, air, and water pollution. Many of the existing empirical results are in line with studies (Wilkinson and Pickett, 2010; Magnani, 2000; Boyce, 1994), which recognizes that income level negatively affects the environment quality.

In this study, we focus on the impact of income level rather than income inequality. Indeed, despite the divergent results in the literature on the supposed impact of income levels on the quality of the environment, we should be reminded that the EC's long-term strategy to move towards a carbon-free economy by 2050 (EC, 2018) places the decoupling[7] of economic prosperity from resource consumption (UNEP, 2016) as a cornerstone instrument. This strategy also assumes that an increase in GDP leads to an increase in the consumption of resources and energy, which is a source of environmental degradation (Crane et al., 2011). Moreover, Global Footprint Network data[8] shows that disparities in people's ecological footprints are strongly related to the level of development of their countries. For example, in 2016, the lifestyle of North Americans required 4.95 planets compared to 2.8 for Europeans and 0.83 for Africans. This suggests that GDP per capita growth can increase $CO_2$ emissions over the long term.

***Hypothesis 3.*** The growth of GDP per capita contributes to the increase in carbon emissions over the long-term.

[6] For an excellent review see (Berthe and Elie, 2015; Cushing et al., 2015). Recent empirical studies (Liu and Feng, 2018; Mader, 2018; Grunewald et al., 2017; Hübler, 2017; Jorgenson et al., 2017; Kasuga and Takaya, 2017)

[7] Decoupling is an economics term refeering to the goal of separating economic prosperity (income generation, economic growth) from resource and energy consumption (negative environmental impact, greenhouse gas emissions, etc.).

[8] https://www.footprintnetwork.org/

*2.4 International Trade Openness*

The degree of economic openness makes it possible to measure the dynamics of a country's international trade. Increasing globalization trade flows over the last two decades have fuelled emerging literature that analyses the effects of international trade on carbon emissions performance. Theoretically, international trade has been claimed as one of the drivers that stimulate economic growth by increasing the size of the market, facilitating specialization and efficiency in the distribution of resources, promoting international transfers of technology and knowledge, increasing competition, and improving governance (Grossman and Helpman, 1995; Barro and Lee, 1994; Edwards, 1989). However, these same mechanisms can also affect the quality of the environment through three main effects. First, the so-called scale effect offers companies opportunities to explore larger markets, which in turn increases the level of production and significantly affects $CO_2$. Secondly, the impact can be intensified by the so-called structure effect (specialization) which implies a better allocation of resources and higher productivity. This effect implies that rich countries tend to focus on capital-intensive industries (labour intensity). Thus, the hypothesis of pollution havens suggest that countries with strict environmental regulations (vs. Laxists) may have to specialize in clean industries (vs. pollution generators), when environmental standards differ. In general, products that produce the most pollution are capital-intensive. Advanced economies have a high capital endowment, but strict environmental policies. The effects of international trade suggest that strict policies would impose pollution-intensive production on developing countries to bear the burden of pollution in advanced economies (Copeland and Taylor, 2013). Thirdly, the so-called technology effect implies that international trade promotes access to more environmentally friendly production technologies, encourages the race for environmental standards and regulation, and encourages countries to use more efficient technologies. These different behaviors reduce $CO_2$ emissions (Thoenig and Verdier, 2003).

On the side of the empirical literature, the results are particularly mixed[9]. Antweiler et al. (2001) found that liberalizing trade reduces carbon emissions. Earlier studies (Frankel, 2005; Cole, 2004; Cole and Elliott, 2003) questioned this positive effect and used different types of pollution emissions. These doubts are confirmed by several studies (Aklin, 2016; Kozul-Wright, 2012; Ang, 2009; Dean, 2002), demonstrating that $CO_2$ emissions increase as a result of trade openness. On the contrary, other studies (Kearsley and Riddel, 2010; Kellenberg, 2008; Prakash, 2006) demonstrated that openness in international trade is not associated with increasing $CO_2$ emissions. Finally, empirical evidence (e.g. Baek et al., 2009; Managi et al., 2009) suggests that openness in international trade tends to benefit the environment of advanced economies (OECD members).

