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1 **The Effects of Environmental**
2 **Innovations on CO₂ Emissions: Empirical Evidence from Europe**

3

4 **Abstract**

5 Environmental innovations are key enablers of transition towards greener economies. Despite
6 their importance, empirical studies examining the effect of green technologies on CO₂
7 emissions are still limited. Using an autoregressive distributed-lag model (ARDL), we analyze
8 the impact of environmental innovations, the consumption of renewable energies, GDP per
9 capita, and degree of economic openness on CO₂ emissions for 15 European countries over 23
10 years. Our results indicate that, in the long-term, environmental innovations tend to lower CO₂
11 emissions, whereas in the short-term the observed effect is the opposite, suggesting the
12 existence of a rebound effect. This study recommends introducing new policies that combine
13 tools of environmental economics with those of ecological economy to integrate economic
14 incentives with regulatory changes and encourage individuals to consume differently by
15 favouring products and/or services with a less negative impact on the environment.

16 **Keywords:** Environmental innovations; CO₂ emissions; Rebound effect; Europe; ARDL
17 model.

18 **JEL Classification:** Q53; Q55

19 **1. Introduction**

20 The current trajectory of global economic development is not without consequence on our
21 planet. Ecological deregulation, unlimited exploitation of natural resources, and growing
22 inequalities are at the heart of contemporary problems. According to a recent report¹,
23 anthropogenic emissions of greenhouse gas as a result of human activities are responsible for
24 almost 95% of global warming. In the absence of a reinforcement of the international action in
25 favor of the climate, the rise of the average global temperature could reach 2 degrees Celsius
26 resulting in even more natural disasters (floods, droughts, degradation of the agricultural yields,
27 accelerated melting mountain glaciers and polar ice caps, rising sea levels, etc.) and irreversible
28 effects on ecosystems. The European Union (EU) is not immune to these effects and by ratifying
29 the Paris Agreement, they committed themselves to 40% increase in their greenhouse gas
30 emissions by 2030. More recently, the European Commission (EC) developed a plan to attain
31 an economy that is a climate-neutral in 30 years (EC, 2018).

32 The stylized facts² show that in the EU³, CO₂ emissions tend to decrease (-26%) over the period
33 1991-2014 while at the same time patent filings in ‘technologies related to the environment’
34 have continued to grow. For example, over the period 1991-2014, patent filings in these
35 technologies increased by 209%. The leaders in this field are Germany, France, and the United
36 Kingdom (with 3707, 1430, and 988 patents respectively, filed in 2014). These patents focus
37 on technologies for combating climate change related to transport and the production,
38 transmission, and distribution of energy.

39 Experts and scholars admit that the transition to a green economy is critical and cannot be
40 achieved without innovation (Aghion et al., 2009). In recent decades, there is remarkable
41 agreement among experts and economists on the importance of green technological progress
42 (or eco-innovation) as an effective instrument for achieving sustainability goals, improving
43 energy efficiency, reduce the negative consequences of resources use, and decrease pollution
44 and other environmental risks (Kemp and Pearson, 2007). Today, eco-innovation is considered
45 a real strategic tool for firms, enabling them to monitor the impacts of their actions, and avoid
46 reputational damage and associated costs. Given the importance of green innovation in shaping
47 environmental sustainability, this study seeks to provide answers to two central questions. First,
48 is there a causal relationship between CO₂ emissions on the one hand and green technologies
49 on the other. Second, if so, what is the nature of this impact?

50 Recent studies showcase the role of technological innovation in achieving environmental
51 sustainability goals (Amri et al, 2018). Technological innovation makes a positive impact on
52 the ecosystem due to using green energy and lowering fossil fuels’ consumption (Jordaan et al.,
53 2017). Moreover, these technologies could help countries to improve the efficiency of their
54 production processes (Gozgor, 2017). Also, there is an increase in the adoption of greener
55 production methods and more sustainable and environmentally friendly products and services
56 (Yu and Du, 2019).

