



Revealing the complexity in the environmental Kuznets curve set in a European multivariate framework

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Received: 16 September 2020 / Accepted: 6 September 2021 / Published online: 12 September 2021
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Abstract

Despite considerable research attention given to the environmental Kuznets curve (EKC), little has been known about its true form and particularly the mechanisms that explain it. Using panel quantile regression, this paper designs a multivariate framework for exploring the EKC in the European Union in the period 2004–2017 and unveils the distributional heterogeneity effect hidden therein. It reveals that complexity in the relationship under consideration turned out to be higher than evidenced or assumed in the literature so far since its shape changed the form across the conditional distribution of greenhouse gas (GHG) emissions. Moreover, the paper shows that the use of efficient energy and renewable energy has the power to outweigh the scale effect. Simultaneously, it questions the efficiency of environmental and energy taxes and opens the issue of the rebound effect and the association between energy poverty and GHG emissions.

Keywords Environmental Kuznets curve · Classical effect · Substitution effect · Regulation effect · Energy poverty · Panel quantile regression

1 Introduction

The European Union (EU) has confirmed its commitment to tackling climate change as its priority and an opportunity for transitioning to a low-carbon economy through its strategic documents (European Commission, 2011, 2014). Although the EU works hard to achieve its emission reduction targets, greenhouse gas (GHG) emissions were at a higher level in 2018 than they were in 2014 (Eurostat, 2020). At the same time, GHG emissions significantly vary across EU countries, ranging from the average 6 tons per capita in Latvia to 24.93 tons per capita in Luxembourg in the period 2004–2018 (Eurostat, 2020). This raises concerns and calls for new policy actions.

Understanding the association between environmental degradation and the economy is important for creating adequate policy mitigation initiatives and consequently fully implementing strategic documents. This is because adequate policy actions and measures can

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stimulate economic growth and simultaneously ensure that it is low-carbon. The earliest empirical studies (e.g., Grossman & Krueger, 1991; Panayotou, 1992; Shafik & Bandyopadhyay, 1992) indicate a nonlinear relationship between environmental quality and income. In the last thirty years, this relationship has been receiving increased research attention within the framework of the environmental Kuznets curve (EKC). It hypothesizes the presence of an inverted *U*-shaped pattern between environmental quality and economic development.

While earlier studies investigated the validity of the EKC in a bivariate framework, and thus suffered from omitted variable bias, recent studies have tested its validity in a multivariate framework. This framework takes into account not only the effect of scale that causes a monotonic increase in GHG emissions, but also the composition and technique effect as well as the substitution and regulation effect that may more or less neutralize the strength of the scale effect. However, research results remain inconclusive. When it comes to the EU, for example, some studies discovered the existence of the EKC in the selected sample of EU countries (e.g., Lapinskiene et al., 2017a; Kasman & Duman, 2015; Destek et al., 2018; Armeanu et al., 2018), some failed to do so (Boluk & Mert, 2014; Mazur et al., 2015; Auci & Trovato, 2018), whereas some found evidence only for some EU countries (Acaravci & Ozturk, 2010; Neagu, 2019). The inconclusive results may stem from different pollutants used to represent environmental quality and the method applied, a different time period and geography covered, and different empirical settings. However, they can be a consequence of the fact that socioeconomic activity and policy decisions change the shape of the distribution of GHG emissions across EU countries. In particular, if larger effects were observed among high-emission countries, such findings would have important policy implications and would be important for GHG emission mitigation. Investigating the distributional heterogeneous effect of socioeconomic and policy variables on GHG emissions should increase our understanding of the effectiveness of programs aimed at reducing harmful emissions.

Recently, several studies have corroborated that the unobserved distributional heterogeneity across countries exists and the effects of determinants on adverse emissions (Chen & Lei, 2018; Zhu et al., 2018; Salman et al., 2019; Akram et al., 2020; Khan et al., 2020) and energy use (Borozan, 2019) are heterogeneous in their nature. Hence, they should not be ignored. However, they were focused on researching the impact of economic variables, while the impact of social and policy variables was neglected. Hence, the present paper aims to examine the distributional heterogeneous effect of socioeconomic (gross domestic product (GDP), energy consumption, human capital, energy poverty) and policy variables (environmental and energy taxes) on GHG emissions within the framework of the EKC in the EU over the period 2004–2017. It pays particular attention to detecting the possible unobserved distributional heterogeneity across EU member states and the role of the selected variables in the process of decoupling economic development from GHG emissions. To that end, it employs quantile regression for panel data (QRPD) developed by Powel (2016).

The contribution of the paper to the literature primarily refers to the improvement of our knowledge of the determinants affecting GHG emissions throughout its conditional distribution. Apart from economic variables, the paper tests the capacity of social and policy variables, which were neglected in previous studies, to outweigh the negative effect of scale on the GHG emissions distribution. The application of QRPD corroborates the heterogeneity effect across the selected quantiles of this distribution and suggests that the EKC shape depends on the power of scale, structural, technical, substitution, regulation and social effects.

The paper is structured as follows. The next section explains the conceptual background behind the EKC and reviews the related academic literature. The third section describes the data, the model and a panel quantile framework, while the fourth section presents and discusses the obtained empirical results. The last section concludes the paper and draws policy implications.

2 A conceptual framework and a literature review

Theoretical thinking on the association between the environment and economy may be found in two opposite streams of the literature (Panayotou, 2003). The first one considers economic growth as a main source of environmental degradation. Namely, further economic growth demands more energy and other resources, and consequently, it leads to ever greater levels of environmental degradation. Even if growth is assumed to have its limits (Meadows et al., 1972), unsustainable use of natural resources, emissions of pollutants, and accumulation of waste will exceed the carrying capacity of the Earth and cause deterioration of environmental quality. On the other hand, the second stream considers economic growth to be an important factor in enhancing environmental quality. If the latter is correct, there may be an inverted *U*-shaped pattern between environmental degradation and economic growth.

