RESEARCH PAPER

IMPACT OF COAL-BASED ELECTRICITY GENERATION, LAND USE CHANGE, STEEL AND CEMENT PRODUCTION ON CO_2 EMISSIONS: EVIDENCE FROM EASTERN EUROPEAN AND CENTRAL ASIAN COUNTRIES

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ABSTRACT. The problem of studying carbon footprint factors is one of the key ones for understanding the relationship between socio-economic development and atmospheric pollution. We employ a panel quantile regression approach to reveal the impact of the energy sector (namely, coal-based electricity and hydropower generation), manufacturing (steel and cement production), and agriculture (cropland area change) on CO_2 emissions in 16 Eastern European and 4 Central Asian countries for the period from 2000 to 2020. We provide evidence for a U-shaped environmental Kuznets curve for countries with a lower carbon footprint, while the countries with the highest emissions are found to have an inverted U-shaped relationship between them and GDP per capita. The relationship between electricity production from coal and emissions is positive and significant at all quantiles (except the 30th quantile), and for hydropower, it is negative and significant from the 20th to 70th quantile: a 1% increase in generation leads to CO_2 emissions increase by 0.08-0.20% and a decrease by 0.04-0.07%, respectively. Crude steel production positively influences emissions (from the 10th to 80th quantile levels): a 1% increase in the output of steel products results in carbon emissions increase by 0.05-0.07%. The relationship between cropland expansion and emissions is positive from the 40th quantile, but the coefficient shows high significance only at the 80th quantile. These findings allow us to conclude that CO_2 emissions reduction in Eastern European and Central Asian countries could be achieved by the replacement of coal in the electricity generation structure by renewables (including hydropower), the introduction of sustainable land use practices to preserve carbon sinks, and technological modernization of crude steel production.

KEYWORDS: CO_2 emissions, coal-based electricity generation, hydropower generation, land use change, steel production, cement production

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INTRODUCTION

Climate change is increasingly affecting global economic growth. More extreme weather events due to rising surface air temperatures make it harder for economies to grow. This means that international organizations and national governments need to create strong climate policies to address these issues. Numerous studies confirm hypotheses about such consequences of global warming as an increase in extreme weather events, melting glaciers and rising sea levels, ocean acidification, and a decrease in biodiversity. It is obvious that humanity will increasingly experience the consequences of climate change – the main threats include deteriorating human health, declining crop yields, and a sharp growth in the number of environmental migrants.

UN expert bodies and international organizations uniting economically developed countries play a coordinating role in developing measures to mitigate the consequences of climate change and adapt humanity to them. Regular international events within the framework of the United Nations Framework Convention on Climate

Change (UNFCCC) play an important role in uniting efforts in the field of regulating anthropogenic influence on the climate. However, a number of environmental organizations consider the decisions made to be half-hearted and not revolutionary enough. The Paris Agreement, signed at the 21st UN Climate Change Conference, stands out in the list of recent climatic treaties. It aims to limit surface temperature increase compared to pre-industrial times to 2°C by 2100. The signatories also set themselves a more ambitious goal: to strive to keep global warming within 1.5°C by the end of the century. As of the end of 2022, of the 194 countries that have signed up to the Paris Agreement, 136 countries have set a target date for achieving carbon neutrality (usually 2050). However, the number of signatories that have become involved in the decarbonization process remains small: fewer than 30 countries have launched programs to reduce CO_2 emissions.

Carbon dioxide emissions are a key dependent variable in econometric studies of anthropogenic pressure on the atmosphere. Several factors explain this fact. First, research on the causes and consequences of carbon dioxide air pollution has been studied to the greatest extent compared to other types of pollutants, including gases and organic and inorganic particulates. The task of constructing hypotheses and explaining the results of mathematical models is greatly simplified if we consider the already studied effects of CO_2 emissions on the environment, described by climatologists, geographers, and ecologists.