57 Existing literature on energy and the environment has largely been dominated by analyzing the
58 association between economic development, energy demand, and carbon emissions, with an
59 underlying focus on testing the Environmental Kuznets Curve (EKC) (Belaïd and Youssef,
60 2017; Bélaïd and Abderrahmani, 2013; Grossman and Krueger, 1991). Further, existing works
61 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

62 pollution (Belaïd and Zrelli, 2019; Belaïd and Youssef, 2017; Apergis and Payne, 2014).
63 Recently, a new research stream has emerged that focuses on the role technological innovation
64 in lowering CO₂ emissions (Erdoğan et al., 2020; Nguyen et al., 2020; Chen and Lei, 2018).

65 To explore the claim that green innovation policies enhance environmental quality through
66 stimulating renewable energy production, this study provides empirical evidence focusing on
67 15 EU countries. Contributions of this study are at least twofold. First, new evidence is put
68 forward on the role played by technological innovation to shape the carbon emissions trend in
69 the case of EU countries. These countries offer an interesting case to study this claim for two
70 reasons. The first reason is that these countries are net importers of fossil fuels and
71 environmental quality is a major challenge for them. The second reason is that most of the EU
72 countries have set ambitious targets for reducing CO₂ emissions, and investment in innovation
73 is at the heart of European energy and environmental policies. Nonetheless, studies exploring
74 the role of green innovations in shaping environmental quality are rather limited (Du et al.,
75 2019). This study contributes to the ongoing debate on the drivers of environmental
76 sustainability by exploring the effects of green innovations on improving the environmental
77 quality in the EU countries.

78 In a recent study, [Töbelmann and Wendler \(2020\)](#) developed a [Generalized Method of Moments](#)
79 [\(GMM\)](#) to explore the environmental innovation impact on carbon emissions in the EU-27
80 countries during the period 1992-2014. Our study is different in several respects using a
81 different empirical approach and focusing on 15 EU countries. While [Töbelmann and Wendler](#)
82 [\(2020\)](#) use a GMM approach to examine mainly the long-run impact of innovation on carbon
83 emissions, our study uses an ARDL model to explore both the short and the long-run impacts
84 of environmental innovations, the consumption of renewable energies, GDP per capita, and
85 degree of economic openness on the environmental quality. Compared to other methods of co-
86 integration, ARDL has many advantages: (i) it provides valid results on whether the variables
87 are I(0) or I(1) or mutually co-integrated and provides very consistent and efficient results in
88 large or small samples; (ii) it allows for capturing the data generation process from a general
89 modeling framework by including a sufficient number of lags; and (iii) it is most appropriate
90 technique in the case of a small sample size, which is the case of our study ([Pesaran et al.,](#)
91 [2001](#)). Furthermore, and in contrast to the [Töbelmann and Wendler \(2020\)](#) study, we chose to
92 focus on a panel of 15 countries for two main reasons: (i) these 15 countries are the richest and
93 invest the most in green innovations, and (ii) for the other EU countries, data on green
94 innovations are generally missing, and even when they are found, they are of poor quality. Since
95 studies on this subject are rare, our study provides new insights that enrich our knowledge on
96 the impact of environmental innovation and inform policies on the role that innovation could
97 play in reducing greenhouse gas emissions.

98 The rest of this study proceeds as follows. Section 2 is devoted to reviewing the literature on
99 the drivers of CO₂ emissions. The following section presents the data and methodology. Section
100 4 discusses the results and section 5 draws the conclusions and provides some policy
101 implications.

102

103 **2. Key Determinants of Carbon Emissions**

104 Since the pioneering work of [Grossman and Krueger \(1991\)](#), who introduced EKC⁴, a growing
105 body of work on the drivers of CO₂ emissions has developed in recent decades ([Lean and](#)
106 [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.

107 degree of economic openness (Hu et al., 2018; Piaggio et al., 2017; Grossman and Krueger,
108 1991), the rate of urbanization (Wang et al., 2019), the structure of the productive apparatus
109 (Du et al., 2019), the level of wealth (Esteve and Tamarit, 2012; Dinda and Coondoo, 2006;
110 Kuznet, 1955), technological innovation (Yii and Geetha, 2017), and the energy structure
111 (Cheng et al., 2018) are the main variables usually used to explain CO₂ emissions. More
112 recently, the work of Zhang et al. (2016) recognizes the critical role of green technologies in
113 reducing CO₂ emissions. However, this research is still limited and far from reaching a
114 consensus. Indeed, some studies (Acemoglu and Gancia, 2012; Jaffe et al., 2002) admit that the
115 effects of green technologies (positive or negative) on CO₂ emissions depend on the country's
116 wealth and the time of the impact (short vs. long-term). The existence of short-term rebound
117 effects⁵ (Braungardt et al., 2016) is particularly noticeable in technologies e.g. fuel (Belaid et
118 al., 2019; Font et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007), and this contributes to the
119 debate on the effect of green technologies on CO₂ emissions. Similarly, the findings of Weina
120 et al. (2016) in the Italy-wide study points to the extent to which environmental innovations
121 increase environmental productivity, but do not reduce CO₂ emissions.