In the early 1990s, three papers written by Grossman and Krueger (1991), Panayotou (1992), Shafik and Bandyopadhyay (1992) unveiled an inverted *U*-shaped pattern between the relationship of interest and initiated a wave of research in this field. Grossman and Krueger (1991) empirically observed that the concentration of air pollutants increases with per capita GDP at its low level, while it decreases with per capita GDP at its higher level. Shafik and Bandyopadhyay (1992) noticed an important role of income and a minor role of economic policy in terms of environmental quality, whereas Panayotou (1992) coined this relationship as the EKC due to its resemblance to the behavioral pattern of income inequality and economic development hypothesized by Kuznets in the mid-1950s.

As already mentioned, the relationship under investigation has intrigued many scholars to continue researching it in order not only to verify its validity within different conditions, but also to explain it. The literature points to several mechanisms that may be responsible for a nonlinear dependence of environmental quality on a country's development path. Besides the classical ones, i.e., the scale and composition (structural) and technique effects, observed by Grossman and Krueger (1991), several other mechanisms were indicated as important ones. Stern (2004) observed the substitution effect, while Kaika and Zervas (2013) noticed, *inter alia*, the importance of equity of income distribution among others. Besides, Gassebner et al., (2011) pointed to the economical, demographic and governance mechanisms.

The scale effect reflects a simple fact that if the scale of economic activities expands, energy production and consumption will rise, and if the nature of those activities remains unchanged, then the pollutants will increase monotonically with economic growth (Grossman and Krueger 1991). However, if economic growth is followed by a structural change, environmental quality may improve or worsen, depending on whether more pollution-intensive activities contract or expand. It is plausible to expect that as the economy grows and produces fewer environmentally damaging products because of, for example, changes in trade and consumer patterns toward more ecologically favorable products, the composition effect will become stronger and result in a reduction of pollution and improvement in

environmental quality. Changes in input mix, which were also observed by Stern (2004), may have a favorable influence on environmental quality, as well as if less environmentally polluting inputs are a substitute for more polluting ones. Technological innovations change the way of producing and, hence, the composition and structure of production function from both the input and the output side. They also create new economic activities. As the economy grows, it can advance education and research and development (R and D) activities and technologically improve itself. New technology is usually more energy and environmentally efficient and conserving, as well as ecologically cleaner. As less pollution-intensive economic activities and output are multiplying, environmental quality is becoming less dependent on economic growth. Finally, economic and environmental policies may play an important role in increasing energy and other input efficiency, stimulating R and D activities and directing economic activities to those less environmentally damaging ones.

Clearly, the mechanisms act interrelatedly, and their net impact depends on the strength of the composition, substitution, technique and regulatory impacts and their capacity to outweigh the unfavorable impact of scale on GHG emissions. The EKC has been explored in many empirical studies, which can be classified into several groups depending on the criterion taken for the classification. Considering the aims of this paper and the fact that numerous reviews of the EKC literature already exist (as mentioned in the introduction), we provide an overview of the literature focused on the European environment.

Acaravci and Ozturk (2010) studied the causal association between adverse emissions, GDP and energy use in terms of per capita for the EU19 in the period 1960–2005. For that purpose, they applied the autoregressive distributed lag bounds testing framework. Their research indicated the presence of the EKC only in Denmark and Italy. Likewise, they discovered a long-run association between the selected variables only for seven EU countries. Morley (2012) revealed a negative impact of environmental taxes on GHG emissions by applying panel analysis for the EU23 and Norway for the period 1995–2006. But, his results were not in favor of the EKC. By applying fixed effects panel analysis, Boluk and Mert (2014) explored the association between CO₂ emissions, real GDP and final energy consumption (renewable and fossil fuels) in terms of per capita for the EU16 in the period 1990–2008. The authors also failed to find any statistical evidence in favor of the existence of the inverted *U*-shaped EKC, but rather a *U*-shaped relationship. Considering energy consumption, they concluded that both types of energy consumption give rise to carbon emissions; though, pollution caused by renewable energy is lower than pollution caused by fossil fuel consumption.

On the other hand, the results of Lapinskiene et al. (2015), obtained by using the fixed effects panel model and panel cointegration, corroborated the existence of the inverse *U*-shaped curve for the EU20 for the period 1995–2011. The size of agriculture, industry and construction, energy taxes, primary production of nuclear energy and R and D proxy have a statistically significant and favorable effect, while primary production of solid fuels has an unfavorable effect on the level of GHG emissions. Using the same methods together with panel causality tests, Kasman and Duman (2015) confirmed the validity of the EKC for the new EU countries in the period 1992–2010. They also revealed the short-run effect of energy consumption, trade openness and urbanization on adverse emissions. However, Mazur et al. (2015) failed to do that for the EU28 over the period 1992–2010. They employed static panel analysis (fixed and random effects) and proxied environmental degradation by CO₂ emissions without introducing other environmental variables.

Lapinskiene et al. (2017a) examined and confirmed the inverted *U*-shaped pattern between GHG emissions and economic growth by applying the fixed effects panel model for the EU22 in the period 1995–2014. Their research showed that higher energy

taxes and R and D decreased GHG emissions, while higher energy consumption had the opposite effect. The same method was applied in Lapinskiene et al. (2017b), when the EU20 were analyzed over the period 2006–2013, and the same results were obtained. Destek et al. (2018) tested the presence of the EKC given as the association between ecological footprint and per capita income by employing the second generation panel data methodologies in the EU28 over the period 1980–2013. They confirmed its existence and the favorable role of renewables and trade openness in decreasing environmental quality and offsetting the scale effect. Armeanu et al. (2018) also confirmed its existence in the case of GHG emissions and some other pollutants for the EU28 in the period 1990–2014. They applied fixed effects panel regression. Moreover, by using the panel vector error correction model, they found a short-run impact of GDP per capita growth on GHG emissions and the bidirectional causal relationship between primary energy consumption and GHG emissions. However, Auci and Trovato (2018), who focused on the dirtiest sectors of the EU25, revealed only a negative association between income and carbon emissions for the period 1997–2005. Their analysis, based on a comparison of a single and simultaneous equation model, showed that the composition effect matters, while the technique effect turned out to be different; the direct effect of R and D expenditures decreases pollution, but the source of R and D spending influences the indirect effect. By employing cointegrating polynomial regression, Neagu (2019) explored the relationship between the economic complexity index and carbon emission for the EU25 from 1995 to 2017. She corroborated the validity of the EKC for the whole panel as well as for six EU countries. Energy intensity statistically, significantly, and positively influences CO₂ emissions.

