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RESEARCH ARTICLE

CO_2 emissions, renewable energy, and environmental regulations in the EU countries

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Abstract
This paper analyzes the factors explaining the slight decrease of CO_2 emissions in the European Union (EU), recorded during the last period. With a focus on 12 EU countries, we apply a panel data analysis over the period 1990 to 2017 and we investigate the impact of renewable energy share in energy production, and the role of EU environmental regulations, in explaining the level of CO_2 emissions. Our static and dynamic panel data analysis points to a negative impact of an increased renewable energy share on CO_2 emissions, while there is no clear evidence about the role of environmental regulations. It appears that the 2020 climate and energy package contributed to the reduction of pollution level, while the ratification of the Kyoto protocol by the EU countries had no significant influence. At the same time, our findings validate the environmental Kuznets curve (EKC) hypothesis and the pollution halo (PH) hypothesis, showing that foreign companies export eco-friendly technologies. Our results prove to be robust regarding the use of static fixed and random effects models, of two-stage least square models and the use of difference and system generalized method of moments (GMM) frameworks.

Keywords CO_2 emissions · Environmental Kuznets curve hypothesis · Pollution halo hypothesis · Renewable energy production · Environmental regulations · Panel data analysis

JEL codes Q43 · Q56 · F21

Introduction

Starting with the 1992 “Earth Summit” in Rio de Janeiro, and afterwards with the Kyoto protocol agreed in 1997, developed countries committed to act against climate change and decided to reduce the greenhouse gas emissions, including CO_2. The European Union (EU) behaved as a world leader in this area and implemented different climate and energy legislative packages and environmental regulations to reach the agreed targets in greenhouse gas emissions. Against this background, several questions remain unanswered in the environmental economics literature: Are the environmental regulations of the EU efficient enough to ensure a reduction of CO_2 emissions? Does the increase of renewable to total energy production ratio explains the slight decrease in CO_2 emissions recorded by the EU during the last period? Can the classical environmental Kuznets curve (EKC) hypothesis and the pollution haven hypothesis (PHH) be validated in the case of the EU, or is the new pollution halo (PH) hypothesis better explaining the situation? The purpose of this paper is to find answers to these questions, resorting to a panel data analysis for selected EU countries, over the period 1990 to 2017.

The theories explaining the determinants of CO_2 emissions (a proxy for the level of greenhouse gas emissions and pollution in general) can be roughly classified in theories addressing the role of economic development and theories addressing the role of international factor movements. In the first case, the EKC theory advanced by Kuznets (1955) shows that the level of pollution increases with the level of per capita income, and decreases if the per capita income is sufficiently high. Holtz-Eakin and Selden (1995) empirically demonstrated the inverted U-shaped relationship between CO_2 emissions and individual income,

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while Stern (2004) brings further clarifications, stating that slow progresses and efforts to reduce pollution in developed countries can overcome the scale effects of economic growth, which put into question the validation of this theory in the case of developed countries. In the second case, the PHH theory investigates the environmental impact of foreign direct investments (FDI) on the host country pollution level. According to this view, the weak environmental policies implemented by developing countries determine multinational companies to invest there and thus to obtain comparative advantages in the production pollution-intensive goods (Copeland and Taylor 1994). However, if the opposite applies and foreign companies implement eco-friendly technologies, the environmental impact of FDI is positive (Hubler and Keller 2010). In this case, we talk about the pollution halo (PH) hypothesis, recently validated by Zhang and Zhou (2016), who show that FDI have a favorable regional impact on CO_2 emissions in China. In the same line, Eskeland and Harrison (2003) argue that US firms are energy efficient and find evidence in the favor of PH hypothesis for Mexico.

Starting from the arguments by Stern (2004), the EKC might be put into question in the case of EU countries where the level of income per capita is high. This is also the case of the PHH, given the common environmental regulations implemented by EU member states. Therefore, our first contribution to the existing literature is represented by the investigation of the factors explaining the reduction in CO_2 emissions in the EU,[1] going beyond the classical theories, and looking to the role of environmental regulations and the increased share of renewable energy to total energy production. We investigate therefore the effect of two legislative packages related to climate change, namely the ratification of the Kyoto protocol in April 2002, with the subsequent legislation, and the independent EU commitment to reduce overall greenhouse gas emissions by 20% compared with 1990 levels. This commitment which generated a package of legislative measures (the 2020 climate and energy package) agreed before the Copenhagen Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in December 2009. Afterwards, we look to the role of renewable energy production in explaining the decrease of CO_2 emissions in the EU. The Enerdata Global Energy Statistical Yearbook provides information about the share of renewable energy production to total energy production for 12 EU countries over the period 1990 to 2017.[2] Further, we explore the channels through which the environmental regulations might contribute to better climate conditions. Using a series of interaction dummy variables, we investigate to what extent the environmental regulations for the reduction of total energy consumption and the promotion of renewable energy sources influence CO_2 emissions.

A second contribution of our paper is represented by an investigation of the environmental and climate change EU regulations, to better understand how these regulations contribute to assumed greenhouse gas emission targets. Third, we investigate the determinants of CO_2 emissions but also the determinants of CO_2 intensity and we therefore consider in our analysis the role of the business cycle. To this end, we use both static and dynamic panel data models to deal with the heteroscedasticity and potential endogeneity effect between CO_2 emissions and FDI underlined by the previous literature (i.e., Bao et al. 2011; Apergis and Ozturk 2015; Sapkota and Bastola 2017).

To preview our findings, we discover that both the EKC and PH hypotheses are validated for the selected EU member states. While the increase share of renewable energy production has a marginal but significant contribution to the reduction of CO_2 emissions, the impact of environmental regulations shows for the moment mixed evidence. It appears that the 2020 climate and energy package has a reduced contribution to the decreasing trend of CO_2 emissions, but the ratification of the Kyoto protocol in 2002 had no significant influence.

The "Related literature" section of the paper presents the literature review on the determinants of CO_2 emissions. The "EU environmental and climate change policies and regulations: a review" section analyzes the EU environmental and climate change regulations and underlines the potential channels by which the targets in greenhouse gas emissions can be reached in the EU countries. The "Data and methodology" describes the data and the methodology. The "Empirical results" section presents the main empirical findings, while the "Robustness check analyses" section addresses the robustness checks. The last section concludes our findings.

Related literature

The EKC hypothesis represents one of the key focuses of environmental economics. The reference study by Holtz-Eakin and Selden (1995) shows that the relationship between pollution and income follows an inverted U-shaped pattern. Starting from that moment, a considerable amount of papers investigates the existence of EKC, especially in the case of developing countries. Early studies document, in general, the existence of an inverted U-shaped relationship. For example, Selden and Song (1994) perform a global-level investigation considering emissions of four important air pollutants. Their

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[1] Figure 1 (Appendix) presents the trend of CO_2 emissions in the EU, using World Bank statistics. We can notice a decrease of CO_2 emissions starting with the 1980s, while the reduction of CO_2 emissions accelerated starting with the 2000s, when the EU legislative packages for climate change enter into force. At the same time, the CO_2 intensity (CO_2 emissions to GDP ratio) continued to decrease starting with the 1970s.

[2] Tiwari and Albulescu (2016) raised a series of questions about the use of Energy Information Agency (EIA) data for the renewable energy share because the renewable to total energy ratio is incredibly high for a series of countries. Therefore, we prefer to use Enerdata for the renewable share, although these data cover only 12 EU countries.

cross-national panel analysis reveals the existence of an inverted U-shaped relationship between all four pollutants and the GDP per capita. Similarly, Grossman and Krueger (1995) argue that environmental deterioration is affected in the initial phase by the economic growth, but in a second phase registers improvements. Representing a contrary point of view, Perman and Stern (2003) reject the EKC hypothesis altogether.

While most of the early papers validate the EKC theory, especially in the case of developing and emerging economies, the recent econometric progress allowed for a deeper understanding of the EKC hypothesis. In this line, Atici (2009) performs a panel data analysis for the period 1980 to 2002 for Bulgaria, Hungary, Romania, and Turkey and validates the EKC hypothesis. In the same spirit, Jalil and Mahmud (2009) employ time series data from 1975 to 2005 for China and find evidence for an inverted U-shaped relationship between CO_2 emissions and economic development. Similar results are reported by Nasir and Rehman (2011) for Pakistan, Shahbaz et al. (2013) for Romania, and Tiwari et al. (2013) for India.

More recent studies resort to more sophisticated techniques to investigate the EKC theory. While Apergis and Ozturk (2015) perform a panel data analysis and use a GMM approach to validate the hypothesis for 14 Asian countries spanning the period 1990–2011, Baek (2015) uses an autoregressive distributed lag (ARDL) modeling and finds little evidence for the EKC hypothesis in the case of Arctic countries, over the period 1960–2010. Relying on a similar ARDL model, Yang et al. (2015) underline in turn the fragility of the EKC theory for China. By contrast, Sapkota and Bastola (2017) show the existence of an inverted U-shaped relationship between CO_2 emission and the GDP per capita using a panel framework for the Latin American countries. Particularly interesting investigations are performed by Youssef et al. (2016) who reported a bi-directional relationship between economic growth and pollution for a panel of fifty-six countries, and by Shahbaz et al. (2017), who performed a historical, nonparametric analysis of the EKC, for the G7 economies.

With a focus on the EU countries, Ang (2007) investigates the case of France and verifies the inverted U-shaped EKC hypothesis. Similarly, Acaravci and Ozturk (2010) investigate the EKC hypothesis for nineteen European countries, using an ARDL specification. They report a long-run relationship between CO_2 emissions per capita and the GDP per capita.

The recent literature also focuses on the investigation of PHH, showing that weak environmental policies implemented by emerging economies favorize the inward FDI given that multinational companies might obtain a comparative advantage in the production of pollution-intensive goods (Copeland and Taylor 1994; Spatareanu 2007). On the contrary, if foreign companies introduce environmentally friendly production technologies, according to the PH hypothesis, FDI might contribute to the reduction of pollution level (Hubler and Keller 2010). Early studies find mixed evidence regarding the PHH-PH trade off. On the one hand, Carrada-Bravo (1995) validates the PHH for the Latin American countries. On the other hand, Eskeland and Harrison (2003) argue that US firms are more energy efficient compared with the Mexican ones and support the PH hypothesis. Mixed evidence is documented by Blanco et al. (2013) for 18 Latin America countries, over the period 1980–2007, who showed that the PHH is validated only in pollution-intensive sectors. Similar findings are reported by Seker et al. (2015) for Turkey, showing that the impact of FDI on CO_2 emissions in the long run is reduced.