122 These various studies on the determinants of CO₂ emissions highlight the important work that
123 remains to be done to untangle the spectrum of the sustainability process, particularly when it
124 comes to environmental innovations. From policy perspectives, the results of such analysis
125 would constitute a strategic tool to better guide public policies aimed at achieving climate
126 objectives. This is one of the major contributions of our study. This original contribution stems
127 from the multidimensional analysis and investigating some of the nuances that are often
128 overlooked in the current economic and policy debate. Despite the growing emphasis on the
129 localized nature of environmental innovations, our understanding of its effects
130 on environmental quality enhancement remains limited. Indeed, environmental innovations are
131 the subject of little research, both in terms of empirical work on the geography of innovation
132 and on the analysis of the determinants of CO₂ emissions (Du et al., 2019; Autant-Bernard et
133 al., 2010). In this context, the specificities of environmental innovations are poorly studied,
134 even less so when it comes to studying the impact of environmental innovations on carbon
135 emissions.

136 This article examines the effects of green technologies on carbon emissions in EU countries.
137 Based on the work of Du et al. (2019), we use CO₂ emissions as a proxy for carbon emissions
138 performance. The explanatory variables are based on the literature findings including
139 environmental innovations and three control variables namely the consumption of renewable
140 energy, GDP per capita, and degree of economic openness.

141

142 *2.1 Environmental Innovations*

143 The patent is an indicator of technological innovation insofar as it captures the R&D activity
144 carried out within firms (Griliches, 1990). Patents filed in environmental technologies are a
145 relevant indicator for approximating environmental innovations. Although many studies have
146 analyzed the effects of environmental innovations on CO₂ emissions, research is still limited
147 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.

148 Italian provinces, shows that environmental technologies have no significant effect on reducing
149 CO₂ emissions, although they increase environmental productivity. However, a recent study by
150 Du et al. (2019), using a panel of 71 countries for the 1996-2012 period, demonstrates that
151 [environmental innovations make a significant contribution to lowering CO₂ emissions,](#)
152 [especially in countries with high-income levels.](#) Other studies underline the existence of a short-
153 term rebound effect especially for environmental technologies related to energy efficiency and
154 transportation (Font Vivanco et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007). Braungardt
155 et al. (2016) examined the impact of energy-efficient innovations on electricity demands for
156 residents across the 27 EU countries. They found that innovations in energy efficiency
157 contribute to better energy efficiency, which tends to limit CO₂ emissions. They also claim that
158 it is essential to combine measures to reduce the rebound effect with the policy measure to
159 promote developing residential energy-efficiency innovations.

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

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

178

179 *2.2 Renewable Energy Consumption*

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

192 developing countries (Liu et al., 2017; Kahia et al., 2016). Thus, renewable energy consumption
193 contributes to the achievement of green growth objectives.

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

196

197 *2.3 GDP per Capita*

198 Following the work of Kuznet (1955), numerous empirical studies have examined the impact
199 of economic growth on carbon emissions to test EKC's validity. Grossman and Krueger's
200 (1991) study empirically examined the association between the level of air quality and
201 economic growth in many cities around the world. They demonstrate that starting from a certain
202 income level or when a certain stage of development is reached, economic growth makes it
203 possible to reduce environmental damage by moving from a polluting industrialized economy
204 to a tertiary cleaner economy. This is particularly relevant to investments in cleaner
205 technologies and the increased environmental awareness, which are the consequence of the
206 improvement in the living conditions of individuals. Although a large body of the literature has
207 tested EKC, consensus is yet to be attained (Ridzuan, 2019). There are mixed results on the
208 association between income inequality and the environment, with reports of positive, negative,
209 and no significant relationship⁶. Berthe and Elie (2015) claim that this heterogeneity in the
210 findings is largely related to the endogenous variables mobilized and no clear trend has been
211 identified for carbon emissions, air, and water pollution. Many of the existing empirical results
212 are in line with studies (Wilkinson and Pickett, 2010; Magnani, 2000; Boyce, 1994), which
213 recognizes that income level negatively affects the environment quality.