To summarize, the EKC has continuously attracted research attention since the 1990s. However, due to different pollutants and methods used, different time periods and geography covered, and different empirical settings, research results are mixed and inconclusive for the EU. An additional reason may be the fact that previous studies ignored in general the possibility that the economic activities and policy influence GHG emissions differently at different levels of its conditional distribution. This is not the case outside of the EU, where several papers aiming at examining the distributional heterogeneous effect on adverse emissions can be found. For example, Chen and Lei (2018) found out that selected economic variables, renewable energy consumption and technological innovation in particular, differently affect carbon emissions across its conditional distribution for 30 countries over the period 1984–2014. Zhu et al. (2018) put special emphasis on studying the heterogeneous effect of urbanization and income inequality on carbon emissions in BRICS countries (Brazil, Russia, India, China and South Africa) in the period 1994–2013. By using panel quantile regression, as Chen and Lei (2018), they unveiled the heterogeneous effect of the variable of interest.

The heterogeneous effect of industrialization and technology innovation on carbon emissions across seven ASEAN countries (Brunei, Indonesia, Malaysia, the Philippines, Singapore, Thailand and Vietnam) was the primary focus of Salman et al. (2019) over the period 1990–2017. To estimate their impact, they used panel quantile regression. The same method was applied in Akram et al. (2020) and Khan et al. (2020). The former paid special attention to studying the heterogeneous effect of energy efficiency and renewable energy on carbon emissions within the EKC framework for 66 developing countries for the period 1990–2014. The latter particularly investigated the effect of renewable energy consumption, financial development and internationalization on carbon emissions in 192 countries. These papers drew the same conclusion—the heterogeneous effect of the variable of interest matters.

Based on this brief review of the literature, it can be seen that only recently the heterogeneous effect of the selected variables across different quantiles of the carbon emission distribution has received much attention from scientists. There is also a lack of knowledge regarding the heterogeneous effect of social and policy variables thereon. This paper tries to fill this gap.

3 Data, model and method

3.1 Data and the model

Environmental degradation can be measured by using various indicators. In this paper, it is proxied by per capita GHG emissions since GHGs are considered to be the most important threat to global warming and climate change. This indicator, expressed in units of CO₂ equivalents, represents total national emissions of the ‘Kyoto basket’ of five GHGs (CO₂, methane, nitrous oxide, F-gases and sulfur hexafluoride) divided by the average population of the reference year. The set of independent variables, as shown in Eq. (1) and briefly described in Table 1 (the first column), includes seven variables:

$$ghg_{it} = f(gdp_{it}, energy_{it}, rmw_{it}, envir_tax_{it}, energy_tax_{it}, human_capital_{it}, poverty_{it}) \quad (1)$$

where indexes i and t denote an EU country ($i=1, \dots, 28$) and a period under consideration ($t=2004, \dots, 2017$), respectively. Table 1 explains the meaning of other symbols. The choice of variables followed primarily our intention to cover the classical regressors of GHG emissions revealed by the literature as well as to introduce a new one, i.e., a social variable. The data were provided by Eurostat (2020). It is annual, covering the period from 2004 to 2017.

The *gdp* variable proxies for economic development, i.e., the scale effect. It is a common independent variable in most studies in the field, whose impact on GHG emissions turned out to be far from straightforward. We followed the majority of studies mentioned in the previous section in terms of including both a linear and a nonlinear form of per capita GDP to be able to test the assumed inverted *U*-shaped pattern of the EKC.

Energy represents final energy use expressed in million tons of oil equivalents (TOE). Its inclusion into Eq. (1) reflects the fact that it is a primary reason for adverse GHG emissions. This variable may also reflect the scale effect since it is closely related to economic activity. Hence, it is frequently found in GHG equations (e.g., Acaravci & Ozturk, 2010; Boluk & Mert, 2014; Kasman & Duman, 2015; Lapinskiene et al., 2017a).

Unlike GDP and energy use, the share of renewables in gross final energy consumption (*rmw*) may simultaneously indicate the composition effect (a transition toward less pollution-intensive industries) and the substitution effect (from fossil fuel energy toward renewables). The EU has put an emphasis on renewable energy, particularly because of its concerns about climate change. It supports the growth in renewables by various measures to boost investment in this sector and consequently ensure a decrease in GHG emissions. The effect of renewables on environmental quality has already been a subject of many empirical studies (e.g., Boluk & Mert, 2014; Destek et al., 2018; Auci & Trovato 2018; Chen & Lei, 2018).