An extensive number of studies have demonstrated the existence of a significant relationship between international trade and the intensity of CO2 emissions (Tiba and Belaid, 2020; Omri and Belaïd, 2020). While economic openness is conducive to reducing carbon emissions and enhancing efficiency in developed countries (Forslid et al. 2018), for developing countries, it tends to increase CO2 emissions (Acheampong et al. 2019). A recent study, based on a panel of 179 world economies, conducted by Du and Li (2019) shows that economic openness impact on environmental quality relies on the income level. The findings argue that international trade tends to increase CO2 emissions for low-income countries, while it improves environmental

[9] For a review see Kim et al. (2019).

quality for the high-income countries. The magnitude of international trade on carbon emissions effect increases with income growth. Based on this, we suggest the following:

> ***Hypothesis 4.*** Trade openness may improve the environmental quality of the 15-EU countries.

## 3. The Study Method

### *3.1 Data*

The variables used in this study are carefully selected based on the availability of data and economic theory (Du et al., 2019; Su and Moaniba, 2017). We use the annual data for the period (1991-2014) for the EU-15 countries[10]: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Spain, Spain, Ireland, Italy, Luxembourg, the Netherlands, Portugal, the United Kingdom, and Sweden.

Our dependent variable is $CO_2$ emissions (expressed in metric tons per capita). In this study, we rely on the work of (Du et al., 2019; Su and Moaniba, 2017) using patent data - 'technologies related to the environment' - to approximate environmental innovations (INNOV). The aggregated category of these technologies includes climate change technologies, water-related adaptation technologies, and environmental management technologies. Control variables include the share of renewable energy in the total consumption level. The latter is used as a proxy for the renewable energies consumption (REC) and represents a composite variable of consumption of solar, hydroelectric, geothermal, biomass, and wind energy in the total energy consumed. Other determinants include per capita of Gross Domestic Product (GDP) (US $), and the degree of economic openness (OPEN) measured as the sum of imports and exports as a percentage of GDP. With the exception of patent data (OECD database)[11], all variables were extracted from the World Bank Group Development Indicator Database[12]. Descriptive statistics of the variables used in our model are shown in Table 1.

Table 1. Descriptive Statistics.

| | **$CO_2$** | **INNOV** | **REC** | **GDP** | **OPEN** |
|---|---|---|---|---|---|
| Mean | 9.21 | 405.01 | 12.96 | 41694.58 | 92.27 |
| Median | 8.66 | 170.93 | 8.28 | 38899.17 | 69.85 |
| Maximun | 27.43 | 4607.71 | 49.94 | 111968.40 | 382.29 |
| Minimun | 4.33 | 0.50 | 0.60 | 17278.30 | 33.98 |
| Std. Dev | 4.00 | 763.76 | 11.95 | 17094.55 | 60.71 |
| Skewness | 2.23 | 3.47 | 1.06 | 1.89 | 2.25 |
| Kurtosis | 9.07 | 15.77 | 3.13 | 7.70 | 8.65 |
| Jarque-Bera | 853.09 | 3174.96 | 68.51 | 547.79 | 784.10 |
| Probability | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sum | 3317.28 | 145804.9 | 4665.76 | 15010049 | 33220.77 |
| Sum Sq.Dev | 5755.33 | $2.09^{E}+08$ | 51289.12 | $1.05^{E}+11$ | 1323501 |

Notes: Observations=360

[10] Countries that belonged to the EU-15 are considered as economically the 'most developed countries' of the EU, compared to the new member countries of Central Europe, still in the process of catching up economically.
[11] https://stats.oecd.org/?lang=fr
[12] https://data.worldbank.org/indicator

We converted our sample to a panel data format, which has the particularity of taking into account the temporal dynamics (adjustment delay, anticipations, etc.) with the explanation of a time series variable. Thus, improving the forecasts and the effectiveness of policies (decisions, actions, etc.), in contrast with the simple (non-dynamic) model whose instantaneous explanation (immediate effect or not spread over time) only restates part of the variation of the variable it explains. The data is also converted into a logarithm format.

### *3.2 Empirical Model and Estimation Procedure*

In line with the recent literature on the drivers of $CO_2$ emissions, we develop an empirical model that takes the following form:

$$CO2 = f\ (\mathrm{INNOV}, \mathrm{REC}, \mathrm{GDP}, \mathrm{OPEN})\ \textbf{(1)}$$

Where $CO_2$ represents $CO_2$ emissions, and is a function of four variables: environmental innovations (INNOV), renewable energy consumption (REC), GDP per capita (GDP), and the degree of economic openness (OPEN).