214 In this study, we focus on the impact of income level rather than income inequality. Indeed,
215 despite the divergent results in the literature on the supposed impact of income levels on the
216 quality of the environment, we should be reminded that the EC's long-term strategy to move
217 towards a carbon-free economy by 2050 (EC, 2018) places the decoupling⁷ of economic
218 prosperity from resource consumption (UNEP, 2016) as a cornerstone instrument. This strategy
219 also assumes that an increase in GDP leads to an increase in the consumption of resources and
220 energy, which is a source of environmental degradation (Crane et al., 2011). Moreover, Global
221 Footprint Network data⁸ shows that disparities in people's ecological footprints are strongly
222 related to the level of development of their countries. For example, in 2016, the lifestyle of
223 North Americans required 4.95 planets compared to 2.8 for Europeans and 0.83 for Africans.
224 This suggests that GDP per capita growth can increase CO₂ emissions over the long term.

225 ***Hypothesis 3.*** The growth of GDP per capita contributes to the increase in carbon
226 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 refereing 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/>

227 2.4 International Trade Openness

228 The degree of economic openness makes it possible to measure the dynamics of a country's
229 international trade. Increasing globalization trade flows over the last two decades have fuelled
230 emerging literature that analyses the effects of international trade on carbon emissions
231 performance. Theoretically, international trade has been claimed as one of the drivers that
232 stimulate economic growth by increasing the size of the market, facilitating specialization and
233 efficiency in the distribution of resources, promoting international transfers of technology and
234 knowledge, increasing competition, and improving governance (Grossman and Helpman, 1995;
235 Barro and Lee, 1994; Edwards, 1989). However, these same mechanisms can also affect the
236 quality of the environment through three main effects. First, the so-called scale effect offers
237 companies opportunities to explore larger markets, which in turn increases the level of
238 production and significantly affects CO₂. Secondly, the impact can be intensified by the so-
239 called structure effect (specialization) which implies a better allocation of resources and higher
240 productivity. This effect implies that rich countries tend to focus on capital-intensive industries
241 (labour intensity). Thus, the hypothesis of pollution havens suggest that countries with strict
242 environmental regulations (vs. Laxists) may have to specialize in clean industries (vs. pollution
243 generators), when environmental standards differ. In general, products that produce the most
244 pollution are capital-intensive. Advanced economies have a high capital endowment, but strict
245 environmental policies. The effects of international trade suggest that strict policies would
246 impose pollution-intensive production on developing countries to bear the burden of pollution
247 in advanced economies (Copeland and Taylor, 2013). Thirdly, the so-called technology effect
248 implies that international trade promotes access to more environmentally friendly production
249 technologies, encourages the race for environmental standards and regulation, and encourages
250 countries to use more efficient technologies. These different behaviors reduce CO₂ emissions
251 (Thoenig and Verdier, 2003).

252 On the side of the empirical literature, the results are particularly mixed⁹. Antweiler et al. (2001)
253 found that liberalizing trade reduces carbon emissions. Earlier studies (Frankel, 2005; Cole,
254 2004; Cole and Elliott, 2003) questioned this positive effect and used different types of
255 pollution emissions. These doubts are confirmed by several studies (Aklin, 2016; Kozul-
256 Wright, 2012; Ang, 2009; Dean, 2002), demonstrating that CO₂ emissions increase as a result
257 of trade openness. On the contrary, other studies (Kearsley and Riddel, 2010; Kellenberg, 2008;
258 Prakash, 2006) demonstrated that openness in international trade is not associated with
259 increasing CO₂ emissions. Finally, empirical evidence (e.g. Baek et al., 2009; Managi et al.,
260 2009) suggests that openness in international trade tends to benefit the environment of advanced
261 economies (OECD members).

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

⁹ For a review see Kim et al. (2019).