The technique effect is proxied with the human capital variable (*human_capital*), i.e., a percent of persons in active population employed in science and technology. Human capital

Table 1 Summary statistics

Variable	Symbol	obs	Mean	Std. Dev	Min	Max	Skewness	Kurtosis	VIF
Greenhouse gas emissions (tones of CO ₂ equivalent per capita)	<i>ghg</i>	392	10.306	4.09	5.0	30.8	2.042	9.393	
Real GDP per capita (in 2010 euro per capita)	<i>gdp</i>	392	24,597.70	15,858.57	3,900	84,400	1.395	5.706	1.05
Final energy consumption, million TOE	<i>energy</i>	392	40.63	53.58	0.45	223.6	1.857	5.561	1.17
Share of renewable energy in gross final energy consumption (in %)	<i>mw</i>	392	4.05	4.16	0	32.112	2.996	17.220	1.21
Total environmental taxes (% of GDP)	<i>envir_tax</i>	392	2.62	0.61	1.57	4.99	0.841	3.845	2.0
Energy taxes (% of GDP)	<i>energy_tax</i>	392	1.95	0.46	1.08	3.32	0.674	3.205	2.09
Human resources in science and technology (% of active population)	<i>human_capital</i>	392	41.67	8.80	21.4	64.5	-0.030	2.328	1.49
Population unable to afford to live in a warm home by poverty status (in %)	<i>poverty</i>	370	11.92	12.44	0.3	69.5	2.036	8.074	1.50

VIF, skewness and kurtosis were calculated by using the log forms of the *ghg*, *energy* and *gdp* variables

enables wise use of energy and other environmental inputs (Borozan, 2018a). On the other hand, it should be an endogenous driver of improvements in technology and ecological innovations as well as of low-carbon growth in general. In turn, technological progress that takes care of the environment may reduce the strength of the scale effect and mitigate GHG emissions by focusing on technologies, processes, goods, and services that generate less environmental damage in general and less damage to the atmosphere in particular. Other studies have incorporated the possible technique effect into the GHG equation mostly in the form of R and D expenditure (e.g., Lapinskiene et al., 2017a, b; Auci & Trovato, 2018). In contrast, we wanted to highlight the endogenous character of technological progress discovered by endogenous growth theories.

Policy variables, i.e., the regulation effect, are represented by environmental and energy taxes. The former (*envir_tax*) includes environmental taxes referring to energy, transport, pollution, and resources. The latter (*energy_tax*) refers to total energy taxes paid for energy products. Both variables enter the model as a percentage of GDP. According to theoretical expectations, they should foster a more efficient use of resources including energy and thus have a favorable influence on GHG emissions. The effect of the environmental and energy tax variables on adverse emissions has been investigated, for example, by Lapinskiene et al. (2017b).

Finally, the social effect is proxied by energy poverty (*poverty*), i.e., population unable to afford to live in a warm home due to their poverty status. The issue of energy poverty has attracted more policy and research attention, particularly after the recent Great Recession and rising energy costs (Borozan, 2018a, b). The reasons therefor have been corroborated by recent studies by Pye et al. (2015), who revealed that nearly 11% of the EU population face energy poverty. However, this variable was mostly ignored in previous EKC studies.

3.2 Method

The assumed presence of significant heterogeneity in the EU considering GHG emissions calls for the implementation of the panel quantile framework. We employed the quantile regression estimator for panel data with non-additive fixed effects developed by Powell (2016). This method generates several advantages compared with commonly used panel regressions (Powell, 2016); it addresses both individual and distributional heterogeneity at the same time and consequently enables us to create a deeper understanding of GHG determinants. More precisely, it provides estimates of the effects of the variables of interest throughout the GHG conditional distribution. As underlined by Powell (2016), the interpretation of the estimated coefficient is the same as in cross-sectional regression, and the method provides reliable estimates from small T (time). Following Powell (2016), the underlying model is expressed as follows:

$$Y_{it} = D'_{it}\beta(U_{it}^*) \quad (2)$$

where Y_{it} represents the outcome variable of an individual i in time t , β_j are parameters of regressors, and D_{it} stands for the set of regressors. The error term related to fixed and time-varying disturbance terms is denoted by U_{it}^* , where $U_{it}^* \sim U(0, 1)$. As stated by Powell (2016), for the τ th quantile of Y_{it} , quantile regression is based on the conditional restriction:

$$P(Y_{it} \leq D'_{it}\beta(\tau) | D_{it}) = \tau \quad (3)$$

which suggests that the probability of the outcome variable is smaller than the quantile function. According to Eq. (3), it is the same for all D_{it} and equals the quantile index (τ). In this paper, in line with Sarkodie and Strezov (2019), QRPD with non-additive fixed effects was employed to estimate the coefficients of regressors of the following model:

$$\begin{aligned} ghg_{it}(t|/2a_i, d_t, x_{it}) = & a_i + d_t + b_{1t}gdp_{it} + b_{2t}gdp_{it}^2 + b_{3t}energy_{it} + b_{3t}rnmw_{it} + b_{4t}envir_tax_{it} \\ & + b_{5t}energy_tax_{it} + b_{6t}human_capital_{it} + b_{7t}poverty_{it} + n_{it} \end{aligned} \quad (4)$$

where x refers to the matrix of independent variables related to a country i and time t , and α_i and δ_t stand for the fixed and time effect, respectively. They are inseparable from the regressors. The error term is denoted with ν_{it} and $\tau = (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9)$. The ghg , gdp and $energy$ variables are expressed in natural logarithms. We expect the effect of regressors to be heterogeneous along the GHG emissions distribution.

Powell (2016) underlined that this method successfully solves an interpretation or consistency issue which is inherent to the additive fixed effects quantile estimator. He also pointed out that his estimator allows for an arbitrary relationship between the country-fixed effects and the instruments, as well as that the relationship between the error term and the fixed effect can be arbitrary. One should note that QRPD is set in an instrumental variable framework to account for the possible endogeneity issue that can be observed in Eq. (2). For additional information, see Powel (2016).

A panel quantile regression analysis was conducted in Stata 13.0. It employs the *qregpd* command (Baker et al., 2016), which uses the adaptive Markov Chain Monte Carlo procedure for numerical optimization and an instrumental variable framework.