Eq. (1) can be rewritten in a logarithmic form with a time series and panel form specification as follows:

$$LogCO2_{it} = \alpha_0 + \alpha_1 LogCO2_{it-j} + \alpha_2 LogINNOV_{it} + \alpha_3 LogREC_{it} + \alpha_4 LogGDP_{it} + \alpha_5 LogOPEN_{it} + \varepsilon_{it}\quad \textbf{(2)}$$

Where the subscript i (i = 1, ..., N) indicate the country i in our sample, N is equal to 15. t (t = 1, ..., T) indicates the time period. Our panel constitutes 15 countries and 24 years. The variables are not stationary at I(0) but they are probably at I(1). This means that the model is dynamic and considers inclusion of lagged dependent variables as a regressor. As suggested by Pesaran and Smith (1995), ARDL model is more appropriate because it has advantages over other dynamic model GMM estimators, fixed effects, or instrumental variables (Arellano and Bover, 1995). Unless the coefficients are the same across countries, these methods produce inconsistent estimation. On the other hand, the ARDL model is relatively more efficient in small t and finite sample sizes.The model has a form of an ARDL (p, q, q…..q) model:

$$LogCO2_{it} = \sum_{j=1}^{p} \alpha_{ij}\, LogCO2_{i,t-j} + \sum_{j=0}^{q} \delta'_{ij}\, X_{i,t-j} + \mu_i + \varepsilon_{it}\quad \textbf{(3)}$$

Reparametrising the model, it becomes:

$$\Delta LogCO2_{it} = \Phi_i \left(LogCO2_{i,t-1} - \beta'_i X_{i,t}\right) + \sum_{j=1}^{p-1} \alpha_{ij}\, \Delta LogCO2_{i,t-j} + \sum_{j=0}^{q-1} \delta'_{ij}\, \Delta X_{i,t-j} + \mu_i + \varepsilon_{it}\quad \textbf{(4)}$$

Where:

- X is the vector of explanatory variables;
- $\Phi_i$ is the group-specific speed of adjustment coefficient (expected that $\Phi_i$<0);
- $\beta'_i$ measures the long-run effect of the determinants on carbon emissions;
- ECT = $[LogCO2_{i,t-1} - \beta'_i X_{i,t}]$ is the error correction term (ECT);

- $\alpha_{ij}$, $\delta'_{ij}$ are the short-run dynamic coefficients;
- $p$ et $q$ are optimal lag orders[13] ; and
- $\mu_i$ is the constant.

We not that, $\varepsilon_{it}$, which is the random disturbance term, is homoscedastic (i.e. constant variance), serially independent, and normally distributed. The specified model in equation 3 is a particular class of error correction models, which enable the coefficients to fluctuate among units. The Pesaran's Pooled Mean Group estimator (MG) is consistent to estimate this model (Pesaran and Smith, 1995; Pesaran et al., 1999). In the case the long-run parameters are homogeneous across groups, the Pooled Mean Group (PMG) estimator (Pesaran et al., 1999) will more efficient. However, this approach is appropriate only if the factors are integrated of order zero (I(0) or one (I(1); and this approach is suitable to both small or large samples. Further, we will display the unit-root tests, the cointegration test, i.e. whether a long-term relationship exists between the factor, and panel model estimates.

*3.2.1 Unit Roots Test*

To test for unit roots (or stationarity), we used various tests including Cross-sectional Augmented Dickey-Fuller (CADF) (Pesaran, 2007), Im–Pesaran–Shi (IPS) (Im et al., 2003), and Levin–Lin–Chu (LLC) (Levin et al., 2002) tests. In these tests, the null hypothesis is that all the panels contain a unit root and alternative null is not true. The findings of this test are presented in Table 2.

Table 2. Unit roots test.

| | **CADF** | | **LLC** | | **IPS** | |
|---|---|---|---|---|---|---|
| **Variables** | **Level** | **First Diff.** | **Level** | **First Diff.** | **Level** | **First Diff.** |
| Log $CO_2$ | 7.77 | 89.67*** | 5.25 | -3.67*** | 5.42 | -5.50*** |
| LogINNOV | 22.08 | 117.50*** | -2.70*** | -2.18*** | 0.47 | -7.75*** |
| LogREC | 4.29 | 9.53*** | 5.23 | -5.88*** | 7.89 | -6.06*** |
| LogOPEN | 31.87 | 144.16*** | -2.91** | -10.04*** | 0.08 | -9.55*** |
| LogGDP | 31.08 | 88.99*** | -5.27*** | -6.27*** | -0.94 | -5.73*** |

Notes: *** denotes significance at 1% level

From the results of ADF, IPS, and LLC unit root tests, it appears that the variable are integrated of order I(0) or I(1). Specifically, in level, the results of the unit root test (LLC) obtained indicate that LogINNOV, LogOPEN and LogGDP are stationary in I(0). Unit root tests in the first difference indicate that all variables are integrated in I(1). The variables' statistics are significant at the 1% level. The null hypothesis can be rejected when these variables are stationary. Thus, we use a mixture of I(1) and I(0) to estimate an ARDL model. Next, we perform the cointegration test to show whether a long-term relationship exists between $CO_2$ emissions, environmental innovations, consumption of renewable energies, GDP per capita, and degree of economic openness.