Secondly, an important reason for using CO_2 emissions as a proxy to assess the anthropogenic load on the climate system is the availability of statistical data at the national and international levels (World Bank, OECD, IEA, EDGAR, Eurostat, etc.). However, statistics are also collected and processed for other gaseous emissions. For example, Climate Watch platform provides data for methane (CH_4), nitrous oxide (N_2O), fluorinated gases (F-gases), and greenhouse gases in total.

Thirdly, studies of carbon dioxide emission factors have important practical significance since they make it possible to develop recommendations for adjusting the climate policies of developed and developing countries. The results of the analysis in most studies are policy implications for government agencies and businesses to reduce CO_2 emissions, including those related to the implementation of international obligations to achieve carbon neutrality. The need to achieve target CO_2 emissions in a short time frame determines the special interest of researchers in carbon dioxide and not in any other air pollutant.

The main objective of this paper is to investigate the impact of coal-based electricity generation, land use change, steel and cement production on carbon dioxide emissions in 16 Eastern European and 4 Central Asian countries (in 2000-2020)[1]. We employed panel quantile regression approach in order to deal with individual and distributional heterogeneity.

Given the high level of elaboration of the topic, it is very difficult for each new study to make a scientific contribution to the problem of understanding the relationship between social development and atmospheric pollution. Typically, the authors proceed by examining a new sample of countries, applying improved econometric models, and incorporating nonobvious explanatory variables. In our case, we focused on studying the countries of Eastern Europe and Central Asia, which are rarely the subject of study, and we chose such independent variables that, to our knowledge, have never been used to estimate the dynamics of CO_2 emissions in the 21st century (steel production, cement production, electricity production from coal and cropland area). We did not succeed in finding any studies that deal explicitly with the nexus between these variables and CO_2 emissions. Essentially, we are trying to understand which areas of the economy – energy sector, agriculture, or manufacturing – have a decisive influence on the increase of carbon footprints in given countries.

As we already mentioned, the countries of Eastern Europe (EE) and Central Asia (CA) were chosen as the object of study since they are rarely in the focus of attention of researchers as a relatively homogeneous group with a comparable set of development characteristics (like embedded institutions, organization of industrial systems, energy balance structure, etc.). Individual Central-Eastern European (CEE) and South-Eastern European (SEE) countries are often included in samples with other OECD or European Union countries. In general, the geographical scope of studies of CO_2 emissions factors was initially limited to high-income economies due to the greater volume of accumulated knowledge, the maturity of climate policy, and the availability of relevant statistical data. Later, an increasing number of authors focused on studying the causes of air pollution in developing countries and emerging markets.

Among the limited number of papers considered EE countries, one can mention Atici (2009) (3 CEE countries and Turkey), Kasman and Duman (2015) (15 EU new member states and candidate countries), Pejovic et al. (2021) (27 EU and Western Balkan countries), Simionescu (2021) and Simionescu et al. (2022) (7 and 10 CEE and SEE countries, respectively), Ugurlu (2022) (4 CEE countries), Balsalobre-Lorente et al. (2023) (7 CEE countries). Research on greenhouse gas emission factors in Central Asian countries is a recent development. For example, Nguyen (2019) and Zhang (2019) studied 5 CA countries, Li et al. (2020) examined 8 CEE and 2 CA countries, and Salahodjaev et al. (2022) focused on 45 European and CA countries. To our knowledge, we use the biggest sample of countries from Eastern Europe and Central Asia in our research (excluding those studies with multiregional scope).

LITERATURE REVIEW

The first attempts to examine the dynamic relationship between air pollution, energy consumption, and GDP (as a proxy for income) on the example of developed countries date back to the middle of 2000-ies – e.g., Richmond and Kaufmann (2006), Ang (2007), Soytas et al. (2007). Since that time, the approach to the set of independent variables in econometric models has changed greatly, and research methods have also become more complex.