Other studies document a bi-directional relationship between inward FDI and CO_2 emissions. Likewise, with a focus of different high-, middle-, and low-income countries, Shahbaz et al. (2015) prove the existence of a bi-directional causal relationship between CO_2 emissions and FDI, which is, however, sensitive to the level of income. In addition, Tang and Tan (2015) investigate the Vietnamese case for the period 1976–2009 and find a similar bi-directional relationship. The PHH is also validated by recent studies (e.g., Sapkota and Bastola 2017; Solarin et al. 2017), while other researchers (e.g., Zhang and Zhou 2016) find evidence for the PH hypothesis.

The recent studies use a large set of control variables to investigate the PHH and the EKC hypothesis, especially the panel-oriented analyses. While the energy consumption is largely used as a control variable (e.g., Acaravci and Ozturk 2010), other control variables are represented by trade openness and energy use per capita (Atici 2009), population density and human capital (Sapkota and Bastola 2017), land, industry shares in GDP, and quality of institutions (Apergis and Ozturk 2015). We include most of these variables in our investigation on the EU countries, and we pay a special attention to the role of environmental regulations and to the increased share of renewable energy in the total energy production.

Although the impact of environmental regulations on CO_2 emissions is barely investigated, there are some recent essays in this direction. Correspondingly, Zhao et al. (2015) perform a micro-level analysis on the role of environmental regulations on the efficiency and CO_2 emissions of power plants in China. They show that market-based regulations and government subsidies contribute to a reduction of CO_2 emissions. A similar study with a focus on the Chinese economy is conducted by Wenbo and Yan (2018), who posit that the nexus between environmental regulations on the one hand, and CO_2 emissions intensity on the other hand, follows a significant inverted U-shaped curve. In opposition, Niedertscheider et al. (2018) find no clear link between climate change policies in Australia and the decreasing trend of CO_2 emissions. Similar findings are reported by Ma et al. (2018) for influence of state regulations on CO_2 emissions in China's mining industry.

The investigation of renewable energy role in influencing CO_2 emissions also gained an increased interest during the last period and the empirical papers report mixed findings. In an analysis conducted over the period 1960 to 2007, Menyah and Wolde-Rufael (2010) state that renewable energy consumption does not cause CO_2 emissions in the sense of a Granger causality. In the same line, with a focus on Italy, Aliprandi et al. (2016) state that the impact of energy produced from renewable sources on CO_2 emissions is lower than expected. While Cherni and Jouini (2017) document the existence of a long-run relationship between CO_2 emissions, economic growth, and renewable energy consumption in Tunisia, their Granger causality analysis shows no relationship between CO_2 emissions and the renewable energy consumption. On the contrary, relying on an unbalanced panel approach of 128 countries over the period 1990 to 2014, Dong et al. (2018) show that the renewable energy intensity leads to a decline in the pollution level, for all analyzed regions. Chen et al. (2019) also document a long-run relationship between CO_2 emissions, GDP per capita, foreign trade, and non-renewable energy production in China. Similar findings are reported by Zoundi (2017) and Inglesi-Lotz and Dogan (2018) for African countries, and by Sinha and Shahbaz (2018) for India. As far as we know, there is no study investigating the role of renewable energy production on CO_2 emission in the EU countries. https://ec.europa.eu/eurostat/statistics-explained/index.php/Foreign_direct_investment_-_stocks#EU-28.27s_inward_and_outward_investment.

EU environmental and climate change policies and regulations: a review

The beginnings of the EU climate policy lie in the 1990s when the issue of climate change has been brought to international attention with the United Nations (UN) Conference on Environment and Development held in Rio de Janeiro from 3 to 14 June 1992. The main result of the summit was the agreement of the United Nations Framework Convention on Climate Change (UNFCCC). This international treaty is the cornerstone of the UN environmental conventions system. With its signing, the EU Council of the EC agreed to stabilize greenhouse gas emissions of the European Community at 1990 levels by the year 2000.[3] The UNFCCC was followed since by the Kyoto Protocol of 1997 and its continuation with the non-binding Copenhagen Accord of 2009, the legally binding Cancun agreement of 2010, the Durban Platform for Enhanced Action of 2011, and finally the Paris Agreement of 2015. The EU as such, beside its member states, has been a signatory of all the treaties named above, thus creating a separate and complementary commitment to the goals expressed in these conventions.

The EU climate policy truly started in 2000s with the adoption of the European Climate Change Program (ECCP) as a result of the Union's implementation of the Kyoto Protocol (the Kyoto Protocol's ratification by the EU member states ended in 2002). The work of experts within the ECCP resulted in the adoption in 2003 of the European Union Emissions Trading System (EU ETS)[4] which established a scheme for greenhouse gas emission allowance trading within the Union. The first phase (trading period) of the ETS (January 2005 to December 2007) was already operational before the entry into force of the Kyoto Protocol. The second phase (January 2008 to December 2012) coincided with the first commitment period of the Kyoto Protocol. The third phase began in January 2013 and will span until December 2020. In this context, we consider the year 2003 as a turning point in the EU environmental regulations.

In 2007, the European Council endorses "an EU objective of a 30% reduction in greenhouse gas emissions by 2020 compared with 1990."[5] The same Council adopted also accompanying targets for renewable energies and energy efficiency. The 2007 commitment led to the adoption, in 2009, of a legislation package, the so-called "Climate and Energy Package 2020," that consists of several Directives on emissions trading, carbon capture and storage, fuel quality, and renewable energy, as well as the regulation on CO_2 emission performance standards for cars. The 2009 package sets as goals the 20% cut in greenhouse gas emissions (from 1990 levels), obtaining 20% of EU energy from renewable sources and a 20% improvement in energy efficiency by 2020. Therefore, we consider in our analysis the year 2010 as an important point for the EU environmental regulations.[6]

Other recent steps were implemented by the EU for the reduction greenhouse gas emissions. Likewise, in October 2014, the European Council adopted the 2030 Climate and Energy Framework and endorsed a binding EU target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared with 1990. Following the 2016 signing by the EU of the Paris Agreement (which replaces the Kyoto Protocol), the European Parliament and the Council adopted

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[3] European Council, Presidency Conclusions—Dublin 25/26 June 1990, Annex II: The Environmental Imperative, Council of the European Union, SN 60/1/90, 1990.

[4] In 2004, the ETS was widened to incorporate the trading certificates of the so-called Kyoto flexible mechanism as compliance tools.

[5] https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/93135.pdf

[6] According to the EU Commission, the ETS is the EU's key tool for cutting greenhouse gas emissions from large-scale facilities in the power and industry sectors, as well as the aviation sector. The ETS covers around 45% of the EU's greenhouse gas emissions. In 2020, the target is for the emissions from these sectors to be 21% lower than in 2005. The sectors not included in the ETS account for 55% of total EU emissions and originate in housing, agriculture, waste, and transport (excluding aviation). The strategy overview of the Commission can be found at: https://ec.europa.eu/clima/policies/strategies/2020_en.

in 2018 a legislation package to implement the 2030 Climate and Energy Framework, relying on three pillars. The first pillar consists of Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by the member states from 2021 to 2030.[7] For the second pillar, the Parliament and the Council decided on the inclusion of greenhouse gas emissions and removals from land use, land use change, and forestry in the 2030 climate and energy framework.[8] Under this regulation, EU member states have to ensure that greenhouse gas emissions from land use, land use change, or forestry (LULUCF) are offset by at least an equivalent removal of CO_2 from the atmosphere in the period 2021 to 2030. As a third pillar of the 2030 framework, the ETS Directive was reviewed[9] in order to include and implement the 4th ETS trading phase from 2021 to 2030. At the end of 2018, the European Commission published a climate strategy proposal up to the year 2050.[10] The commitment to a climate neutral EU is the main goal for 2050, the Commission proposing that up to 25% of its yearly budget be allocated to this task.

We notice a sustained EU effort to reduce the level of pollution and to improve environmental and energy policies. One of the objectives of this paper is to see how effective these policies are in reduction of the CO_2 emissions.

Data and methodology

Data

The annual data for 12 EU countries[11] is extracted from the Enerdata database (2018 Global Energy Statistical Yearbook) and covers the period from 1990 to 2017 (324 observations). Our dependent variables are the CO_2 emissions ($MtCO_2$) from fuel combustion expressed in natural log (co_2em) and the CO_2 intensity (please refer to our third robustness check analysis), computed as the ratio between CO_2 emissions and GDP (co_2in). According to the EU Climate Policy[12], the CO_2 emissions represent more than 80% from the global greenhouse gas emissions, which shows the interest for investigating the CO_2 emission determinants.

The share of renewable in total electricity production (*renewable*) represents the first interest variable[13]. Second, we investigate the role of EU environmental regulations, whose effects are captured using two regulation dummy variables namely *dummy*2003, which takes value 1 after the ratification of the Kyoto protocol by the EU member states, and *dummy*2010 that takes value 1 starting with 2010, when the EU started the implementation of the 2020 climate and energy package. For robustness purposes, we also use a *dummy*2005 variable (instead of *dummy*2003). The reason is represented by the existence of a potential time delay for the effective entry into force of the Kyoto protocol, after the EU ETS adoption in 2003. In fact, the first phase of the ETS called "trading period" started only in 2005.