4 Results with discussion

4.1 Preliminary analysis

In an effort to unveil the distributional heterogeneity effect hidden in the EKC, a descriptive analysis is performed. Its results, shown in Table 1, indicate the presence of considerable heterogeneity across EU countries. GHG emissions vary considerably across countries, whereby more developed ones generally have higher emissions. Notable exceptions are Sweden, with relatively small average emissions (6.61 tons of CO₂ equivalent per capita), but the highest average share of renewable energy (15.08%), and Estonia, with high average emissions (15.16 tons of CO₂ equivalent per capita) and the lowest average share of renewable energy in gross final energy consumption (0.32%). More developed countries consume more energy and have more developed human capital and fewer people facing fuel poverty. Environmental and energy taxes also vary across EU countries, but they are not statistically significantly correlated with GDP (Table 3 in the appendix). All variables are more or less skewed. This fact provides an additional argument to implement the QRPD framework to explore the effect of selected regressors on the quantiles of GHG emissions.

Regarding GHG emissions, the lower quantiles (below the 25th percentile) include countries with lower per capita GHG emissions, such as Latvia, Romania, Croatia or Sweden. The quantiles between the 25th and the 50th percentile include countries such as France, Bulgaria, Spain, Italy or Slovenia. The quantiles between the 50th and the 75th percentile include countries such as the UK, Austria, Poland, Belgium or Cyprus, while

quantiles above the 75th percentile include countries with high GHG emissions, such as the Netherlands, Finland, Estonia and Luxembourg.

The correlation matrix (Table 3) does not reveal a strong correlation between GHG emissions and its regressors, which further lessens the probability that estimated coefficients would be inconsistent and biased. Additionally, the estimated variance inflation factors (VIF) (Table 1) point out that multicollinearity will not adversely affect the QRPD results. Our preliminary analysis ended with stationarity testing. For that purpose, the Levin–Lin–Chu test and the Im–Pesaran–Shin unit-root test with removed cross-sectional dependence were used. Their results, which suggest a rejection of the null hypothesis of panel unit roots at the 5% significance level, are provided in Table 4 in the appendix. Consequently, the analysis continues with the variables at level.

4.2 Results

The empirical analysis started with the estimation of static panel models. Its results, given in Table 5 in the appendix, suggest per capita real GDP has ceased to be a statistically significant determinant of GHG emissions, indicating thereby that the EKC is not a valid case for the EU. According to Model 3A in the appendix, which is the quadratic representation of Eq. (1), the larger the share of renewables, the higher the energy taxes, human capital and poverty leading to the mitigation of GHG emissions, while final energy consumption and environmental taxes have the opposite effect. However, the estimated coefficients of the QRPD models with non-additive fixed effects (Table 2) confirm that the nonlinear association between adverse emissions and economic development together with other explanatory variables is more complex than suggested by the estimated fixed effects panel models.

Table 2 displays the results of three different models for the selected percentiles of the GHG emission conditional distribution. Model 1 shows the results for the bivariate case, while Models 2 and 3 give results for the models specified by Eq. (1). Different specifications of the models in Table 2 corroborate the robustness of the results obtained. The ratio of renewable energy within total energy consumption, human capital and poverty variables is statistically significant determinants across almost all quantiles of the GHG emissions distribution, while the effects of economic development and policy variables vary from significant to insignificant. Considering the aims of the paper, we proceed by focusing primarily on the discussion of the results of Model 3, keeping the *ceteris paribus* assumption in mind.

4.3 Discussion

The relationship between GHG emissions and economic development turned out to be statistically significant only at lower quantiles of GHG emissions distribution. At the lowest quantiles, which is characteristic of less developed EU countries such as Latvia, Romania or Croatia (except Sweden), it had a statistically significant *U*-shaped form, indicating that economic development itself cannot ultimately cause a reduction in adverse emissions. Boluk and Mert (2014) drew the same conclusion for their sample composed of 16 mostly developed EU countries for the period 1990–2008. Yet, the considered relationship in that paper transformed into a statistically significant inverted *U*-shaped form around the median quantile and the EKC became valid for countries such as Italy, Slovenia, Spain or the UK. However, at the highest quantiles, in countries such as Luxembourg, Estonia, Ireland of Finland, an observed inverted *U*-shaped relationship remained, but it became statistically

Table 2 Panel quantile regression results

Independent variable	Estimated coefficients								
	10th	20th	30th	40th	50th	60th	70th	80th	90th
Model 1									
<i>ln(gdp)</i>	-1.044*	-0.438*	-2.772*	1.710*	2.797	3.331	0.396	0.317	-0.511
<i>ln(gdp)²</i>	0.055*	0.023*	0.139*	-0.087*	-0.146	-0.169	-0.017	-0.005	0.012
Model 2									
<i>ln(gdp)</i>	0.034*	-0.157*	-0.091*	-0.064*	-0.075*	0.139*	-0.025***	-0.039	-0.043
<i>ln(energy)</i>	0.070*	0.002	0.054*	0.034*	0.032*	0.022*	0.002	0.005	-0.058***
<i>rnw</i>	-0.018*	-0.015*	-0.035*	-0.039*	-0.035*	-0.024*	-0.022*	-0.018***	-0.002
<i>envir_tax</i>	0.210*	0.161*	0.183*	0.049*	0.006	0.094*	0.021	-0.036	0.371
<i>energy_tax</i>	-0.237*	-0.190*	-0.219*	-0.082*	-0.016*	-0.122*	0.039	0.188**	-0.312
<i>human_capital</i>	0.008*	0.003*	0.018*	0.018*	0.018*	-0.005	-0.017	0.012***	0.018*
<i>poverty</i>	0.002*	0.001*	0.002*	-0.001*	-0.003*	-0.009*	-0.005*	-0.005***	0.012
Model 3									
<i>ln(gdp)</i>	-2.352*	-3.342*	0.601*	1.275*	0.364	0.456	0.222	0.758	0.745
<i>ln(gdp)²</i>	0.120*	0.170*	-0.033*	-0.069*	-0.022	-0.027	-0.018	-0.041	-0.041
<i>ln(energy)</i>	0.084*	0.085*	0.045*	0.024*	0.014*	0.010	-0.029*	-0.028*	-0.059*
<i>rnw</i>	-0.014*	-0.022*	-0.035*	-0.043*	-0.037*	-0.034*	-0.033*	-0.039*	-0.038*
<i>envir_tax</i>	0.219*	0.227*	0.142*	0.008	0.011	0.000	-0.014	-0.037	-0.013
<i>energy_tax</i>	-0.202*	-0.243*	-0.190*	-0.041	0.009	0.011	0.110	-0.007	0.086
<i>human_capital</i>	0.001	0.005*	0.018*	0.019*	0.015*	0.017*	0.017*	0.016*	0.009*
<i>poverty</i>	-0.005*	-0.008*	0.002*	-0.002*	-0.004*	-0.004*	-0.007*	-0.006*	-0.010*