We carefully studied the conclusions of more than 80 scientific papers (from 1997 to 2023) and carried out a grouping of variables typically used to consider carbon emission factors. The length limitations of scientific publication make it hard to present the differences in conclusions about emission factors in detail, but we can discuss this issue in general. We identified the following groups of independent variables:

Energy system

Indicators of the development of national energy systems are included in models in most studies (about 90%, according to our estimates), which is due, first of all, to the

[1] Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Montenegro, North Macedonia, Poland, Romania, Serbia, Slovakia, Slovenia, Tajikistan and Uzbekistan.

fact that energy-related greenhouse gas emissions account for the major share of total anthropogenic emissions (energy sector accounts for 1/4 of global greenhouse gas emissions). As for carbon dioxide, electricity generation is responsible for 43% of global CO_2 emissions (15.1 Gt, according to Climate Watch). In the top CO_2 emitters – China, the USA and India – this share reaches 55, 43 and 52%, respectively.

Researchers have reached a consensus regarding the role of *energy consumption* in expanding the volume of anthropogenic emissions: almost all studies using this dependent variable indicate a statistically significant positive impact of energy use on CO_2 emissions. Likewise, most models show a significant negative impact on emissions from *renewable energy consumption (generation)*, while non-renewables' influence is usually significant and positive. However, the situation becomes more complicated if we consider not aggregate data but more precise data on individual energy generation sources. If, in relation to fossil fuel energy use, coal or hydrocarbon consumption, the model results coincide with generally accepted hypotheses, in the case of *hydroelectricity and nuclear energy consumption (generation)*, researchers' conclusions are often ambiguous and lead to completely different policy recommendations. Regarding *wind, solar, and biomass energy,* the authors do not provide a clear answer to the question about the role of these types of renewable energy in reducing atmospheric emissions (insignificant relationship, negative or even positive effects are identified with approximately the same frequency).

Economy

Independent variables related to economic development are present in almost all models explaining air pollution. This is especially true for economic performance and welfare indicators – GDP and GDP per capita, used as a proxy for national income. It is well known that Grossman and Krueger (1991) first found the inverted U-shaped relationship between income and pollution, which was named the Environmental Kuznets Curve (EKC). The inverted U-shaped EKC hypothesis means that pollution initially increases with income growth, then stabilizes, and finally declines. Quite quickly the validity of the original EKC hypothesis in the long run was called into question: after passing a certain income level, an increase in income might result in the expanding of environmental degradation once again (N-shaped EKC). This can be explained by the idea that the scale effect is more important than the composition and technical effects when the benefits from green innovation decrease (de Bruyn et al. 1998; Torras and Boyce 1998).

The numerous empirical studies testing the validity of the EKC hypothesis show various forms of relationship between income and air pollution. In the frames of our literature review, we identified 73 papers that used GDP or income as an independent variable. Half of the authors made a conclusion about the connection between these variables and CO_2 emissions. Most found an inverted U-shaped EKC (20 papers) or said there is no evidence for the existence of EKC at all (10 papers). A few researchers discovered U-shaped EKC (3), N-shaped EKC (3), and inverted N-shaped EKC (2).

A number of researchers are studying the influence of the *economic structure* on carbon footprint, primarily the relationship between the volume (or share in GDP) of agricultural or industrial production and CO_2 emissions. In almost all cases, industry increases the level of air pollution, and the results for agriculture are ambiguous (Li et al. 2020, Simionescu 2021, Raihan 2023). Gross fixed *capital formation* is also included in the models, but the connection with carbon emissions most often turns out to be insignificant. A fruitful area of research is studying foreign economic activity (through components of the *balance of payments*). The impact of FDI inflows on emissions is ambiguous, as well as the influence of trade in goods (total trade usually affects negatively, but trade openness (trade to GDP), export and import, on the contrary, affect positively). The relationship between the indicators of labor market development (labor force, labor productivity) and environmental degradation is insignificant in most cases. The most frequently used dependent variable in the field of *financial systems* is domestic credit *to the* private sector (% of GDP). However, the number of authors proving its positive impact on carbon dioxide emissions is approximately the same as those with the opposite viewpoint.

Population

A study of the influence of indicators related to *population* dynamics and settlement patterns began in the 2000s: the hypothesis was tested that the growth in the number of residents, especially their concentration in cities, inevitably leads to negative environmental consequences. As for demographic indicators (population, population density, population growth), only 3 of the 14 studies we analyzed with these variables showed a significant impact on emissions, both negative and positive (Salman et al. 2019). In contrast, most authors claim that *urbanization* growth leads to higher CO_2 emissions – a direct relationship between these indicators was found in 13 out of 22 studies (Voumik et al. 2023).