In a subsequent analysis, we explore the channels through which these regulations might contribute to a reduction in CO_2 emissions. On the one hand, the regulatory effect may stimulate the renewable energy production and we capture this effect using interaction dummy variables ($dummy \times rnw$) between regulations dummy (*dummy*2003/*dummy*2005,-*dummy*2010) and renewable to total energy production ratio (*renewable*). On the other hand, the regulation may act in the favor of the reduction of the total energy consumption and we investigate this channel resorting to a second category of interaction dummy variables ($dummy \times tec$) between regulations dummy and total energy consumption, and between regulations dummy and energy intensity ($dummy \times ei$).[14]

The set of control variables starts with the income (*gdp*), calculated in terms of GDP per capita in 2010 constant US$ (World Bank Development Indicators). If the *gdp*-estimated coefficient is positive and significant, while the coefficient of gdp^2 is negative and significant, then the EKC hypothesis is validated. The second control variable is the inward foreign direct investment (data is extracted from the UNCTAD database). When we test the determinants of CO_2 emissions, we refer to the log of FDI stock in US$ (*fdi*1). When we test the determinants of CO_2 intensity for robustness purposes, we consider the FDI stock to GDP ratio (*fdi*2). In line with Sapkota and Bastola (2017) and Soytas et al. (2007), the remaining control variables refer to the following: (i) the total energy consumption (*tec*) and the energy intensity of GDP at

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[7] The Regulation lays down obligations on the member states with respect to their minimum contributions for the period from 2021 to 2030 to fulfilling the Union's target of reducing its greenhouse gas emissions by 30% below 2005 levels in 2030.

[8] Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change, and forestry in the 2030 climate and energy framework

[9] Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814, OJ Nr. L 76/3, 2018

[10] https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf

[11] Enerdata contains statistics for 12 EU countries namely Belgium, Czech Republic, France, Germany, Italy, Netherlands, Poland, Portugal, Romania, Spain, Sweden, and the UK.

[12] https://ec.europa.eu/clima/sites/clima/files/eu_climate_policy_explained_en.pdf

[13] Similar to Chen et al. (2019), we refer here to the renewable energy production and not energy consumption, given data availability of this indicator in Enerdata database. However, renewable electricity production and consumption are closely linked (Twumasi 2017).

[14] Table 13 (Appendix) presents the list of explanatory variables for the two type of estimations addressing the determinants of CO_2 emissions (main results) and of CO_2 intensity (robustness analysis).

Table 1 Summary statistics

	co_2em	co_2in	*renewable*	*gdp*	gdp^2	*fdi1*	*fdi2*	*tec*	*ei*	*gfcf1*	*gfcf2*	*popdens*	*unemp*
Mean	5.263	0.262	18.93	10.16	103.7	11.74	39.74	4.490	0.113	22.39	25.70	163.5	8.704
SD	0.877	0.143	15.76	0.639	12.51	1.942	32.02	0.806	0.038	3.636	1.057	131.7	4.167
Min	3.644	0.076	1.119	8.373	70.11	− 4.605	0.000	2.846	0.062	14.42	23.32	0.136	2.120
Max	6.862	6.862	63.29	10.94	119.8	14.27	199.7	5.871	0.262	33.91	27.33	508.5	26.09

co_2em, CO_2 emissions; co_2in, CO_2 intensity; *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *fdi2*, stock of inward FDI to GDP ratio; *tec*, total energy consumption in natural log; *ei*, energy intensity of GDP; *gfcf1*, gross fixed capital formation in natural log; *gfcf2*, gross fixed capital formation to GDP ratio; *popdens*, population density; *unemp*, unemployment rate

constant purchasing power parities (*ei*), whose effect on CO_2 emissions and CO_2 intensity, respectively, is expected to be positive; (ii) the investment measured in terms of gross fixed capital formation in 2010 constant US$ (*gfcf*1) and as GDP percentage (*gfcf*2) whose impact on CO_2 emissions/intensity is expected to be positive; (iii) population density calculated in terms of people per km^2 of land (*popdens*), with a positive impact on CO_2 emissions; and (iv) the unemployment rate (*unemp*), which may have either a positive impact on pollution if the governments allocate more financial resources for social adds and neglect the environmental issues (Lan et al. 2012), or a negative impact, if unemployment is associated with smaller revenues and smaller investments and consumption. These data are extracted from the World Bank database. Given the downward trend in the CO_2 emissions at EU level, our analysis also considers a linear time trend as explanatory variable (*time*). The general statistics are presented in Table 1[15] and show noteworthy disparities between countries, in terms of the share of renewable energy or population density. At the same time, the differences in terms of GDP per capita are much smaller.

In Table 2, we perform a series of panel unit root tests. In a preliminary analysis, we apply cross-sectional dependence tests to see in the first-generation or the second-generation panel unit root tests are recommended (first-generation tests are more powerful in the presence of cross-sectional independence).

However, because it is no clear evidence in the favor of cross-sectional independence (Frideman's and Frees's tests point in the favor of cross-sectional dependence), we present the results of the classic LLC test and Pesaran's CIPS test. Except for gross fixed capital formation to GDP ratio (*gfcf*2), population density (*popdens*), and unemployment rate (*unemp*), the pooled CIPS test of Pesaran (2007) shows that our variables are stationary. For these variables, however, the LLC test indicates the absence of unit root processes. Therefore, we conclude that our variables are stationary.

Methodology

To analyze the determinants of CO_2 emissions, we first resort to a fixed effect model that allows to avoid the omitted variable bias. We also run a random effect model to control for all stable covariates and we chose between these models performing a Hausman test. The general equations for the fixed (Eq. (1)) and the random (Eq. (2)) models are:

$$Y_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 Z_{i,t} + \alpha_i + \varepsilon_{i,t} \tag{1}$$

where Y_{it} is the dependent variable (*CO_2 emissions*, *CO_2 intensity*); X_{it} represents the vector of interest variables (*renewable* and environmental dummy variables); Z_{it} represents the vector of control variables; β_0 is the intercept; α_i represents all the stable characteristics of countries; β_1 and β_2 are the coefficients; $\varepsilon_{i,t}$ is the error term.

$$Y_{i,t} = \beta_0 + \beta_1 X_{i,t} + \beta_2 Z_{i,t} + \alpha_i + \mu_{i,t} + \varepsilon_{i,t} \tag{2}$$

where μ represents between-entity errors; $\varepsilon_{i,t}$ is the within-entity error.

However, an endogeneity bias may appear between CO_2 emissions and FDI. Foreign investors may not want to invest in a country that is already polluted because they risk paying higher environmental taxes in the future, or because their business model promotes a reduced carbon intensity (see for example Bao et al. 2011; Sapkota and Bastola 2017).[16] Therefore, in a second step, we perform an instrumental variable regression, verifying the presence of endogeneity (Wu-Hausman and Durbin-Wu-Hausman tests), and of disturbance heteroscedasticity (Pagan-Hall general test). If heteroscedasticity is present, we correct the bias using robust standard errors (see Baum et al. 2007). However, in this case, GMM models may perform better (Baum et al. 2003). Therefore, in the third step, we resort to a

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[15] We have also performed a series of panel unit root tests, which provide mixed evidence regarding the stationarity of our variables (these results can be provided by the authors upon request).

[16] An endogeneity bias may also appear in the case of unemployment rate (Lan et al. 2012) or renewable share in total energy production (Chen et al. 2019). In the empirical models addressing the endogeneity issues, we have considered the FDI as an endogenous variable. At the same time, we have performed all the computations considering FDI, unemployment, and renewable share as endogenous. Nevertheless, the results do not change and remain robust (these results can be provided by authors upon request).

Table 2 Cross-sectional dependence and panel unit root tests

Cross-sectional dependence tests								
	Pearson CD normal		**Friedman Chi-square**		**Frees normal**			
					Test	**10%**	**5%**	**1%**
Level	0.680	(0.496)	31.59	(0.000)	1.736	0.095	0.124	0.179
Panel unit root tests								
	Levin–Lin–Chu (first generation)		**Pesaran's CIPS test (second generation)**					
	t*	***p* value**	**CIPS**		**10%**	**5%**	**1%**	
co₂em	1.155	(0.876)	− 2.556		− 2.070	− 2.170	− 2.340	
co₂in	−3.206	(0.000)	− 2.319		− 2.070	− 2.170	− 2.340	
renewable	7.598	(0.990)	− 2.521		− 2.070	− 2.170	− 2.340	
gdp	− 3.115	(0.000)	− 2.184		− 2.070	− 2.170	− 2.340	
gdp^2	− 2.645	(0.004)	− 2.175		− 2.070	− 2.170	− 2.340	
fdi1	− 4.888	(0.000)	− 4.788		− 2.070	− 2.170	− 2.340	
fdi2	− 0.108	(0.456)	− 2.417		− 2.070	− 2.170	− 2.340	
tec	− 0.446	(0.327)	− 2.710		− 2.070	− 2.170	− 2.340	
ei	− 1.486	(0.068)	− 2.523		− 2.070	− 2.170	− 2.340	
gfcf1	− 1.967	(0.024)	− 2.159		− 2.070	− 2.170	− 2.340	
gfcf2	− 1.628	(0.000)	− 1.318		− 2.070	− 2.170	− 2.340	
popdens	− 1.745	(0.040)	− 1.412		− 2.070	− 2.170	− 2.340	
unemp	− 2.013	(0.022)	− 1.525		− 2.070	− 2.170	− 2.340	

(i) *p* values in brackets; (ii) Pesaran CIPS test with two lags; (iii) for the cross-sectional dependence tests, the null hypothesis is the existence of cross-sectional independence, (iv) for both unit root tests, the null hypothesis is the presence of unit root (non-stationarity)

dynamic GMM estimator, comparing the difference-GMM estimator proposed by Arellano and Bond (1991) with the system-GMM estimator advanced by Blundell and Bond (1998). Equation (3) describes the difference-GMM model:

$$\Delta \mathrm{Y}_{\mathrm{i,t}} = \beta_0 + \sum_{\mathrm{j=t-p}}^{\mathrm{t-1}} \theta_{\mathrm{j}} \Delta \mathrm{Y}_{\mathrm{i,j}} + \beta_1 \Delta \mathrm{X}_{\mathrm{i,t}} + \beta_2 \Delta \mathrm{Z}_{\mathrm{i,t}} + \Delta \mu_{\mathrm{i,t}} + \Delta \mathrm{u}_{\mathrm{i,t}} \tag{3}$$

where θ is the lagged-variable parameter and p is usually established to 1 (first lag); $u_{\mathrm{i,t}}$ is the error term which varies over both country and time.