* $p < 0.01$; ** $p < 0.05$; *** $p < 0.1$. *ln(g/g)* is a dependent variable. A robust standard error was employed in all model specifications to account for the possible issues of heteroscedasticity and autocorrelation

insignificant. This, supported by the effect paths of total and renewable energy consumption, could be a sign of decoupling environmental quality from economic development. However, the assessment of the success and the magnitude of decoupling in this group of countries requires further analysis. One should note that the evidence in favor of decoupling was found in some studies (e.g., Vavrek & Chovancova 2016, for the Czech Republic, Hungary, Poland and Slovakia; Mikayilov et al., 2018, for eight developed EU countries). However, Moreau et al. (2019) delineated that much of perceived decoupling in the EU is virtual, and Ward et al. (2016) even argued that decoupling is impossible. Zhu et al. (2018) also detected a stronger presence of the inverted *U*-shape form of the EKC in BRICS countries at lower quantiles, but it also become statistically insignificant at higher quantiles of the CO₂ distribution.

Energy consumption statistically significantly influences GHG emissions at almost all quantiles. This effect, particularly unfavorable to GHG emissions at lower energy consumption levels and in the fixed effects panel model, indicates that energy consumption is their significant source. The unfavorable effect of energy consumption on GHG emissions has been revealed by other studies in the EU (Acaravci & Ozturk, 2010; Boluk & Mert, 2014; Lapinskiene et al., 2017a; Kasman & Duman, 2015) and on CO₂ emissions in BRICS countries (Zhu et al., 2018). This study shows that energy is utilized more efficiently. Thus, its unfavorable effect becomes first weaker and then favorable and stronger at the higher GHG levels, meaning that higher values of this indicator are associated with lower levels of GHG emissions. This may be a result of not only an increase in energy efficiency, but also structural changes happening in these economies, particularly in relation to the changes in the energy mix directed toward using more environmentally friendly energy.

The effect of renewable energy is always significantly favorable, suggesting that it mitigates the scale effect and fastens the shift of the EU toward a low-carbon economy. This is particularly pronounced at higher quantiles, where the estimated coefficients become higher and more powerful. Lapinskiene et al. (2017a, b) corroborated that the effect of structural changes expressed in terms of the transition from highly polluting sectors toward less polluting ones happened, and hence, this matters to the EU. Likewise, Cruz and Diaz (2016) found that structural changes toward less carbon-intensive transformation processes, activities and products together with an increase in energy efficiency contributed to a decrease in carbon emissions in the EU. However, Boluk and Mert (2014) found an unfavorable effect of both fossil and renewable energy consumption, whereby the former has a larger effect on environmental degradation. It seems, which can explain the divergence in these results, that renewable energy technologies have advanced so much and the share of renewables has increased enough over the past ten years to increase efficiency of renewables and reduce GHG emissions. Destek et al. (2018) also recognized the potential of renewable energy in reducing GHG emissions in the EU, and Akron et al. (2020) and Khan et al. (2020) confirmed that the aforementioned holds for developing countries. However, as Chen and Lei (2018) pointed out, its role in reducing harmful emissions, although significant, is limited by a small share it still has in total energy consumption.

Environmental and energy taxes have a statistically significant unfavorable and favorable effect on GHG emissions at lower GHG quantiles, respectively, and an insignificant effect at higher quantiles of the GHG conditional distribution. Additionally, energy taxes influence GHG emissions relatively stronger than environmental taxes, which can be a consequence of the fact that energy taxes still play a more important role in energy use than, for example, carbon taxes (OECD, 2017). Likewise, Lapinskiene et al. (2017b) showed that higher energy taxes decreased, while environmental taxes increased the level of GHGs in the EU20 over the period 2006–2013. However, Morley (2012) discovered a negative

sign in front of the estimated environmental tax variable. From a theoretical point of view, a negative, i.e., favorable impact of taxes on adverse emissions is expected. The EU has favored these taxes because of numerous benefits they may generate (see Gago et al., 2014). However, Borozan (2018b) revealed poor efficiency of energy or environmental taxes and a redistribution effect in the EU over the period 2005–2017. This may be a consequence of abundant subsidies, exemptions or reduction schemes that have reduced the efficiency of taxes. Interestingly enough, Morley (2012) pointed out that a reduction in GHG emissions is predominantly a consequence of using cleaner technologies and not environmental taxes since they do not reduce energy consumption. Clearly, to be fully efficient and effective, the whole environmental policy set of instruments should be reformed.