Living standards

According to theoretical assumptions, *living standards* indirectly affect greenhouse gas emissions, since societies with higher welfare and quality of life should contribute to reducing the ecological footprint. However, proxies of living standards (poverty, health expenditure, life expectancy, Human Development Index, etc.) are rarely used in the models, and the available results are ambiguous (Li et al. 2020, Simionescu 2021).

Institutional setting

As in other areas of econometric model application, the proxies of the *institutional setting* are increasingly used when studying the causes of atmospheric pollution – for example, the Institutional Quality Index (Worldwide Governance Indicators), Index of Economic Freedom, Political Rights and Civil Liberties Index, Environmental Policy Stringency Index (by OECD), Economic Complexity Index, and Globalization Index (by KOF). It is assumed that a developed institutional environment contributes to the implementation of international ecological obligations, including efforts to achieve climate neutrality. As a rule, the calculation results confirm the hypothesis about the negative impact of institutions on emissions. However, the long-term relationship between indices and emissions does not always remain linear but has a U-shape or N-shape (Apergis and Ozturk 2015, Shahnazi and Dehghan Shabani 2021).

Technology and innovation

Following many researchers, we believe that indicators of *technological development* are one of the key determinants of environmental pressure. However, an important problem is raised: the vast majority of technological development indicators can lead to a false interpretation of the impact of innovation on the carbon footprint. For example, a country may have a high level of R&D expenditure or a number of patent applications, which are in no way related to environmental issues, and the reduction of emissions within its borders can be entirely related to the import of green technologies and know-how. Most often, works examine the impact of patent applications (ambiguous results), less often – the impact of R&D expenditure, research intensity (R&D expenditure to GDP), number of researchers, high-technology exports, etc. (Allard et al. 2018, Cheng et al. 2021, Petrović and Lobanov 2020).

Other independent variables

The process of studying the factors that influence CO_2 emissions is developing towards the inclusion of more independent variables, the connection of which with the carbon footprint at first glance seems illusory. The authors of such works often make a lot of effort to substantiate the results of their calculations. Examples of non-obvious variables include such proxies for economic development as market capitalization of listed companies, interest rates, consumer price indicators, personal remittances, or mobile cellular subscriptions (Attílio et al. 2023, Paramati et al. 2017). Social development and institutional maturity indicators are also widespread (e.g. the share of women in parliament, the tenure of regional and municipal officials, etc.).

MATERIALS AND METHODS

The aim of this work is to study the impact of the energy sector (coal-based electricity and hydroelectricity generation), the manufacturing industry (steel and cement production) and agriculture (cropland area change) on carbon dioxide emissions in 16 Eastern European and 4 Central Asian countries for the period from 2000 to 2020. An explanation of the selection of appropriate countries for the sample is contained in the Introduction section. In this part of the article, we would like to briefly dwell on the presentation of explanatory and dependent variables (Table 1).

We chose carbon dioxide emissions (in Mt) as the dependent variable. An analysis of more than 80 scientific papers on the factors determining greenhouse gas emissions dynamics shows that authors often use CO_2 emissions as a dependent variable. The Introduction section describes three reasons for the popularity of this type of greenhouse gas. Absolute values (in t, kt or Mt) are used in 2/5 of the works we analyzed, and the rest of them consider relative values (CO_2 emissions per GDP or per capita). Many authors believe that absolute measures provide a more accurate picture of the cause-and-effect relationship of air pollution and are more meaningful from a practical point of view since countries' international commitments to reduce emissions are determined in absolute figures (e.g. see Friedl and Getzner (2003), Zhang and Cheng (2009), Pao and Tsai (2011)).

As for income data, we used GDP per capita PPP measured in USD at 2017 prices. The authors of other papers considering EE and CA countries also use GDP per capita as a proxy for income (Atici (2009), Kasman and Duman (2015), Li et al. (2020), Simionescu et al. (2022)).