Nevertheless, as in the case of the instrumental variable approach, for the difference-GMM estimator, the lagged levels of the explanatory variables might be considered poor instruments when the autoregressive process is significantly persistent (Albulescu and Tămăşilă 2016). If $\Delta Y_{i,\ j}$ is still correlated with $\Delta u_{i,\ t}$, the difference-GMM estimator cannot reach the best estimation. Therefore, to overcome this limitation, the Blundell and Bond's (1998) system-GMM estimator relies on a system of two simultaneous equations, one in level (with lagged first differences as instruments) and the other in first difference (with lagged levels as instruments).

Empirical results

We first present the results of the static analysis, comparing a fixed and a random effects model (Table 3). For each estimator, we test two models. Model 1 considers the environmental dummy variables. If we admit the impact of the environmental and climate change regulations on the CO_2 emissions, we explore that the channels throughout these regulations influence the pollution level, using the interaction dummy variables described above (Model 2).[17]

For the first model, we notice that the effect of renewable electricity share on the CO_2 emissions is significant and has the expected sign, but is marginal (result in agreement with that reported for Italy by Aliprandi et al. 2016). At the same time, it appears that the second set of environmental regulations, implemented starting with 2010, contributes in a significant way to the reduction of pollution. This result is documented for both fixed and random effect estimations, although according to the Hausman statistics, the random model performs better. In addition, the EKC hypothesis is validated, but also the PH hypothesis, meaning that foreign investors avoid the countries with a high level of CO_2 emissions given the polluter pays principle.[18] This result can be explained by the fact that multinational companies use eco-friendly

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[17] The low-order dummy variables of the interaction terms are included in Model 2 only if their coefficients are significant in Model 1.

[18] We do not consider here the FDI structure. Nevertheless, these results are not surprising given the fact that in 2010, for example, the intra-EU inward FDI represented 67% of the EU GDP, while the extra-EU inward FDI represented less than 1% (Faes-Cannito et al. 2012). Furthermore, in 2015, the extra-EU inward FDI was dominated by the USA (41.4%), offshore financial centers (25.8%), and Switzerland (10.8%).

Table 3 Determinants of CO_2 emissions: static panel data analysis

Variable	Model 1		Model 2	
	Fixed effects	Random effects	Fixed effects	Random effects
renewable	−0.001 (0.022)*	−0.001 (0.000)*	−0.000 (0.000)*	−0.005 (0.001)***
gdp	1.632 (0.254)***	1.639 (0.251)***	1.572 (0.254)***	6.086 (0.550)***
gdp^2	−0.084 (0.013)***	−0.086 (0.013)***	−0.079 (0.013)***	−0.328 (0.028)***
fdi1	−0.024 (0.005)***	−0.022 (0.005)***	−0.022 (0.005)***	−0.031 (0.017)*
tec	1.074 (0.032)***	1.076 (0.031)***	1.097 (0.031)***	1.123 (0.025)***
gfcf1	−0.004 (0.001)***	−0.004 (0.001)***	−0.004 (0.001)***	−0.008 (0.003)***
popdens	0.001 (0.000)***	0.001 (0.000)***	0.001 (0.000)***	0.000 (0.000)***
unemp	−0.004 (0.000)***	−0.004 (0.000)***	−0.002 (0.001)***	−0.006 (0.002)***
dummy2003	0.002 (0.008)	0.002 (0.008)		
dummy2010	−0.035 (0.009)***	−0.036 (0.009)***	−0.137 (0.035)***	−0.382 (0.140)***
dummy2003 × *rnw*			−0.000 (0.000)	0.000 (0.001)
dummy2010 × *rnw*			−0.001 (0.000)	0.002 (0.001)
dummy2003 × *tec*			0.001 (0.001)	0.000 (0.008)
dummy2010 × *tec*			0.025 (0.006)***	0.060 (0.026)**
time	−0.003 (0.001)**	−0.002 (0.001)*	−0.003 (0.001)***	0.007 (0.003)*
β_0	−1.097 (3.066)	−2.391 (3.042)	0.645 (1.223)	−41.23 (8.472)***
R^2	0.876	0.899	0.882	0.967
F test (*p*-values)	541.3 [0.000]		578.4 [0.000]	
Hausman test (recommended)	chi2 = 9.26; prob > chi2 = 0.598 (Random)		chi2 = 62.88; prob > chi2 = 0.000 (Fixed)	

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

technologies. The coefficients of the control variables are significant and have the expected sign, except for the investment, which has a negative contribution to pollution.

Although this result is in contrast with several previous finings reported in literature (i.e., Sapkota and Bastola 2017), it can be explained by the increased share of green investment. Consequently, in the presence of green technology, the effect on investment on CO_2 emissions might become positive. The increase of energy consumption has an important impact on the pollution level; the results are in agreement with previous findings.

These results remain unchanged in the case of Model 2. In addition, it seems that the second set of environmental regulations contributed to a decrease of CO_2 emissions by generating a contraction in total energy consumption. However, the ratification of the Kyoto protocol has no significant impact on the level of pollution in the EU countries.

We continue our analysis with the instrumental variable analysis, where the first lag of FDI stock is used as instrument (the results are presented in Table 4). In this case, we also have the two models (Models 1 and 2) which consider the impact of environmental regulations and the channels throughout the regulations might influence the pollution level. In the first step, we use GMM errors. While the endogenity tests (Wu-Hausman and Durbin-Wu-Hausman) show no endogeneity bias, on the contrary, the Pagan-Hall test clearly points a heteroscedasticity. In this case, robust errors should be used. However, the Sargan test becomes inconsistent in the presence of robust errors and a Hansen test statistic must be used to identify over-identification problems (Roodman 2009). Table 4 shows that the instruments are exactly identified.

Compared with the previous analysis (Table 3), we notice that the results remain the same. In terms of environmental regulations, we notice on the one hand that the first set of regulations has no significant effect, while the second set contributed to a decrease of CO_2 emissions. These findings agree to those reported for the random effect model. On the other hand, the coefficients of interaction dummies are significant for the same 2010

Table 4 Determinants of CO_2 emissions: instrumental variable analysis

Variable	Model 1		Model 2	
	GMM errors	Robust errors	GMM errors	Robust errors
renewable	−0.004 (0.001)***	−0.004 (0.000)***	−0.005 (0.001)***	−0.005 (0.001)***
gdp	6.103 (0.556)***	6.103 (0.372)***	6.163 (0.552)***	6.163 (0.382)***
gdp^2	−0.328 (0.028)***	−0.328 (0.019)***	−0.332 (0.028)***	−0.332 (0.019)***
fdi1	−0.040 (0.019)**	−0.040 (0.012)*	−0.037 (0.020)*	−0.037 (0.012)***
tec	1.147 (0.023)***	1.147 (0.017)***	1.126 (0.025)***	1.126 (0.021)***
gfcf1	−0.009 (0.003)***	−0.009 (0.002)***	−0.010 (0.003)***	−0.010 (0.002)***
popdens	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***
unemp	−0.006 (0.002)***	−0.006 (0.002)***	−0.006 (0.002)***	−0.006 (0.001)***
dummy2003	−0.002 (0.036)	−0.002 (0.026)		
dummy2010	−0.062 (0.035)*	−0.062 (0.037)*	−0.380 (0.136)***	−0.380 (0.152)**
dummy2003 × *rnw*			0.000 (0.001)	0.000 (0.000)
dummy2010 × *rnw*			0.002 (0.001)	0.002 (0.001)*
dummy2003 × *tec*			0.000 (0.008)	0.000 (0.008)
dummy2010 × *tec*			0.059 (0.026)**	0.059 (0.034)*
time	0.009 (0.003)**	0.009 (0.003)**	0.007 (0.003)**	0.007 (0.003)**
β_0	−45.34 (8.914)***	−45.34 (8.017)***	−43.18 (8.907)***	−43.19 (7.834)***
Sargan statistic – over-identification	0.000		0.000	
Hansen J statistic – over-identification		0.000		0.000
Pagan-Hall test – heteroscedasticity	93.85 [0.000]		106.2 [0.000]	
Wu-Hausman test – endogeneity	0.319 [0.572]		0.335 [0.562]	
Durbin-Wu-Hausman test – endogeneity	0.332 [0.564]		0.352 [0.552]	

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) Sargan statistic represents the over-identification test for all instruments and equals to 0.000 if the equation is exactly identified; (iv) the instrumented variable is *fdi1* (included instruments: *tec*, *renewable*, *gdp*, gdp^2 , *gfcf1*, *popdens*, *unemp*, *dummy* variables; excluded instruments: first lag of *fdi1*); (v) *p* values are reported in square brackets; (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

regulatory package and the same total energy consumption channel.

Both the EKC and the PH hypotheses are validated, while the control variable coefficients are in general significant and have the expected sign. However, the coefficient of the GDP per capita and the intercept becomes very high with the instrumental variable approach. Therefore, given the presence of heteroskedasticity (Pagan-Hall test) which may introduce a bias in our results, we proceed to a GMM analysis, which according to Baum et al. (2003) provides better estimates in the presence of heteroscedasticity.

Table 5 presents the results of the GMM approach, comparing a difference- and a system-GMM model. To avoid the over-proliferation of instruments, we have restricted the maximum lag length of the lagged instruments to one. Given the presence of heteroscedasticity, we report the results for robust errors.[19]

The results of the difference-GMM estimator confirm the first set of results and show the negative impact of the share of renewable electricity production and environmental regulations (e.g., the 2020 climate and energy package) on the level of CO_2 emissions. When we look to the transmission channels, we notice that the total energy consumption channel is significant for the second regulatory package. However, in this case, the renewable energy channel associated with the implementation of the Kyoto protocol (*dummy2003* × *rnw*) became also significant; the results are confirmed by the system-GMM specification.

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[19] Using GMM errors does not, however, change in a significant way the estimated coefficients.