Technological innovations matter for GHG emission mitigation, and the share of highly educated labor force, particularly those employed in R and D sectors, is important. In fixed effects panel models (Models 2A and 3A), the estimated regression coefficients referring to this variable have a negative sign, meaning that their higher values are associated with lower levels of GHG emissions. However, in panel quantile models, it has been shown that people employed in R and D activities rebound. Although they get higher salaries and have better financial capacities to buy environment-friendly products than poorer and less educated people, they demand and consume more energy as well as energy and environmental services (Borozan, 2018a, 2019). Hence, they produce more GHG emissions. This effect is particularly small at the lowest level and exhibits a decreasing tendency at higher levels of GHG emissions. Vivanco et al. (2016) have already observed the rebound effect in the EU as a potential cause of offsetting some of predicted reduction in adverse emissions. However, as they highlighted, the effect itself is not fully understood and adequately tackled by EU policy. To reverse a possible effect of highly educated people on GHG emissions, changes in consumption behavioral patterns and new low-carbon investments are likely to be needed, as suggested by Borozan (2019), who detected a rebound effect of highly educated people with respect to energy consumption. Moreover, Bjelle et al. (2018) demonstrated that preventing the rebound effect from triggering may contribute to reduced harmful emissions. Therefore, behavioral changes in consumption patterns are necessary to that end. Investments in low-carbon technology are specifically needed to improve environmental efficiency and energy efficiency in particular. This was confirmed in a study by Salman et al. (2019), who stressed that the importance of technology innovation is especially pronounced at higher quantiles of carbon emission distribution. The authors particularly highlighted the indirect effect of technology innovation on the process of reducing harmful emissions: it reduces energy consumption by augmenting energy efficiency and stimulates changes in energy consumption patterns toward more sustainable ones.

Finally, energy poverty statistically significantly and mainly negatively affects GHG emissions at all quantiles. Although the magnitude of this effect is the lowest compared to other regressors, the existence of energy poverty should not be ignored in the EU. Energy and generally poverty is a huge economic, social and political issue that should be eradicated. Zhu et al. (2018) provided evidence that an increase in income inequality leads to the environmental quality deterioration. In the highest quantile level, our finding is consistent with their finding—the impact of income inequality is statistically insignificant as it is the impact of energy poverty in Model 2. However, as expected, the impact of income inequality is much stronger in BRICS countries than the impact of energy poverty in the EU. Li et al. (2018) showed that economically deprived areas are facing even more environmental degradation, while Chakravarty and Tavoni (2013) pointed out that although energy poverty eradication on a global level would increase energy demand and adverse emissions, this could be done within manageable boundaries and the benefits to human life and

dignity would be immense. Hence, economic strategies directed toward minimizing this issue should be combined with energy and environmental measures and actions. However, as highlighted by Malerba (2019), little is known about how energy poverty may impact carbon reduction targets and climate changes; thus, new research in this field is needed.

To summarize, the paper demonstrates that a behavioral pattern between environmental degradation and economic development is far more complex than the existing literature has ever thought. All regressors turned out to be important determinants of GHG emissions but mostly at different levels of the GHG conditional distribution, which calls for different policy mitigation measures and actions.

5 Conclusion

In an effort to unveil the true form of the behavioral pattern between economic development and environmental quality and the mechanisms explaining it such that proper policy measures aimed to improve the environment without endangering growth can be defined, the EKC associated hypothesis has gained significant research attention. However, there is limited understanding of its true form and mechanisms explaining it. The present paper explored the relationship between GHG emissions and economic development for 28 EU Member States in a multivariate framework over the period 2004–2017. A panel quantile regression method employed to that end enabled us to investigate the effects of selected regressors on the specified quantiles of the GHG conditional distribution.

The results corroborated a heterogeneous effect across the GHG conditional distribution in general and revealed that at lower quantiles, referring to those lower GHG emission economies, the effect of per capita real GDP followed a *U*-shaped curve. However, at higher quantiles, the inverted *U*-shaped form became valid, significantly below the median and insignificantly after the 50th quantile. The results also revealed that unlike the rebounding technique effect, the structural effect mitigates the scale effect. Policy variables (a regulatory effect) turned out to be ineffective at most quantiles, while the energy poverty variable statistically significantly influenced GHG emissions across all quantiles.

Based on empirical results, several policy implications may be drawn. Since the EU is strongly devoted to achieving environmental and energy policy targets between 2020 and 2050 and becoming a low-carbon economy, it has adapted a wide range of policies and measures. However, their implementation remains a challenge, particularly due to considerable differences in the level of economic development. Per capita GDP turned out to have a heterogeneous effect on GHG emissions, indicating that in general economic development itself cannot ultimately reduce GHG emissions. It is a necessary but not a sufficient condition. Environmental and energy policies, instruments and measures are important for that purpose, but their effectiveness and efficiency vary across GHG distribution. This implies that, in addition to a general framework that should be more pro-environmental, the EU still needs specific and country-fitted national policies.

Specifically, the existing environmental regulation effect expressed through environmental and energy taxes needs to be reformed to discourage inefficient energy use and mitigate GHG emissions. Namely, it seems that numerous subsidiaries, exemptions or reduction schemes implemented in EU countries have a counterproductive effect. An exemption is the energy tax, which is effective, but only in countries with the lowest level of GHG emissions. The government of each country should create a more efficient package of policy instruments, taking into account at the same time the need to have a more uniform

distribution of the tax burden. Moreover, regarding collected tax revenues, more pro-environmental recycling options have to be implemented.

In addition, as shown by the results, energy consumption and GHG emissions are inter-related. A mitigation effect occurs when renewable energy consumption comes into play and energy is used in a more efficient way. Estimated coefficients of energy consumption show that the unfavorable effect on GHG emissions becomes first weaker and then inverse and stronger at higher GHG levels. Structural shifts toward less pollution-intensive activities and sources of energy as well as an increase in energy efficiency showed positive effects and, consequently, have to be additionally supported. Investment in new innovative and advanced energy-efficient and low-carbon technology is certainly a good way of achieving that goal. Technological progress is the driving force that may ensure the substitution of non-renewable energy with renewable one and, consequently, as the results of this paper corroborate, reduce GHG emissions.

However, to have such effects, investment and technological progress in general have to be followed by changes in the existing and the development of new education programs, which will put specific emphasis on environmental aspects that have to be implemented in regular education programs at all levels. Namely, our results show that highly educated people, even employed in R and D, rebound irrespective of the level of GHG pollution involved. The role of media can also be important in promoting environmental awareness and energy-efficient and environmentally friendly behavioral patterns, and policy measures should accelerate the transition toward the desirable one.