In addition, we examine the impact of technological development on CO_2 emissions using the indicator of research intensity – R&D expenditure to GDP (%). For example, Ang (2009) and Ganda (2019) use the same variable. As we wrote earlier (see the Literature review section), there is no adequate indicator to prove the given relationship: R&D expenditure and patent applications in a particular country are not necessarily aimed at reduction in air pollution, which can be entirely achieved through the import of green technologies. Data on R&D could also be noisy because of the differences in national methodology in statistics collection (Allard et al. 2018).

To analyze the impact of industry and agriculture on CO_2 emissions, we chose crude steel and cement production and change in cropland area. To our knowledge, no studies have yet explored this connection. A serious omission of other works is that almost all researchers use aggregated data (agriculture or industry value-added/value-added per capita/share in GDP). However, almost all carbon dioxide emissions in the industry are associated with the activities of 3-4 branches (cast iron and steel, aluminium, cement, ammonia) and in agriculture – only with land-use change in favor of croplands. The search for a relationship between agriculture/industry value-added with CO_2 emissions has no theoretical or practical significance: according to the data by IPCC and Climate Watch, global greenhouse gas emissions in the 21st century are the result of activities in the energy sector (25%), agriculture (24%) and industry (21%), but CO_2 emissions are connected to the energy sector (92%), industry (5%) and land-use change (3%).

In order to find the extent of influence of renewable and non-renewable energy on carbon emissions, we use such proxies as electricity production from coal and hydropower generation (% of total). The coal-fired thermal

Table 1. Description of variables

Variables	Definition and measurement	Source
EM	CO_2 emissions, Mt	CO_2 emissions of all world countries – 2022 Report, Publications Office of the European Union
GDP	GDP per capita PPP, constant USD 2017	WDI database, World Bank
RD	R&D expenditure, % of GDP	WDI database, World Bank
CR	Cropland, thous. ha	FAOSTAT
CO	Electricity production from coal, % of total	Ember Electricity Data Explorer
HY	Hydroelectricity production, % of total	Ember Electricity Data Explorer
CE	Cement production, thous. t	USGS Minerals yearbook
ST	Crude steel production, thous. t	USGS Minerals yearbook

power stations have the highest carbon footprint among power plants using fossil fuels, and hydropower remains a key type of renewable energy. In many EE and CA countries, both types are widely represented in the structure of electricity output and the installed capacity of power plants. Fossil fuel energy use or production is referenced by Al-Mulali (2014), Güney (2022), Raihan and Tuspekova (2022). Meanwhile, hydroelectric energy use or production is included in the model by Al-Mulali et al. (2015), Solarin et al. (2017), and Bilgili et al. (2021).

Following the approach of Cheng et al. (2021), Akram et al. (2020) and Allard et al. (2018), we estimated the effect of the above-mentioned variables on CO_2 emissions with this panel quantile regression model (Eq. 1):

$$\begin{aligned} QEM_{i,t}(\tau/\cdot) = & a_{1,\tau}GDP_{i,t} + a_{2,\tau}GDP2_{i,t} + \\ & + a_{3,\tau}RD_{i,t} + a_{4,\tau}CO_{i,t} + a_{5,\tau}CR_{i,t} + \\ & + a_{6,\tau}CE_{i,t} + a_{7,\tau}ST_{i,t} + a_{8,\tau}HY_{i,t} + \\ & + \beta_i + \mu_t \end{aligned} \quad (1)$$

$$i = 1, \ldots, N,\ t = 1, \ldots, T$$

where β_i and μt are the country and time fixed effects, respectively, while $a_{1,\tau}$ to $a_{8,\tau}$ are coefficients. EM_{it} represents CO_2 emissions; GDP_{it} is the GDP per capita; $GDP2_{it}$ stands for the square of GDP per capita; *RD* denotes research and development expenditures as a share of *GDP*; *CO* is electricity generated by coal (% of total); *CR* denotes cropland area; *CE* and *ST* are cement and crude steel production, respectively; and *HY* stands for electricity generated by hydropower plants (% of total). All variables are expressed in natural logarithms.