Table 5 Determinants of CO_2 emissions: dynamic panel data analysis

Variable	Difference-GMM		System-GMM	
	Model 1	Model 2	Model 1	Model 2
$L.co_2em$	0.354 (0.028)***	0.329 (0.028)***	0.858 (0.056)***	0.861 (0.056)***
renewable	−0.001 (0.000)***	−0.001 (0.000)***	−0.001 (0.000)***	−0.001 (0.000)**
gdp	1.130 (0.173)***	1.093 (0.174)***	0.917 (0.346)***	0.857 (0.356)**
gdp^2	−0.057 (0.009)***	−0.055 (0.009)***	−0.048 (0.018)***	−0.045 (0.018)**
fdi1	−0.015 (0.003)***	−0.013 (0.003)***	−0.002 (0.005)	−0.000 (0.005)
tec	0.691 (0.037)***	0.737 (0.037)***	0.147 (0.068)**	0.141 (0.069)**
gfcf1	−0.003 (0.000)***	−0.003 (0.000)***	−0.000 (0.001)	−0.000 (0.001)
popdens	0.000 (0.000)***	−0.000 (0.001)	0.000 (0.000)	0.000 (0.000)
unemp	−0.003 (0.000)***	−0.002 (0.001)*	−0.000 (0.000)	−0.000 (0.000)
dummy2003	−0.006 (0.005)		−0.015 (0.010)	
dummy2010	−0.011 (0.006)*	−0.089 (0.023)***	0.009 (0.008)	
dummy2003 × rnw		−0.000 (0.000)**		−0.000 (0.000)**
dummy2010 × rnw		0.000 (0.000)		0.000 (0.000)
dummy2003 × tec		0.000 (0.001)		0.000 (0.001)
dummy2010 × tec		0.017 (0.004)***		0.001 (0.002)
time	−0.001 (0.000)**	−0.002 (0.000)***	0.000 (0.001)	0.000 (0.000)
β_0	−1.740 (2.028)	−0.397 (1.993)	−5.712 (3.383)*	−4.416 (3.363)
Hansen statistic – over-identification			11.43 [0.325]	11.92 [0.452]
AR (1) - z			−2.970 [0.003]	−2.970 [0.003]
AR (2) - z			0.160 [0.871]	0.160 [0.872]

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) robust standard errors are used; (iv) the variable *fdi1* is considered as endogenous, while all the others explanatory variables are considered strictly exogenous; (v) $L.co_2em$ is the first lag of the CO_2 emissions from fuel combustion (expressed in natural log); (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003 × rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010 × rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003 × tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010 × tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept; (vii) AR (1) and AR (2), Arellano-Bond tests for autocorrelation

While both specifications validate the EKC hypothesis, the PH hypothesis is not validated by the system-GMM approach. Compared with the difference-GMM approach, the system-GMM has better performance for large N and small T samples. However, the system-GMM might suffer from the over-proliferation of instruments. Thus, we have applied the Hansen test for instruments over-proliferation (consistent with robust errors) and the Arellano-Bond tests for autocorrelation (AR (1) and AR (2)). While the Hansen test shows that the instruments are correctly identified, the Arellano-Bond test (AR (2)) indicates no autocorrelation bias.[20]

All in all, our results show consistence between the static and dynamic specifications. To prove the robustness of our findings, in what follows we perform three robustness checks.

Robustness check analyses

Re-sampling considering old EU members

For the first robustness check, we retain in the sample nine EU countries for the same period, 1990 to 2017. We exclude the Central and Eastern European (CEE) countries from the sample. These countries became EU members in 2004 (the Czech Republic and Poland) and in 2007 respectively (Romania), only after the ratification of the Kyoto protocol by the old EU member states.

Table 6 shows the results for the static analysis. We notice that the negative impact of the share of renewable energy is marginal, and significant as in the main analysis. As for the main results, we observe a consensus between the fixed and the random effect models. First, the EKC and PH hypotheses are both validated. Second, the coefficients of the control variables are significant and have the expected sign. Third, the *dummy2010* variable negatively influences the level of CO_2 emissions in old EU member states, meaning that the environmental regulation which agreed in 2010 contributed to a

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[20] Arellano-Bond AR (1) test result is ignored in that context given that the first lag of variables is used as instrument.

Table 6 Determinants of CO_2 emissions: static panel data analysis (nine EU countries)

Variable	Model 1		Model 2	
	Fixed effects	Random effects	Fixed effects	Random effects
renewable	−0.001 (0.000)*	−0.001 (0.000)*	−0.000 (0.000)	−0.005 (0.001)***
gdp	1.632 (0.254)***	1.639 (0.251)***	1.572 (0.254)***	6.086 (0.550)***
gdp^2	−0.084 (0.013)***	−0.086 (0.013)***	−0.079 (0.013)***	−0.328 (0.028)***
fdi1	−0.024 (0.005)***	−0.023 (0.005)***	−0.022 (0.005)***	−0.031 (0.172)*
tec	1.074 (0.032)***	1.074 (0.031)***	1.097 (0.031)***	1.123 (0.025)***
gfcf1	−0.004 (0.001)***	−0.004 (0.001)***	−0.004 (0.001)***	−0.009 (0.003)***
popdens	0.001 (0.000)***	0.001 (0.000)***	0.001 (0.000)***	0.000 (0.000)***
unemp	−0.004 (0.001)***	−0.004 (0.000)***	−0.002 (0.001)***	−0.006 (0.002)***
dummy2003	0.002 (0.005)	0.002 (0.008)		
dummy2010	−0.035 (0.009)***	−0.036 (0.009)***	−0.137 (0.035)***	−0.382 (0.140)***
dummy2003 × *rnw*			−0.000 (0.000)	0.000 (0.001)
dummy2010 × *rnw*			−0.000 (0.000)	0.002 (0.001)
dummy2003 × *tec*			0.001 (0.001)	0.000 (0.008)
dummy2010 × *tec*			0.025 (0.006)***	0.060 (0.026)**
time	−0.003 (0.001)**	−0.002 (0.001)**	−0.003 (0.001)***	0.007 (0.003)*
β_0	−1.097 (3.066)	−2.391 (3.042)	0.645 (2.994)	−41.23 (8.472)***
R^2	0.876	0.899	0.882	0.968
F test (*p*-values)	541.3 [0.000]		578.4 [0.000]	
Hausman test (recommended)	chi2 = 9.26; prob > chi2 = 0.598 (Random)		chi2 = 62.88; prob > chi2 = 0.000 (Fixed)	

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

reduction in the pollution level. Finally, the channel through which the regulation impacts the CO_2 emission is once again the total energy consumption channel.

While the production of renewable energy marginally contributed to the reduction in CO_2 emissions, the environmental regulations from 2010 affected the CO_2 emissions by generating a reduction of energy consumption. The results are consistent with those reported in Table 4.

We continue with the dynamic analysis and we present the GMM results with robust errors.[21] Table 7 indicates the negative impact of the share of renewable electricity production to the CO_2 emissions, showing the robustness of the previous findings. However, in this case, the EKC hypothesis holds only for the difference-GMM specification, while the PH hypothesis is validated by both approaches. Different from the main results, the impact of environmental regulations is unclear. Against this background, we perform a second set of robustness checks, considering the delay associated with the effective entry into force of EU environmental regulations.

Entry into force of Kyoto protocol through ETF trading period (*dummy2005*)

The implementation of the Kyoto protocol requirements adopted in 2003 might be made with some delay. In fact, only in 2005 starts the first phase of ECCP. Therefore, in the second robustness check analysis, we consider the effective entry into force of the Kyoto protocol that started in 2005, and we use a *dummy*2005 variable instead of *dummy*2003. Table 8 shows the static panel data results.

The results presented in Table 8 are very consistent with those reported in Table 4, showing the negative effect of the increase renewable electricity share in total electricity production, on CO_2 emissions, and validating the EKC and PH hypotheses. Moreover, the second environmental regulation package from 2010 significantly contributed to a reduction in CO_2 emissions, while the channel is represented by the total energy consumption as before.

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[21] We have presented in Appendix (Table 14) the results of the instrumental variable analysis. Given the presence of heteroscedasticity signalized by the Pagan-Hall test, as Baum et al. (2003) recall, the GMM estimators perform better compared with the instrumental variable analysis.

Table 7 Determinants of CO_2 emissions: dynamic panel data analysis (nine EU countries)

Variable	Difference-GMM		System-GMM	
	Model 1	Model 2	Model 1	Model 2
$L.co_2em$	0.378 (0.083)***	0.329 (0.071)***	0.929 (0.038)***	0.930 (0.037)***
renewable	−0.001 (0.000)***	−0.000 (0.000)	−0.002 (0.000)***	−0.002 (0.000)***
gdp	2.765 (1.284)**	2.600 (1.237)**	−1.008 (0.924)	−0.935 (0.909)
gdp^2	−0.127 (0.062)**	−0.119 (0.061)*	0.046 (0.044)	0.043 (0.043)
fdi1	−0.027 (0.011)**	−0.019 (0.009)**	−0.028 (0.013)**	−0.026 (0.012)**
tec	0.683 (0.086)***	0.763 (0.064)***	0.078 (0.050)	0.075 (0.049)
gfcf1	−0.009 (0.001)***	−0.009 (0.001)***	−0.000 (0.001)	0.000 (0.001)
popdens	0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)
unemp	−0.007 (0.001)***	−0.006 (0.001)***	−0.000 (0.000)	−0.000 (0.000)
dummy2003	−0.000 (0.011)		−0.009 (0.012)	
dummy2010	0.019 (0.012)	0.011 (0.050)	0.017 (0.003)***	0.012 (0.039)
dummy2003 × *rnw*		−0.000 (0.000)		−0.000 (0.000)
dummy2010 × *rnw*		−0.000 (0.000)**		0.000 (0.000)
dummy2003 × *tec*		0.001 (0.002)		0.000 (0.000)
dummy2010 × *tec*		0.006 (0.009)		−0.000 (0.008)
time	−0.004 (0.001)***	−0.005 (0.001)***	0.002 (0.001)	0.002 (0.001)
β_0	−5.045 (6.255)	−3.219 (6.097)	0.432 (6.422)	0.268 (6.441)
Hansen statistic – over-identification			8.970 [0.535]	8.850 [0.784]
AR (1) - z			−2.710 [0.007]	−2.710 [0.007]
AR (2) - z			1.470 [0.142]	1.470 [0.142]

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) robust standard errors are used; (iv) the variable *fdi1* is considered as endogenous, while all the others explanatory variables are considered strictly exogenous; (v) $L.co_2em$ is the first lag of the CO_2 emissions from fuel combustion (expressed in natural log); (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2, square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept; (vii) AR (1) and AR (2), Arellano-Bond tests for autocorrelation

We continue with the dynamic analysis. Table 15 (Appendix) presents the results of the instrumental variable approach, while Table 9 highlights the findings of the GMM models with robust errors.