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

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

274 3. The Study Method

275 3.1 Data

276 The variables used in this study are carefully selected based on the availability of data and
 277 economic theory (Du et al., 2019; Su and Moaniba, 2017). We use the annual data for the period
 278 (1991-2014) for the EU-15 countries¹⁰: Austria, Belgium, Denmark, Finland, France, Germany,
 279 Greece, Spain, Spain, Ireland, Italy, Luxembourg, the Netherlands, Portugal, the United
 280 Kingdom, and Sweden.

281 Our dependent variable is CO₂ emissions (expressed in metric tons per capita). In this study,
 282 we rely on the work of (Du et al., 2019; Su and Moaniba, 2017) using patent data - ‘technologies
 283 related to the environment’ - to approximate environmental innovations (INNOV). The
 284 aggregated category of these technologies includes climate change technologies, water-related
 285 adaptation technologies, and environmental management technologies. Control variables
 286 include the share of renewable energy in the total consumption level. The latter is used as a
 287 proxy for the renewable energies consumption (REC) and represents a composite variable of
 288 consumption of solar, hydroelectric, geothermal, biomass, and wind energy in the total energy
 289 consumed. Other determinants include per capita of Gross Domestic Product (GDP) (US \$),
 290 and the degree of economic openness (OPEN) measured as the sum of imports and exports as
 291 a percentage of GDP. With the exception of patent data (OECD database)¹¹, all variables were
 292 extracted from the World Bank Group Development Indicator Database¹². Descriptive statistics
 293 of the variables used in our model are shown in Table 1.

294

295 Table 1. Descriptive Statistics.

	CO₂	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
Minimum	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

296 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>

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

303

304 *3.2 Empirical Model and Estimation Procedure*

305 In line with the recent literature on the drivers of CO₂ emissions, we develop an empirical model
 306 that takes the following form:

$$307 \quad CO2 = f (INNOV, REC, GDP, OPEN) \quad (1)$$

308 Where CO₂ represents CO₂ emissions, and is a function of four variables: environmental
 309 innovations (INNOV), renewable energy consumption (REC), GDP per capita (GDP), and the
 310 degree of economic openness (OPEN).

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

$$313 \quad LogCO2_{it} = \alpha_0 + \alpha_1 LogCO2_{it-j} + \alpha_2 LogINNOV_{it} + \alpha_3 LogREC_{it} + \alpha_4 LogGDP_{it} + \\ 314 \quad \alpha_5 LogOPEN_{it} + \varepsilon_{it} \quad (2)$$

315

316 Where the subscript i (i = 1, ..., N) indicate the country i in our sample, N is equal to 15. t (t =
 317 1, ..., T) indicates the time period. Our panel constitutes 15 countries and 24 years. The variables
 318 are not stationary at I(0) but they are probably at I(1). This means that the model is dynamic
 319 and considers inclusion of lagged dependent variables as a regressor. As suggested by Pesaran
 320 and Smith (1995), ARDL model is more appropriate because it has advantages over other
 321 dynamic model GMM estimators, fixed effects, or instrumental variables (Arellano and Bover,
 322 1995). Unless the coefficients are the same across countries, these methods produce
 323 inconsistent estimation. On the other hand, the ARDL model is relatively more efficient in small
 324 t and finite sample sizes. The model has a form of an ARDL (p, q, q....q) model:

$$325 \quad LogCO2_{it} = \sum_{j=1}^p \alpha_{ij} LogCO2_{i,t-j} + \sum_{j=0}^q \delta'_{ij} X_{i,t-j} + \mu_i + \varepsilon_{it} \quad (3)$$

326 Reparametrising the model, it becomes:

$$327 \quad \Delta LogCO2_{it} = \Phi_i (LogCO2_{i,t-1} - \beta'_i X_{i,t}) + \sum_{j=1}^{p-1} \alpha_{ij} \Delta LogCO2_{i,t-j} + \\ 328 \quad \sum_{j=0}^{q-1} \delta'_{ij} \Delta X_{i,t-j} + \mu_i + \varepsilon_{it} \quad (4)$$

329 Where:

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

- 334 • $\alpha_{ij}, \delta'_{ij}$ are the short-run dynamic coefficients;
- 335 • p et q are optimal lag orders¹³ ; and
- 336 • μ_i is the constant.