If the coefficients $a_{1,\tau}$ and $a_{2,\tau}$ are positive and negative, respectively, this will indicate that there is the classical inverted U-shaped curve of the relationship between GDP per capita and CO_2 emissions. However, in case the coefficients $a_{1,\tau}$ and $a_{2,\tau}$ are negative and positive, respectively, there is a U-shaped relationship between CO_2 emissions and income. The dependent variable is EM emissions, while our main variables of interest are *CO, CR, ST*, and *CE*.

We applied the panel quantile regression approach in order to examine the determinants of air pollution caused by carbon dioxide. This statistical method, created by Koenker and Bassett (1978), fits the linear function of CO_2 emissions based on the conditional distribution of the explained variable (Zheng et al. 2021). Contrary to the least square estimation method, its main econometric advantage is that it is robust to outliers and heavy distributions, and we are able to analyze potential heterogeneity and asymmetry (Akram et al. 2020). Ordinary Least Squares (OLS) estimators measure the average impact of independent variables on a dependent variable. In contrast, panel quantile regression estimates the effect of the explanatory variables on the explained variables at different quantile points (Xu and Lin 2020). Cade and Noon (2003) state that quantile regression provides a more complete view of possible causal functional relationships between variables for all portions of probability in ecological processes. Since the statistical distribution of ecological data is characterized by unequal variation, the authors pointed out that this method "estimates multiple rates of change from the minimum to maximum response, providing a more complete picture of the relationships between variables missed by other regression methods". The conditional quantile of yi given xi can be expressed as (Eq. 2):

$$Q_{yit}\left(\tau / x_{it}\right) = x_{it}^{\tau}\beta_{\tau} \quad (2)$$

where Q_{yit} $(\tau|x_{it})$ represents the τ_{th} quantile of the dependent variable, x^{τ}_{it} stands for the vector of independent variables (*i* and *t* denoting country and time) for quantile τ, while β_{τ} is the slope of the independent variable for quantile τ (Allard et al. 2018).

Based on this approach, it is possible to achieve detailed analysis across quantiles since it provides estimates of the dependent variables at each specific point of the conditional distribution, as pointed out by Allard et al. (2018). The importance of the panel quantile approach is particularly evident in cases when the error term is characterized by heteroskedasticity and does not have a normal distribution (Xu and Lin 2016). In order to provide a detailed analysis of the relationship between different conditional distributions of environmental degradation and the explanatory variables, we chose nine quantile points (0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, and 0.90), whereas the 50th quantile denoted the median. In this study, we employed STATA 14 to calculate the panel quantile regression.

RESULTS AND DISCUSSION

In this section, we present the main results of our calculations. In Table 2, we reported descriptive statistics for each variable, which include mean, standard deviation, minimum and maximum values, skewness, kurtosis, and the number of observations. We also provide the correlation matrix for EM regression variables. The correlation of EM and HY is negative, while it is positive for all other variables.

The correlation coefficients between EM and the explanatory variables like CR, ST, and CE had a value higher than 0.7, which might indicate the presence of multicollinearity problems. Therefore, we performed additional tests to confirm that there was no harmful multicollinearity, which occurs if a variance inflation factor (VIF) is in excess of 5. Since none of the variables had a VIF over 5, as can be seen from Table 4, we concluded that the results were suitable for further analysis.

The panel unit root tests are conducted to check whether the variables are stationary. We applied the Levin-Lin-Chu, Im, Pesaran, Shin, and Fisher ADF tests. According to the results (see Table 5), the test results of the variable's level data have not passed the significance test, meaning that these variables are not stationary at level I(0). We took the first difference since some of our variables contain a unit root at a level. This results in all variables becoming stationary at the 1% significance level, leading us to conclude that each variable has an integration of order one. Since the first-difference sequence is stationary for all variables included in our empirical analysis, we will use the first difference of our data.