While the role of renewable energy in the reduction of CO_2 emissions remains the same and both EKC and PH hypotheses are validated, an important difference appears in the case of environmental regulations. According to the GMM results (both difference- and system-GMM approaches), the first set of regulations has a negative and significant impact on CO_2 emissions, while the second set releases in 2010 has no significant impact. We observe that the effects of environmental regulations produce with a considerable delay, results that put into questions the robustness of the analysis. Our findings may be, however, considerably influenced by the EU business cycle.

Renewable energy, environmental regulation, and CO_2 intensity

Finally, we want to control for the effect of the business cycle on our results. To this end, we look to the CO_2 intensity (computed as the ratio between CO_2 emissions and GDP) and we consider as explanatory variable the GDP energy intensity, the FDI to GDP ratio, and the gross fixed capital formation to GDP ratio. This represents another way of looking to the pollution level and to the role of environmental regulations. The determinants of the CO_2 intensity are investigated for the

Table 8 Determinants of CO_2 emissions: static panel data analysis (*dummy2005*)

Variable	Model 1		Model 2	
	Fixed effects	Random effects	Fixed effects	Random effects
renewable	−0.001 (0.000)*	−0.001 (0.000)*	−0.000 (0.000)	−0.005 (0.001)***
gdp	1.629 (0.254)***	1.636 (0.251)***	1.542 (0.254)***	6.073 (0.549)***
gdp^2	−0.084 (0.013)***	−0.085 (0.013)***	−0.078 (0.013)***	−0.327 (0.028)***
fdi1	−0.024 (0.005)***	−0.023 (0.005)***	−0.021 (0.005)***	−0.032 (0.017)*
tec	1.074 (0.032)***	1.077 (0.031)***	1.099 (0.031)***	1.122 (0.025)***
gfcf1	−0.004 (0.001)***	−0.004 (0.001)***	−0.004 (0.001)***	−0.009 (0.003)***
popdens	0.001 (0.000)***	0.001 (0.000)***	0.001 (0.000)***	0.000 (0.000)***
unemp	−0.004 (0.001)***	−0.004 (0.000)***	−0.002 (0.001)***	−0.006 (0.002)***
dummy2005	−0.004 (0.007)	−0.003 (0.007)		
dummy2010	−0.035 (0.009)***	−0.036 (0.009)***	−0.139 (0.034)***	−0.383 (0.138)***
dummy2005 × *rnw*			−0.000 (0.000)	0.000 (0.001)
dummy2010 × *rnw*			−0.000 (0.000)	0.002 (0.001)
dummy2005 × *tec*			0.001 (0.001)	0.000 (0.008)
dummy2010 × *tec*			0.025 (0.006)***	0.060 (0.027)**
time	−0.002 (0.001)**	−0.001 (0.001)*	−0.003 (0.001)***	0.007 (0.003)**
β_0	−1.808 (3.041)	−3.108 (3.014)	0.031 (2.975)	−41.23 (8.110)***
R^2	0.875	0.899	0.885	0.968
F test (*p*-values)	541.7 [0.000]		580.3 [0.000]	
Hausman test (recommended)	chi2 = 9.37; prob > chi2 = 0.588 (Random)		chi2 = 65.19; prob > chi2 = 0.000 (Fixed)	

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2005*, dummy variable which takes the value 1 starting with 2005; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2005* × *rnw*, interaction dummy variable between *dummy2005* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2005* × *tec*, interaction dummy variable between *dummy2005* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

initial sample of 12 EU countries. Table 10 presents the findings for the static analysis.

In this case, the EKC is validated only for the Model 1, while the PH hypothesis is not validated. The role of renewable energy in reducing CO_2 intensity is significant only for the Model 2. The energy intensity of GDP has the most important explanatory power for the decreasing trend of CO_2 intensity in the EU. The influence of environmental regulations is ambiguous. It appears that the regulations contributed to the reduction of CO_2 intensity, considering the renewable energy channel. This result is valid, however, only for the fixed effect estimation (Model 2).

Given the presence of heteroscedasticity (see the results of the Pagan-Hall test in Table 16, Appendix), robust standard errors are used, and we present, for consistency reasons, the results of the GMM models. Table 11 confirms the static analysis results and shows that the role of environmental regulations in the reduction of CO_2 intensity is unclear in this case.

To sum up our findings, we posit that both the income and the FDI influence the level of CO_2 emission, validating thus both the EKC and the PH hypotheses. In addition, the increasing share of the renewable electricity to total electricity production negatively influences the CO_2 emissions level, showing thus the importance of financial stimulus for renewable energy (Table 12).

However, when we consider the role of environmental regulation, we discover mixed evidence. First, the main results show that the 2020 climate and energy package adopted by the EU in 2009 contributed to the reduction of CO_2 emissions, and the total energy consumption channel was at work. At the same time, the ratification of the Kyoto protocol in 2002 and implemented in 2003 had no significant influence. These findings are confirmed by our robustness checks. Second, if we consider the time delay in the implementation of the Kyoto protocol, according to the GMM models estimations, this set of environmental

Table 9 Determinants of CO_2 emissions: dynamic panel data analysis (*dummy 2005*)

Variable	Difference-GMM		System-GMM	
	Model 1	Model 2	Model 1	Model 2
$L.co_2em$	0.365 (0.089)***	0.337 (0.070)***	0.862 (0.054)***	0.859 (0.058)***
renewable	−0.001 (0.000)**	−0.001 (0.001)	−0.001 (0.000)***	−0.001 (0.000)**
gdp	1.117 (0.591)*	1.069 (0.515)**	0.905 (0.343)***	0.896 (0.362)**
gdp^2	−0.057 (0.031)*	−0.053 (0.027)*	−0.047 (0.018)***	−0.047 (0.019)**
fdi1	−0.015 (0.004)***	−0.012 (0.005)**	0.002 (0.005)	−0.000 (0.006)
tec	0.676 (0.113)***	0.731 (0.082)***	0.143 (0.066)**	0.139 (0.069)**
gfcf1	−0.003 (0.001)*	−0.002 (0.001)*	−0.000 (0.001)	−0.000 (0.001)
popdens	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
unemp	−0.003 (0.001)**	−0.001 (0.001)	−0.000 (0.000)	−0.000 (0.000)
dummy2005	−0.015 (0.007)**	−0.096 (0.050)*	−0.031 (0.007)***	−0.063 (0.032)**
dummy2010	−0.009 (0.012)		0.013 (0.007)*	0.001 (0.035)
dummy2005 × rnw		−0.000 (0.000)		−0.000 (0.000)
dummy2010 × rnw		−0.000 (0.000)		0.000 (0.000)
dummy2005 × tec		0.017 (0.010)*		0.008 (0.006)
dummy2010 × tec		0.001 (0.003)		0.001 (0.007)
time	−0.001 (0.001)	−0.002 (0.002)	0.001 (0.000)*	0.001 (0.000)
β_0	−2.696 (5.233)	−0.453 (5.534)	−7.068 (3.152)**	−6.662 (3.418)*
Hansen statistic –over-identification			11.55 [0.316]	11.78 [0.316]
AR (1) - z			−2.970 [0.003]	−2.970 [0.003]
AR (2) - z			0.160 [0.872]	0.160 [0.872]

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) robust standard errors are used; (iv) the variable *fdi1* is considered as endogenous, while all the others explanatory variables are considered strictly exogenous; (v) $L.co_2em$ is the first lag of the CO_2 emissions from fuel combustion (expressed in natural log); (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2, square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2005*, dummy variable which takes the value 1 starting with 2005; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2005 × rnw*, interaction dummy variable between *dummy2005* and *renewable*; *dummy2010 × rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2005 × tec*, interaction dummy variable between *dummy2005* and *tec*; *dummy2010 × tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept; (vii) AR (1) and AR (2), Arellano-Bond tests for autocorrelation

regulations (EU ETS) also contributed to the reduction of CO_2 emissions. However, this result lacks in robustness. We conclude that the regulations might had a negative impact on the CO_2 emission throughout the total energy consumption. At the same time, the regulations regarding the production and consumption of renewable energy that have established clear goals are important for the reduction in CO_2 emission levels.

Conclusions

This paper investigates the impact of renewable energy share in energy production, and the role of EU environmental regulations on CO_2 emissions in 12 EU countries for the period 1990 to 2017. Static and dynamic panel data results support the EKC and PH hypotheses, showing an inverted U-shaped relationship between CO_2 emissions and income level, and that foreign companies export eco-friendly technologies inside the EU.

According to the static fixed and random effect models, the impact of renewable electricity share on the CO_2 emissions is significant and has the expected sign, but is marginal (similar results are reported by Aliprandi et al. 2016), while the second set of environmental regulations implemented starting with 2010 contributes in a significant way to the reduction of CO_2 emissions. This result can be explained by the fact that the Kyoto protocol is an exponent of international, multilateral agreements, without disposing of real constraints for the signing parties. Further, its entry into force happened with some delays. On the contrary, the 2020 climate and energy regulations represent an internal EU set of rules, which are more effective in terms of constraints, sanctions, or financial stimulus applied to the EU member states.