*3.2.2 Cointegration test*

We tested the variables cointegration with Pedroni's (2004) test. This approach is based on examining residuals. The residuals must be stationary if cointegration among the variables

[13] Given the size of our sample, in our case the optimal model will be of the form ARDL (1, 1, 1, 1, 1)

exists. The absence of cointegration is expressed by the null hypothesis, in which the residuals $\varepsilon_{it}$ will be I (1). The result of the cointegration test is shown in Table 3.

Table 3. Results of the Cointegration tests

The alternative hypothesis is: common AR coefs. (within-dimensions)

| | **Weighted** | | | |
|---|---|---|---|---|
| | **Statistic** | **Prob** | **Statistic** | **Prob** |
| Panel v-Statistics | 0.58 | 0.28 | 0.63 | 0.26 |
| Panel rho-Statistics | 0.09 | 0.53 | -0.88 | 0.18 |
| Panel PP-Statistics | -3.42*** | 0.00 | -5.19*** | 0.00 |
| Panel ADF-Statistics | -1.79** | 0.03 | -1.43* | 0.07 |

The alternative hypothesis is: individual AR coefs. (between-dimensions)

| | **Statistic** | **Prob** |
|---|---|---|
| Group rho-Statistics | 0.63 | 0.73 |
| Group PP-Statistics | -5.79*** | 0.00 |
| Group ADF-Statistics | -0.97 | 0.16 |

Notes : *** denotes significance at 1% level

The cointegration results indicate that PP-Statistics panels; ADF Statistics and Group PP-Statistics are significant allowing to reject the null hypothesis of no cointegration, suggesting that there is long-term co-integration between the determinants considered in our empirical model. Note that the PP-Statistics and PP-Statistics groups have the best properties. At a 1% threshold, we reject the null hypothesis with no cointegration by the PP-Statistics panel and PP-Statistics group. These results confirm that a cointegration association exists between the series under study, which gives the possibility of estimating the long-term effects of LogINNOV, LogREC, LogOPEN, and LogGDPH on Log $CO_2$.

## 4. ARDL Results

Using the Pooled Mean Group (PMG), the results of the estimates are presented in Table 4 highlighting the long-term and the short-term equilibrium for the entire sample. Table 4. Panel ARDL long-Run and short-Run PMG estimation.

Long-term equation

| **Variables** | **Coefficient** | **t-Statistics** | **P-value** |
|---|---|---|---|
| LogINNOV | -0.12*** | -5.63 | 0.00 |
| LogREC | -0.13*** | -12.55 | 0.00 |
| LogOPEN | 0.22*** | 9.31 | 0.00 |
| LogGDP | 0.15*** | 2.69 | 0.00 |

Short-term equation

| Variables | Coefficient | t-Statistics | P-value |
|---|---|---|---|
| ECT | -0.33*** | -2.93 | 0.00 |
| DLogINNOV | 0.04*** | 2.93 | 0.00 |
| DLogREC | -0.28*** | -2.93 | 0.00 |
| DLogOPEN | 0.07 | 1.20 | 0.22 |
| DLogGDP | 0.50*** | 2.81 | 0.00 |
| Constant | 0.22** | 2.17 | 0.03 |

Dependent variable D(log $CO_2$); Level of significance *** $p<0.01$, ** $p<0.05$, * $p<0.1$

*4.1 Long-term Effect*

The results indicate that all variables have long-term effects. Environmental innovations (LogINNOV) has a significant and negative effect on $CO_2$ emissions. More specifically, over the long-term, a 1% increase in patent filings in environment-related technologies contributes to a 0.12% decrease in $CO_2$ emissions. This result is in line with the findings of Du et al. (2019) on a sample of 71 countries. These results are also consistent with Braungardt et al.'s (2016) findings from a sample of 27 EU countries.