Finally, this paper opens a question of the association between energy poverty and GHG emissions. Energy poverty should be eradicated, no doubt about it. However, this should be done simultaneously with addressing adequately GHG emissions and climate change. Environmental and energy policies cannot do that alone; they should be consistently combined with economic policies. In so doing, they should not only stimulate economic growth, among others, by promoting investment in new environmentally and energy friendly technology aimed at reducing production costs, but also ensure more and more efficient environmental public services and goods and provide different environmentally informative, education and awareness-raising programs for poor people.

Since environmental and energy taxes turned out to be inefficient instruments in higher-emission countries, further research should focus more on testing the effectiveness of other policy instruments in countries with different levels of GHG emissions. In this regard, it would also be interesting to investigate the short- and long-term effects of social and policy variables on GHG emissions, particularly in lower- and higher-emission countries. Moreover, testing their heterogeneous effect in the sample made of more lower- and higher-emission countries will reduce the main limitations of the paper, its relatively small sample at the extreme of the GHG emissions distribution and its regional character, and thus provide a better foundation for the generalization of the findings.

Appendix

See Appendix Tables 3, 4 and 5.

Table 3 Pearson correlation coefficients

	<i>ln(ghg)</i>	<i>ln(gdp)</i>	<i>ln(energy)</i>	<i>rnw</i>	<i>envir_tax</i>	<i>energy_tax</i>	<i>human_capital</i>	<i>poverty</i>
<i>ln(ghg)</i>	1							
<i>ln(gdp)</i>	-0.0549	1						
<i>ln(energy)</i>	0.0115	-0.0828	1					
<i>rnw</i>	-0.2510*	0.0317	0.2445*	1				
<i>envir_tax</i>	0.051	0.0278	-0.2446*	-0.1774*	1			
<i>energy_tax</i>	-0.0251	-0.0291	-0.1386	-0.1156	0.6717*	1		
<i>human_capital</i>	0.4209*	0.1065	0.0936	0.3361*	0.0778	-0.075	1	
<i>poverty</i>	-0.3256*	-0.1638*	-0.2366*	-0.2471*	0.0547	0.1929*	-0.5052*	1

* $p < 0.05$

Table 4 Stationarity test results

	Levin-Lin-Chu unit-root test				Im-Pesaran-Shin unit-root test	
	Constant only		Trend		Const	Trend
	Adjusted t^* stat	p value	Adjusted t^* stat	p value	t -bar	t -bar
<i>ln(ghg)</i>	-3.3147	0.0005	-7.3202	0.000	-1.4328	-2.3188
<i>ln(gdp)</i>	-4.5825	0.0000	-9.5719	0.000	-1.2030	-1.5748
<i>ln(energy)</i>	-2.1187	0.0171	-4.3203	0.000	-1.6953	-2.3880
<i>rnw</i>	-2.5155	0.0059	-8.5755	0.000	-1.4226	-1.9774
<i>poverty</i> *	177.7300	0.0000	232.4750	0.000		
<i>human_capital</i>	-3.6850	0.0001	-5.5636	0.000	-1.4560	-2.1758
<i>envir_tax</i>	-3.2596	0.0006	-5.4953	0.000	-1.2683	-1.8979
<i>energy_tax</i>	-1.4268	0.0768	-5.5748	0.000	-1.2282	-2.0447

The null hypothesis: panels contain unit roots.

*The Fisher-type Phillips-Peron unit-root test was employed to test for the stationarity. We reported the statistics for inverse chi-squared. The null hypothesis for this test: all panels contain unit roots

Table 5 Static panel models

Independent variables	Model 1A random effects		Model 2A fixed effects		Model 3A fixed effects	
	Estimated coeff	Robust std.err	Estimated coeff	Robust std.err	Estimated coeff	Robust std.err
<i>ln(gdp)</i>	-0.007	1.304	0.042	0.109	-0.027	1.177
<i>ln(gdp)2</i>	0.007	0.066			0.004	0.062
<i>ln(energy)</i>			0.526**	0.213	0.524**	0.211
<i>rmw</i>			-0.007*	0.002	-0.007*	0.002
<i>envir_tax</i>			0.145*	0.045	0.145*	0.046
<i>energy_tax</i>			-0.101**	0.046	-0.101**	0.046
<i>human_capital</i>			-0.002	0.003	-0.002	0.003
<i>poverty</i>			-0.003***	0.002	-0.003***	0.002
<i>const</i>			0.426	1.053	0.747	5.580
<i>Pseudo R²</i>	0.6178 ^a		0.7411 ^a		0.7411 ^a	
<i>F-stat</i>	(15, 27) 784.15		(20, 27) 110.93		(21, 27) 206.74	
Hausman test	3.38 (<i>p</i> =0.185)		51.31 (<i>p</i> <0.01)		50.54 (<i>p</i> <0.01)	
Time variable test	427.44 (<i>p</i> <0.01)		7.79 (<i>p</i> <0.01)		8.01 (<i>p</i> <0.01)	

p* < 0.01; *p* < 0.05; ****p* < 0.1.

^adenotes the coefficient of determination (*R*²) within statistics. *ln(g/g)* is a dependent variable. A robust standard error was utilized in all models. Time variables were included in all models and they turned out to be statistically significant (*F*(13 27) = 8.01; *p* < 0.01). The Hausman test confirmed the application of the panel regression model with fixed effects for Models 2A and 3A, and the panel model with random effects for Model 1A

Funding This work was supported by the Croatian Science Foundation (IP-2020-02-1018) and the Faculty of Economics in Osijek (EFOS_ZIP2020/21–4). No funding was received to assist with the preparation of this manuscript.

Declarations

Conflict of interest The author has no relevant financial or non-financial interest to disclose.

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