Table 10 Determinants of CO_2 intensity: static panel data analysis

Variable	Model 1		Model 2	
	Fixed effects	Random effects	Fixed effects	Random effects
renewable	0.000 (0.000)	−0.000 (0.000)	−0.001 (0.000)*	−0.013 (0.002)***
gdp	0.947 (0.120)***	0.743 (0.115)***	0.617 (0.358)*	−0.723 (0.864)
gdp^2	−0.045 (0.006)***	−0.025 (0.006)***	0.017 (0.018)	−0.002 (0.045)
fdi2	−0.000 (0.000)	−0.000 (0.000)*	−0.000 (0.000)	−0.000 (0.000)
ei	3.136 (0.121)***	3.033 (0.116)***	7.764 (0.338)***	4.056 (0.715)***
gfcf2	0.052 (0.012)***	0.027 (0.011)***	0.047 (0.036)	0.992 (0.039)***
popdens	0.000 (0.000)***	−0.000 (0.000)	0.001 (0.000)**	0.000 (0.000)
unemp	−0.000 (0.000)	0.000 (0.000)	0.002 (0.001)	−0.003 (0.003)
dummy2003	0.005 (0.000)	0.004 (0.004)		
dummy2010	0.008 (0.004)**	0.006 (0.004)	−0.020 (0.046)	0.724 (0.178)***
dummy2003 × *rnw*			−0.001 (0.002)**	−0.000 (0.001)
dummy2010 × *rnw*			−0.001 (0.000)***	0.001 (0.002)
dummy2003 × *ei*			0.137 (0.110)	0.140 (0.478)
dummy2010 × *ei*			0.120 (0.403)	−6.776 (1.581)***
time	−0.000 (0.000)	−0.000 (0.000)	−0.002 (0.001)	−0.004 (0.004)
β_0	4.546 (1.325)***	3.459 (1.310)***	−0.235 (2.763)	−4.814 (10.68)
R^2	0.309	0.660	0.039	0.943
F test (*p*-values)	169.2 [0.000]		555.6 [0.000]	
Hausman test (recommended)	chi2 = 23.43; prob > chi2 = 0.015 (Fixed)		chi2 = 1704; prob > chi2 = 0.000 (Fixed)	

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi2*, stock of inward FDI as GDP percentage; *ei*, energy intensity of GDP; *gfcf1*, gross fixed capital formation as GDP percentage; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *ei*, interaction dummy variable between *dummy2003* and *ei*; *dummy2010* × *ei*, interaction dummy variable between *dummy2010* and *ei*; *time*, linear time trend; β_0, the intercept

The results of the dynamic GMM models (in particular the difference-GMM model) validate the static models' findings, including the impact of environmental regulation dummies. We notice that the first set of regulations has no clear contribution to a decrease of CO_2 emissions, while the second set has a significant effect. However, in the case of dynamic estimations, these results lack in robustness. The unclear effect of environmental regulation on the reduction of CO_2 emissions was also underlined by Niedertscheider et al. (2018).

To check the robustness of our findings, we first excluded from the sample the CEE countries. In this case, the static analysis reveals that the negative impact of the share of renewable energy is marginal, as in the case of the main findings. At the same time, the environmental regulations which agreed in 2009 contributed to a reduction in the pollution level. Second, we have considered the time delay regarding the entry into force of the Kyoto protocol and the results are consistent with the main findings, except for the dynamic specifications. Third, we have focused on the determinants of the CO_2 intensity for the initial sample of 12 EU countries. In this case also, the influence of environmental regulations looks ambiguous. Overall, we conclude that both the income and the FDI influence the level of CO_2 emission, validating thus the EKC and PH hypothesis. Additionally, an increasing share of the renewable electricity to total electricity production negatively influences the pollution level. However, the overall impact of environmental regulations is unclear.

Two policy implications result from our findings. First, our findings highlight the importance of financial stimulus for renewable energy production. Precise policy goals which sustain the use of renewable energy (e.g., obtaining 20% of EU energy from renewable sources by 2020), as those established in 2009, are effective in stimulating the reduction of CO_2 emissions. Second, it appears that the EU ETS system is not so efficient for the reduction of CO_2 emissions. On the contrary, regulations that constraint the total energy consumption and sustain the energy efficiency are more effective for controlling the EU pollution level.

Table 11 Determinants of CO_2 intensity: dynamic panel data analysis

Variable	Difference-GMM		System-GMM	
	Model 1	Model 2	Model 1	Model 2
$L.co_2in$	0.675 (0.071)***	0.545 (0.061)***	0.857 (0.032)***	0.848 (0.034)***
renewable	−0.000 (0.000)**	−0.001 (0.000)**	−0.000 (0.001)***	−0.000 (0.000)***
gdp	−0.157 (0.252)	0.304 (0.426)	0.068 (0.050)	0.051 (0.042)
gdp^2	0.009 (0.012)	0.006 (0.017)	−0.003 (0.002)	−0.002 (0.002)
fdi2	0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)	−0.000 (0.000)
ei	1.078 (0.328)***	3.690 (0.817)***	0.301 (0.186)	0.307 (0.183)*
gfcf2	−0.003 (0.007)	0.039 (0.042)	−0.000 (0.005)	−0.000 (0.005)
popdens	−0.000 (0.000)	−0.000 (0.000)	0.000 (0.000)	−0.000 (0.000)
unemp	−0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.001)
dummy2003	0.000 (0.003)		0.002 (0.003)	
dummy2010	0.009 (0.001)***	0.029 (0.036)	0.007 (0.001)***	0.015 (0.008)*
dummy2003 × *rnw*		−0.001 (0.000)***		0.000 (0.000)
dummy2010 × *rnw*		−0.001 (0.000)		0.000 (0.000)
dummy2003 × *ei*		0.126 (0.089)		−0.004 (0.035)
dummy2010 × *ei*		−0.165 (0.344)		−0.094 (0.068)
time	−0.000 (0.000)	−0.000 (0.001)	−0.000 (0.000)	−0.000 (0.000)
β_0	1.103 (1.924)	−1.515 (3.247)	0.242 (0.454)	0.346 (0.409)
Hansen statistic – over-identification			11.01 [0.357]	10.78 [0.630]
AR (1) - z			−2.780 [0.005]	−2.780 [0.005]
AR (2) - z			−0.710 [0.481]	−0.710 [0.479]

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) standard errors are reported in brackets; (iii) robust standard errors are used; (iv) the variable *fdi2* is considered as endogenous, while all the others explanatory variables are considered strictly exogenous; (v) $L.co_2in$ is the first lag of the CO_2 intensity; (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2 , square GDP per capita; *fdi2*, stock of inward FDI as GDP percentage; *ei*, energy intensity of GDP; *gfcf2*, gross fixed capital formation as GDP percentage; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *ei*, interaction dummy variable between *dummy2003* and *ei*; *dummy2010* × *ei*, interaction dummy variable between *dummy2010* and *ei*; *time*, linear time trend; β_0, the intercept; (vii) AR (1) and AR (2), Arellano-Bond tests for autocorrelation

Table 12 Centralized results

Models	CO_2 emission (12 countries)—main results			CO_2 emission (9 countries)—robustness			CO_2 emission (12 countries) dummy 2005—robustness			CO_2 intensity (12 countries)—robustness		
	renew.	*dummy*		*renew.*	*dummy*		*renew.*	*dummy*		*renew.*	*dummy*	
		2003	*2010*		*2003*	*2010*		*2005*	*2010*		*2003*	*2010*
Fixed effects	−*	+	−***	−*	+	−***	−*	−	−***	+	+	+**
Random effects	−*	+	−***	−*	+	−***	−*	−	−***	−	+	+
Instrumental variable	−***	−	−*	−*	−	−	−***	+	−*	−***	+	+
Difference-GMM	−***	−	−*	−***	−	−	−**	−**	−	−**	+	+***
System-GMM	−***	−	+	−***	+	+***	−***	−***	+*	−***	+	+***

(i) *, **, and *** mean significance at 10%, 5%, and 1%; (ii) "−" shows a negative impact of the share of renewable electricity in total electricity production (renew.) and of the environmental regulations (*dummy 2003*, *2005*, and *2010*) on the CO_2 emission/CO_2 intensity, while "+" means a positive influence; (iii) robustness standard errors are used (except for the static estimators); (iv) results from Model 1 are reported

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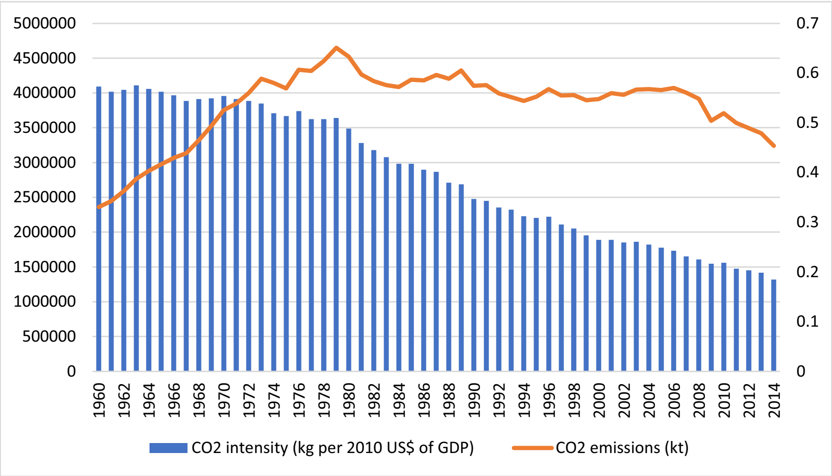
Appendix



Source: World Bank Development Indicators

Fig. 1 Dynamic of CO_2 emissions and CO_2 intensity in the EU (source: World Bank Development Indicators)

Table 13 Explanatory variables

Variable	CO_2 emissions			CO_2 intensity (robustness analysis)		
	Sign	Database	Explanations	Sign	Database	Explanations
renewable	–	Enerdata	Share of renewables in electricity production	–	Enerdata	Share of renewables in electricity production
gdp	+	WDI	GDP per capita (constant 2010 US$)	+	WDI	GDP per capita (constant 2010 US$)
gdp^2	–		Square GDP per capita	–	Calculated	Square GDP per capita
fdi1	+/–	UNCTAD	Inward stock of FDI (current US$)			
fdi2				+/–	UNCTAD	Inward stock of FDI to GDP ratio
tec	+	Enerdata	Total energy consumption			
ei				+	Enerdata	Energy intensity of GDP
gfcf1	+	WDI	Gross fixed capital formation (constant 2010 US$)			
gfcf2				+	WDI	Gross fixed capital formation (% of GDP)
popdens	+	WDI	Population density (people per sq. km of land area)	+	WDI	Population density (people per sq. km of land area)
unemp	+/–	WDI	Unemployment rate (% of total labor force)	+/–	WDI	Unemployment rate (% of total labor force)
dummy2003	–		Dummy variable, which takes value 1 after 2003	–		Dummy variable, which takes value 1 after 2003
dummy2010	–		Dummy variable, which takes value 1 after 2010	–		Dummy variable, which takes value 1 after 2010
dummy2003 × *rnw*	–		Interaction dummy variable between *dummy2003* and *renewable*	–		Interaction dummy variable between *dummy2003* and *renewable*
dummy2010 × *rnw*	–		Interaction dummy variable between *dummy2010* and *renewable*	–		Interaction dummy variable between *dummy2010* and *renewable*
dummy2003 × *tec*	–		Interaction dummy variable between *dummy2003* and *tec*			
dummy2010 × *tec*	–		Interaction dummy variable between *dummy2010* and *tec*			
dummy2003 × *ei*				–		Interaction dummy variable between *dummy2003* and *ei*
dummy2010 × *ei*				–		Interaction dummy variable between *dummy2010* and *ei*
year	–		Linear time trend	–		Linear time trend