337 We note that, ε_{it} , which is the random disturbance term, is homoscedastic (i.e. constant
 338 variance), serially independent, and normally distributed. The specified model in equation 3 is
 339 a particular class of error correction models, which enable the coefficients to fluctuate among
 340 units. The Pesaran's Pooled Mean Group estimator (MG) is consistent to estimate this model
 341 (Pesaran and Smith, 1995; Pesaran et al., 1999). In the case the long-run parameters are
 342 homogeneous across groups, the Pooled Mean Group (PMG) estimator (Pesaran et al., 1999)
 343 will be more efficient. However, this approach is appropriate only if the factors are integrated of
 344 order zero (I(0) or one (I(1); and this approach is suitable to both small or large samples.
 345 Further, we will display the unit-root tests, the cointegration test, i.e. whether a long-term
 346 relationship exists between the factor, and panel model estimates.

347 3.2.1 Unit Roots Test

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

353 Table 2. Unit roots test.

Variables	CADF		LLC		IPS	
	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***

354 Notes: *** denotes significance at 1% level

355 From the results of ADF, IPS, and LLC unit root tests, it appears that the variables are integrated
 356 of order I(0) or I(1). Specifically, in level, the results of the unit root test (LLC) obtained
 357 indicate that LogINNOV, LogOPEN and LogGDP are stationary in I(0). Unit root tests in the
 358 first difference indicate that all variables are integrated in I(1). The variables' statistics are
 359 significant at the 1% level. The null hypothesis can be rejected when these variables are
 360 stationary. Thus, we use a mixture of I(1) and I(0) to estimate an ARDL model. Next, we
 361 perform the cointegration test to show whether a long-term relationship exists between CO₂
 362 emissions, environmental innovations, consumption of renewable energies, GDP per capita,
 363 and degree of economic openness.

364 3.2.2 Cointegration test

365 We tested the variables cointegration with Pedroni's (2004) test. This approach is based on
 366 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)

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

369

370 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

371 Notes : *** denotes significance at 1% level

372 The cointegration results indicate that PP-Statistics panels; ADF Statistics and Group PP-
 373 Statistics are significant allowing to reject the null hypothesis of no cointegration, suggesting
 374 that there is long-term co-integration between the determinants considered in our empirical
 375 model. Note that the PP-Statistics and PP-Statistics groups have the best properties. At a 1%
 376 threshold, we reject the null hypothesis with no cointegration by the PP-Statistics panel and PP-
 377 Statistics group. These results confirm that a cointegration association exists between the series
 378 under study, which gives the possibility of estimating the long-term effects of LogINNOV,
 379 LogREC, LogOPEN, and LogGDPH on Log CO₂.

380

381 4. ARDL Results

382 Using the Pooled Mean Group (PMG), the results of the estimates are presented in Table 4
 383 highlighting the long-term and the short-term equilibrium for the entire sample. Table 4. Panel
 384 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

385 Dependent variable D(log CO₂); Level of significance *** p<0.01, ** p<0.05, * p<0.1

386

387 4.1 Long-term Effect

388 The results indicate that all variables have long-term effects. Environmental innovations
389 (LogINNOV) has a significant and negative effect on CO₂ emissions. More specifically, over
390 the long-term, a 1% increase in patent filings in environment-related technologies contributes
391 to a 0.12% decrease in CO₂ emissions. This result is in line with the findings of Du et al. (2019)
392 on a sample of 71 countries. These results are also consistent with Braungardt et al.'s (2016)
393 findings from a sample of 27 EU countries.

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

398 For their part, variables approximating degree of economic openness (LogOPEN) and GDP per
399 capita (LogGDP) show significant and positive effects on CO₂ emissions. More specifically,
400 over the long-term, an increase of 1% in international trade openness (LogOPEN) and GDP per
401 capita (LogGDP) contributes respectively to an increase of 0.22% and 0.15% in CO₂ emissions.
402 The negative impact of economic openness on CO₂ emissions is contrary to the results of earlier
403 empirical studies (Baek et al., 2009; Managi et al., 2009) emphasizing that liberalization of
404 trade in developed economies can be beneficial for the environment. These results, however,
405 are in line with previous studies (Aklin, 2016; Ang, 2009; Dean, 2002; Kozul-Wright, 2012)
406 suggesting that CO₂ emissions increase due to increased trade openness. This result could be
407 explained by the effect of scale and structure.