It is still necessary to check the short-term effects in order to detect the existence of a supposed rebound effect. The consumption of renewable energies (LogREC) has a significant and negative effect on the long-run. These results are in line with those of Gozgor (2018b) for the case of the United States and with those of Cerdeira et al. (2016) for the case of Italy.

For their part, variables approximating degree of economic openness (LogOPEN) and GDP per capita (LogGDP) show significant and positive effects on $CO_2$ emissions. More specifically, over the long-term, an increase of 1% in international trade openness (LogOPEN) and GDP per capita (LogGDP) contributes respectively to an increase of 0.22% and 0.15% in $CO_2$ emissions. The negative impact of economic openness on $CO_2$ emissions is contrary to the results of earlier empirical studies (Baek et al., 2009; Managi et al., 2009) emphasizing that liberalization of trade in developed economies can be beneficial for the environment. These results, however, are in line with previous studies (Aklin, 2016; Ang, 2009; Dean, 2002; Kozul-Wright, 2012) suggesting that $CO_2$ emissions increase due to increased trade openness. This result could be explained by the effect of scale and structure.

Finally, EKC's hypothesis is not validated in the case of our sample. In fact, the rise in GDP per capita tends to increase the deterioration of the environment ($CO_2$ emission). This result appears to be consistent with the theoretical analyses (Boyce, 1994; Magnani, 2000; Wilkinson and Pickett, 2010) suggesting that income inequality has a negative effect on the environment. Wilkinson and Pickett (2010) argue that, in developed countries, this is largely due to consumerist and individualistic behavior. In the EU, the significant increase in GDP per capita over the studied period (1990-2014) was accompanied by a serious social crisis (Turquet, 2015), which tends to amplify income inequalities. In this context, public policies focus more on economic growth than on the protection of the environment (Magnani, 2000), and individuals seem to focus more on improving their economic situation than the environment.

### *4.2 Short-term Effect*

Short-term dynamics modeling provides information on how adjustments are made between different determinants to restore long-term equilibrium. The ECT captures this relationship with a coefficient indicating the speed of adjustment, i.e. the rate at which the system returns to equilibrium after an impact. A long-term relationship exists if the sign of the coefficient of the ECT is significantly negative and varies between -1 and -2. As shown in Table 4, we note that the estimated coefficient for the ECT is significant and negative (-0.33) at the 1% threshold, which indicates the existence of a long-term relationship. The rebound effect is observed in the short-term through the impact of the variable (LogINNOV), which has a significant and positive effect at the 1% level. In other words, environmental innovations tend to increase $CO_2$ emissions in the EU-15 countries in the short-run.

Nevertheless, these results suggest the existence of a possible rebound effect, which is a behavioral response to an improvement in energy efficiency. One of the rational explanations for this failure is that the increased energy efficiency does not necessarily translate into a corresponding decrease in the environmental quality in absolute terms (Belaïd et al., 2018; 2020; Bureau et al., 2019). Various microeconomic studies on the rebound effect show that income and substitution effects help explain how the rebound effect influences users' attitudes and behaviors. The rebound effect has occupied an increasingly important place on the agenda of policy makers since the early 1980s, but it has its origins in the seminal work of Jevons (1865). Davis et al., (2014) found that a replacement program for air conditioners and refrigerators in Mexico increases electricity consumption. Sorrell (2007) and Vivanco et al. (2016) show that, in the case of Europe, the rebound effect is particularly noticeable for green technologies related to energy efficiency and the transport sector. The effect of the consumption of renewable energies (LogREC) remains unchanged (significant and negative at the 1% threshold) in the short-term and again tends to contribute to a reduction of $CO_2$ emissions. The degree of economic openness has no effect in the short-term. Lastly, GDP per capita (LogGDP) has a positive impact on $CO_2$ emissions.

## 5. Conclusions and Policy Implications

Actions in favor of the climate are imperative today. Environmental innovations can play a key role in the green transition of economies. At the EU level, stylized facts show an inverse relationship between $CO_2$ emissions and patenting of environmental technologies. According to OECD data, $CO_2$ emissions tend to decrease (-26%) over the period 1990-2014, while at the same time patent filings of these technologies have not stopped growing (+209% in the same period). This phenomenon is also geo-localized and particularly noticeable in a few countries such as Germany, France, and the United Kingdom. Despite these stylized facts, the empirical work to examine the effects of environmental technologies on carbon emissions is still limited. Indeed, environmental innovations are the subject of little analysis both in terms of empirical work relating to the geography of innovation and those relating to the analysis of the determinants of $CO_2$ emissions. This study attempts to contribute to filling this important gap by examining the effect of green technologies on $CO_2$ emissions of 15 EU countries using an ARDL model.