Table 14 Determinants of CO_2 emissions: instrumental variable analysis (nine EU countries)

Variable	Model 1		Model 2	
	GMM errors	Robust errors	GMM errors	Robust errors
renewable	−0.003 (0.001)*	−0.003 (0.001)*	−0.003 (0.002)*	−0.003 (0.001)**
gdp	−1.442 (3.909)	−1.452 (2.333)	−1.612 (3.910)	−1.584 (2.390)
gdp^2	0.019 (0.188)	0.019 (0.113)	0.028 (0.188)	0.026 (0.116)
fdi1	0.040 (0.039)	0.046 (0.039)	0.036 (0.040)	0.036 (0.044)
tec	1.155 (0.032)***	1.155 (0.028)***	1.151 (0.034)***	1.151 (0.030)***
gfcf1	−0.005 (0.004)	−0.005 (0.003)*	−0.005 (0.004)	−0.005 (0.003)*
popdens	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***
unemp	−0.012 (0.003)***	−0.012 (0.002)***	−0.012 (0.003)***	−0.012 (0.002)***
dummy2003	−0.026 (0.046)	−0.026 (0.045)		
dummy2010	−0.047 (0.043)	−0.047 (0.047)	−0.226 (0.192)	−0.225 (0.172)
dummy2003 × *rnw*			0.000 (0.001)	0.000 (0.000)
dummy2010 × *rnw*			0.001 (0.002)	0.001 (0.001)
dummy2003 × *tec*			−0.005 (0.010)	−0.005 (0.010)
dummy2010 × *tec*			0.030 (0.034)	0.030 (0.036)
year	0.006 (0.005)	0.006 (0.005)	0.006 (0.005)	0.006 (0.005)
β_0	−0.164 (21.83)	−0.135 (12.60)	0.822 (21.76)	0.735 (12.76)
Sargan statistic – over-identification	0.000		0.000	
Hansen J statistic – over-identification		0.000		0.000
Pagan-Hall test – heteroscedasticity	102.7 [0.000]		106.8 [0.000]	
Wu-Hausman test – endogeneity	0.307 [0.579]		0.284 [0.594]	
Durbin-Wu-Hausman test – endogeneity	0.324 [0.569]		0.303 [0.581]	

(i) *, **, and *** mean significance at 10%, 5%, and 1%, respectively; (ii) standard errors are reported in brackets; (iii) Sargan statistic represents the over-identification test for all instruments and equals to 0.000 if the equation is exactly identified; (iv) the instrumented variable is *fdi1* (included instruments: *tec*, *renewable*, *gdp*, gdp^2, *gfcf1*, *popdens*, *unemp*, *dummy* variables; excluded instruments: first lag of *fdi1*); (v) *p* values are reported in square brackets; (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2, square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *tec*, interaction dummy variable between *dummy2003* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

Table 15 Determinants of CO_2 emissions: instrumental variable analysis (dummy 2005)

Variable	Model 1		Model 2	
	GMM errors	Robust errors	GMM errors	Robust errors
renewable	−0.004 (0.001)***	−0.004 (0.000)***	−0.005 (0.001)***	−0.005 (0.001)***
gdp	6.104 (0.555)***	6.104 (0.372)***	6.153 (0.551)***	6.153 (0.382)***
gdp^2	−0.328 (0.028)***	−0.328 (0.019)***	−0.331 (0.027)***	−0.331 (0.019)***
fdi1	−0.040 (0.019)**	−0.040 (0.012)***	−0.037 (0.019)*	−0.037 (0.012)***
tec	1.147 (0.023)***	1.147 (0.017)***	1.125 (0.025)***	1.125 (0.021)***
gfcf1	−0.009 (0.003)***	−0.009 (0.002)***	−0.010 (0.003)***	−0.010 (0.002)***
popdens	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)***
unemp	−0.006 (0.002)**	−0.006 (0.002)***	−0.006 (0.002)***	−0.006 (0.001)***
dummy2005	0.000 (0.034)	0.000 (0.032)		
dummy2010	−0.061 (0.034)*	−0.061 (0.036)*	−0.382 (0.135)***	−0.382 (0.151)**
dummy2005 × *rnw*			0.000 (0.001)	0.000 (0.000)
dummy2010 × *rnw*			0.002 (0.001)	0.002 (0.001)**
dummy2005 × *tec*			0.000 (0.008)	0.000 (0.009)
dummy2010 × *tec*			0.059 (0.026)**	0.059 (0.034)*
year	0.008 (0.003)**	0.008 (0.003)**	0.008 (0.003)**	0.008 (0.003)**
β_0	−44.97 (8.652)***	−44.97 (7.599)***	−43.35 (8.633)***	−43.35 (7.525)***
Sargan statistic – over-identification	0.000		0.000	
Hansen J statistic – over-identification		0.000		0.000
Pagan-Hall test – heteroscedasticity	93.79 [0.000]		106.7 [0.000]	
Wu-Hausman test – endogeneity	0.300 [0.583]		0.365 [0.546]	
Durbin-Wu-Hausman test – endogeneity	0.313 [0.575]		0.383 [0.535]	

(i) *, **, and *** mean significance at 10%, 5%, and 1%, respectively; (ii) standard errors are reported in brackets; (iii) Sargan statistic represents the over-identification test for all instruments and equals to 0.000 if the equation is exactly identified; (iv) the instrumented variable is *fdi1* (included instruments: *tec*, *renewable*, *gdp*, gdp^2, *gfcf1*, *popdens*, *unemp*, *dummy* variables; excluded instruments: first lag of *fdi1*); (v) *p* values are reported in square brackets; (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2, square GDP per capita; *fdi1*, stock of inward FDI in natural log; *tec*, total energy consumption in natural log; *gfcf1*, gross fixed capital formation in natural log; *popdens*, population density; *unemp*, unemployment rate; *dummy2005*, dummy variable which takes the value 1 starting with 2005; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2005* × *rnw*, interaction dummy variable between *dummy2005* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2005* × *tec*, interaction dummy variable between *dummy2005* and *tec*; *dummy2010* × *tec*, interaction dummy variable between *dummy2010* and *tec*; *time*, linear time trend; β_0, the intercept

Table 16 Determinants of CO_2 intensity: instrumental variable analysis

Variable	Model 1		Model 2	
	GMM errors	Robust errors	GMM errors	Robust errors
renewable	−0.001 (0.000)***	−0.001 (0.000)***	−0.015 (0.002)***	−0.015 (0.001)***
gdp	0.604 (0.180)***	0.604 (0.170)***	−0.730 (0.849)	−0.750 (0.822)
gdp^2	−0.036 (0.009)***	−0.026 (0.008)***	−0.002 (0.044)	−0.002 (0.043)
fdi2	−0.000 (0.000)	−0.000*(0.000)*	0.000 (0.000)	0.000 (0.000)
ei	2.605 (0.150)***	2.605 (0.205)***	4.052 (0.700)***	4.052 (0.595)***
gfcf2	0.020 (0.008)**	0.02 (0.007)***	0.992 (0.040)***	0.952 (0.035)***
popdens	0.000 (0.000)***	0.000 (0.000)***	0.000 (0.000)	0.000 (0.000)
unemp	0.000 (0.000)	0.000 (0.000)	−0.003 (0.002)	−0.003 (0.002)
dummy2003	0.000 (0.010)	0.000 (0.009)		
dummy2010	0.008 (0.009)	0.008 (0.009)	0.723 (0174)***	0.723 (0161)***
dummy2003 × *rnw*			−0.000 (0.001)	−0.000 (0.001)
dummy2010 × *rnw*			0.001 (0.002)	0.001 (0.001)
dummy2003 × *ei*			0.142 (0.467)	0.142 (0.361)
dummy2010 × *ei*			−6.768 (1.547)***	−6.768 (1.340)***
year	0.001 (0.001)	0.001 (0.000)	−0.003 (0.004)	−0.003 (0.004)
β_0	−5.618 (2.296)**	−5.618 (1.876)***	−4.913 (10.50)	−4.913 (9.485)
Sargan statistic – over-identification	0.000		0.000	
Hansen J statistic – over-identification		0.000		0.000
Pagan-Hall test – heteroscedasticity	56.32 [0.000]		87.21 [0.000]	
Wu-Hausman test – endogeneity	0.081 [0.775]		0.006 [0.926]	
Durbin-Wu-Hausman test – endogeneity	0.085 [0.770]		0.006 [0.934]	

(i) *, **, and *** mean significance at 10%, 5%, and 1%, respectively; (ii) standard errors are reported in brackets; (iii) Sargan statistic represents the over-identification test for all instruments and equals to 0.000 if the equation is exactly identified; (iv) the instrumented variable is *fdi1* (included instruments: *ei*, *renewable*, *gdp*, gdp^2, *gfcf2*, *popdens*, *unemp*, *dummy* variables; excluded instruments: first lag of *fdi2*); (v) *p* values are reported in square brackets; (vi) *renewable*, share of renewables in electricity production; *gdp*, GDP per capita in natural log; gdp^2, square GDP per capita; *fdi2*, stock of inward FDI as GDP percentage; *ei*, energy intensity of GDP; *gfcf2*, gross fixed capital formation as GDP percentage; *popdens*, population density; *unemp*, unemployment rate; *dummy2003*, dummy variable which takes the value 1 starting with 2003; *dummy2010*, dummy variable which takes the value 1 starting with 2010; *dummy2003* × *rnw*, interaction dummy variable between *dummy2003* and *renewable*; *dummy2010* × *rnw*, interaction dummy variable between *dummy2010* and *renewable*; *dummy2003* × *ei*, interaction dummy variable between *dummy2003* and *ei*; *dummy2010* × *ei*, interaction dummy variable between *dummy2010* and *ei*; *time*, linear time trend; β_0, the intercept

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