408 Finally, EKC's hypothesis is not validated in the case of our sample. In fact, the rise in GDP
409 per capita tends to increase the deterioration of the environment (CO₂ emission). This result
410 appears to be consistent with the theoretical analyses (Boyce, 1994; Magnani, 2000; Wilkinson
411 and Pickett, 2010) suggesting that income inequality has a negative effect on the environment.
412 Wilkinson and Pickett (2010) argue that, in developed countries, this is largely due to
413 consumerist and individualistic behavior. In the EU, the significant increase in GDP per capita
414 over the studied period (1990-2014) was accompanied by a serious social crisis (Turquet, 2015),
415 which tends to amplify income inequalities. In this context, public policies focus more on
416 economic growth than on the protection of the environment (Magnani, 2000), and individuals
417 seem to focus more on improving their economic situation than the environment.

418

419

420 4.2 Short-term Effect

421 Short-term dynamics modeling provides information on how adjustments are made between
422 different determinants to restore long-term equilibrium. The ECT captures this relationship with
423 a coefficient indicating the speed of adjustment, i.e. the rate at which the system returns to
424 equilibrium after an impact. A long-term relationship exists if the sign of the coefficient of the
425 ECT is significantly negative and varies between -1 and -2. As shown in Table 4, we note that
426 the estimated coefficient for the ECT is significant and negative (-0.33) at the 1% threshold,
427 which indicates the existence of a long-term relationship. The rebound effect is observed in the
428 short-term through the impact of the variable (LogINNOV), which has a significant and positive
429 effect at the 1% level. In other words, environmental innovations tend to increase CO₂
430 emissions in the EU-15 countries in the short-run.

431 Nevertheless, these results suggest the existence of a possible rebound effect, which is a
432 behavioral response to an improvement in energy efficiency. One of the rational explanations
433 for this failure is that the increased energy efficiency does not necessarily translate into a
434 corresponding decrease in the environmental quality in absolute terms (Belaïd et al., 2018;
435 2020; Bureau et al., 2019). Various microeconomic studies on the rebound effect show that
436 income and substitution effects help explain how the rebound effect influences users' attitudes
437 and behaviors. The rebound effect has occupied an increasingly important place on the agenda
438 of policy makers since the early 1980s, but it has its origins in the seminal work of Jevons
439 (1865). Davis et al., (2014) found that a replacement program for air conditioners and
440 refrigerators in Mexico increases electricity consumption. Sorrell (2007) and Vivanco et al.
441 (2016) show that, in the case of Europe, the rebound effect is particularly noticeable for green
442 technologies related to energy efficiency and the transport sector. The effect of the consumption
443 of renewable energies (LogREC) remains unchanged (significant and negative at the 1%
444 threshold) in the short-term and again tends to contribute to a reduction of CO₂ emissions. The
445 degree of economic openness has no effect in the short-term. Lastly, GDP per capita (LogGDP)
446 has a positive impact on CO₂ emissions.

447

448 5. Conclusions and Policy Implications

449 Actions in favor of the climate are imperative today. Environmental innovations can play a key
450 role in the green transition of economies. At the EU level, stylized facts show an inverse
451 relationship between CO₂ emissions and patenting of environmental technologies. According
452 to OECD data, CO₂ emissions tend to decrease (-26%) over the period 1990-2014, while at the
453 same time patent filings of these technologies have not stopped growing (+209% in the same
454 period). This phenomenon is also geo-localized and particularly noticeable in a few countries
455 such as Germany, France, and the United Kingdom. Despite these stylized facts, the empirical
456 work to examine the effects of environmental technologies on carbon emissions is still limited.
457 Indeed, environmental innovations are the subject of little analysis both in terms of empirical
458 work relating to the geography of innovation and those relating to the analysis of the
459 determinants of CO₂ emissions. This study attempts to contribute to filling this important gap
460 by examining the effect of green technologies on CO₂ emissions of 15 EU countries using an
461 ARDL model.