We estimated an ARDL model from the PMG estimator to examine the effects of environmental innovations, renewable energy consumption, GDP per capita, and the degree of economic openness on $CO_2$ emissions. Our main results show that: in the long-term, environmental innovations tend to lower $CO_2$ emissions, whereas in the short-term the observed effect is the opposite, suggesting the existence of a rebound effect. These results are in line with previous studies (Vivanco et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007), which underline the existence of a short-term rebound effect in EU countries. Moreover, the consumption of renewable energy (long and short-term) tends to lower $CO_2$ emissions in Europe. An analysis of country specificities would be relevant in order to observe the persistence of this phenomenon at the country level. Indeed, the energy mix and the decarbonization strategies of electricity production tend to increase the $CO_2$ emissions. In France, for example, nuclear energy accounts for nearly 71.6% of electricity production. However, according to the Réseau de Transport d'Électricité, the massive investment in solar panels paradoxically increases $CO_2$ emissions in France as photovoltaic panels emit nearly 3 times more $CO_2$ than nuclear energy (considered as carbon-free energy). Finally, economic openness and GDP per capita have significant and positive effects on $CO_2$ emissions. The results of trade openness are in line with previous work (Aklin, 2016; Ang, 2009; Dean, 2002; Kozul-Wright, 2012), which shows that increased trade openness increases $CO_2$ emissions. This result could be explained by the effect of scale and structure. Also, the rise in GDP per capita tends to increase the deterioration of the environment ($CO_2$ emission). This result appears to be consistent with prior studies (Wilkinson and Pickett 2010; Magnani, 2000; Boyce, 1994), recognising that income inequality negatively affects the environment.

In light of these results, several public policy orientation can be suggested. First, public environmental policies tend to revolve around a combination of several political instruments. These include, on the one hand, economic instruments focused on the price signal and the polluter pays principle (within this framework, there are instruments such as environmental taxation, incentives or dissuasive, and policies that provide significant support for green technologies). On the other hand, environmental policies incorporate instruments of a regulatory nature and focused on supporting individuals towards profound changes in their consumption and production patterns. The theoretical basis of the later instruments is based on work in ecological economics claiming that the earth is a finite space and that everyone is responsible for preserving it. Policy makers find it difficult to balance these different instruments in order to guarantee the most efficient environmental policy possible. In relation to our results on the effect of environmental innovations on long-term $CO_2$ emissions, it appears that green technologies constitute one of the solutions to favor the fight against global warming because of their resilience capacity. However, the short-term effects, on the contrary, the increase in $CO_2$ emissions caused by environmental innovations signal the extent to which it is necessary to support using these technologies through education and access to information. This can lead to perverse effects such as the rebound effect observed in this study. Sorrell (2010) claims that the rebound effects raise the question of the effectiveness of energy efficiency policies given the behavioral responses that tend to reduce the scale of energy savings. Thus, measures other than prices must be considered by policy makers to limit the rebound effect. Specifically, it is imperative to encourage individuals to consume more effectively by reducing the environmental effects of each product and/or service. New policies should encourage people to consume differently by focusing on products and services that have less negative effect on the environment. This would result in the purchase of greener products or increased spending on services rather than manufactured goods.

The rise in $CO_2$ emissions brought about by the rise in GDP and degree of economic openness, not to mention the plausible effects of irreversibility, the fragility of environments, accumulation of pollutants in ecosystems, and exhaustion of stockpiles and energy motivates the questioning the current model of economic growth. For proponents of the ecological economy, the environment must be considered as the support of any human activity in which the inputs are the capability of the environment to absorb waste and provide resources, and the outputs (resulting) growth and development (Boutaud et al., 2006). Taking the principle of 'strong' sustainability, there is a need to rely to a lesser extent on green technologies, and to rely more on measures to accompany the structural changes deep in lifestyles of individuals to deal with possible rebound effect. In practice, public decision-makers must focus their actions on environmental policies of a green and inclusive economy that combine tools of environmental economics with those of the ecological economy. This can be done by associating economic incentives with regulatory changes that enable promoting individual approaches focused on structural changes in lifestyles (e.g. the multitude of standards and labels based on voluntary membership such as 'eco-products', initiatives for the 'collaborative economy', among others).

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