462 We estimated an ARDL model from the PMG estimator to examine the effects of environmental
463 innovations, renewable energy consumption, GDP per capita, and the degree of economic
464 openness on CO₂ emissions. Our main results show that: in the long-term, environmental
465 innovations tend to lower CO₂ emissions, whereas in the short-term the observed effect is the
466 opposite, suggesting the existence of a rebound effect. These results are in line with previous
467 studies (Vivanco et al., 2016; Herring and Sorrell, 2009; Sorrell, 2007), which underline the
468 existence of a short-term rebound effect in EU countries. Moreover, the consumption of
469 renewable energy (long and short-term) tends to lower CO₂ emissions in Europe. An analysis
470 of country specificities would be relevant in order to observe the persistence of this
471 phenomenon at the country level. Indeed, the energy mix and the decarbonization strategies of
472 electricity production tend to increase the CO₂ emissions. In France, for example, nuclear
473 energy accounts for nearly 71.6% of electricity production. However, according to the Réseau
474 de Transport d'Électricité, the massive investment in solar panels paradoxically increases CO₂
475 emissions in France as photovoltaic panels emit nearly 3 times more CO₂ than nuclear energy
476 (considered as carbon-free energy). Finally, economic openness and GDP per capita have
477 significant and positive effects on CO₂ emissions. The results of trade openness are in line with
478 previous work (Aklin, 2016; Ang, 2009; Dean, 2002; Kozul-Wright, 2012), which shows that
479 increased trade openness increases CO₂ emissions. This result could be explained by the effect
480 of scale and structure. Also, the rise in GDP per capita tends to increase the deterioration of the
481 environment (CO₂ emission). This result appears to be consistent with prior studies (Wilkinson
482 and Pickett 2010; Magnani, 2000; Boyce, 1994), recognising that income inequality negatively
483 affects the environment.

484 In light of these results, several public policy orientation can be suggested. First, public
485 environmental policies tend to revolve around a combination of several political instruments.
486 These include, on the one hand, economic instruments focused on the price signal and the
487 polluter pays principle (within this framework, there are instruments such as environmental
488 taxation, incentives or dissuasive, and policies that provide significant support for green
489 technologies). On the other hand, environmental policies incorporate instruments of a
490 regulatory nature and focused on supporting individuals towards profound changes in their
491 consumption and production patterns. The theoretical basis of the later instruments is based on
492 work in ecological economics claiming that the earth is a finite space and that everyone is
493 responsible for preserving it. Policy makers find it difficult to balance these different
494 instruments in order to guarantee the most efficient environmental policy possible. In relation
495 to our results on the effect of environmental innovations on long-term CO₂ emissions, it appears
496 that green technologies constitute one of the solutions to favor the fight against global warming
497 because of their resilience capacity. However, the short-term effects, on the contrary, the
498 increase in CO₂ emissions caused by environmental innovations signal the extent to which it is
499 necessary to support using these technologies through education and access to information. This
500 can lead to perverse effects such as the rebound effect observed in this study. Sorrell (2010)
501 claims that the rebound effects raise the question of the effectiveness of energy efficiency
502 policies given the behavioral responses that tend to reduce the scale of energy savings. Thus,
503 measures other than prices must be considered by policy makers to limit the rebound effect.
504 Specifically, it is imperative to encourage individuals to consume more effectively by reducing
505 the environmental effects of each product and/or service. New policies should encourage people
506 to consume differently by focusing on products and services that have less negative effect on

507 the environment. This would result in the purchase of greener products or increased spending
508 on services rather than manufactured goods.

509 The rise in CO₂ emissions brought about by the rise in GDP and degree of economic openness,
510 not to mention the plausible effects of irreversibility, the fragility of environments,
511 accumulation of pollutants in ecosystems, and exhaustion of stockpiles and energy motivates
512 the questioning the current model of economic growth. For proponents of the ecological
513 economy, the environment must be considered as the support of any human activity in which
514 the inputs are the capability of the environment to absorb waste and provide resources, and the
515 outputs (resulting) growth and development (Boutaud et al., 2006). Taking the principle of
516 ‘strong’ sustainability, there is a need to rely to a lesser extent on green technologies, and to
517 rely more on measures to accompany the structural changes deep in lifestyles of individuals to
518 deal with possible rebound effect. In practice, public decision-makers must focus their actions
519 on environmental policies of a green and inclusive economy that combine tools of
520 environmental economics with those of the ecological economy. This can be done by
521 associating economic incentives with regulatory changes that enable promoting individual
522 approaches focused on structural changes in lifestyles (e.g. the multitude of standards and labels
523 based on voluntary membership such as ‘eco-products’, initiatives for the ‘collaborative
524 economy’, among others).

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