Based on the Q-Q, which represents the probability graph (Fig. 1), it is possible to determine whether the data distribution is normal. As it can be seen from the graphs, the linear diagonal line denotes normal distributions, while the dotted line shows the deviation from the previously mentioned line. For instance, the economic data is normally distributed in the case when the Q-Q plot coincides with the X_j Y line, and vice versa. Fig. 1 shows that all economic variables do not follow a normal distribution, which has also been confirmed by the Jarque-Bera probability test (see Table 2).

In Table 6, we reported the estimated results of the panel quantile regression approach. The signs of the coefficients of the explanatory variables are as expected.

Table 2. Descriptive statistics

Variables	Mean	Median	Std. dev.	Min	Max	Skewness	Kurtosis	Pr. (J-B test)	N
EM	3.292	3.078	1.283	1.03	5.80	0.205	2.036	0.00	420
GDP	9.639	9.837	0.737	7.17	10.62	-1.204	3.799	0.00	420
RD	-0.831	-0.607	1.043	-4.605	0.941	-0.895	3.816	0.00	420
CO	3.437	3.662	0.992	-2.525	4.552	-2.603	14.406	0.00	325
CR	7.462	7.220	1.263	4.82	10.31	0.266	2.777	0.05	420
CE	7.547	7.600	1.075	4.60	9.85	0.012	2.461	0.08	399
HY	2.644	3.131	1.683	-2.52	4.605	-1.008	3.261	0.00	419
ST	6.839	6.621	1.571	1.79	9.27	-0.463	2.557	0.00	313

Table 3. Correlation matrix

Variable	EM	GDP	RD	CR	CO	ST	CE	HY
EM	1.00							
GDP	0.10	1.00						
RD	0.03	0.68	1.00					
CR	0.88	-0.08	-0.18	1.00				
CO	0.22	-0.08	-0.24	0.22	1.00			
ST	0.75	0.31	0.20	0.63	0.20	1.00		
CE	0.86	0.08	0.08	0.75	-0.02	0.62	1.00	
HY	-0.53	-0.28	-0.34	-0.44	-0.07	-0.57	-0.39	1.00

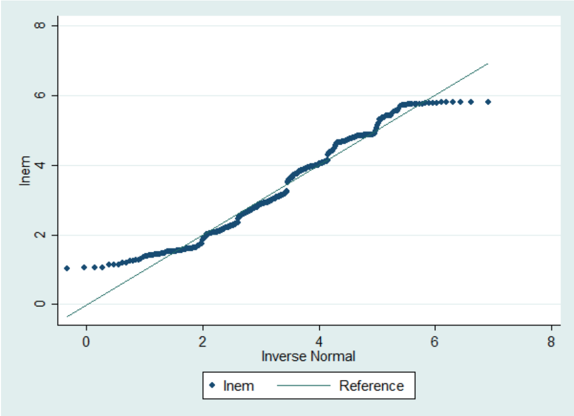
Table 4. VIF test

Variables	VIF	1/VIF
CR	3.87	0.258
CE	3.04	0.328
ST	2.65	0.377
RD	2.42	0.412
GDP	2.07	0.482
HY	1.79	0.559
CO	1.26	0.795
Mean VIF	2.44	

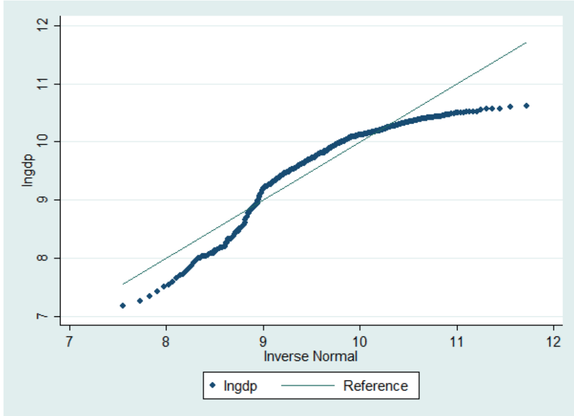
Table 5. Panel data unit root test results

Variables	Levin-Lin-Chu test		Im, Pesaran, Shin		Fisher-ADF test	
	Level	1st difference	Level	1st difference	Level	1st difference
EM	-0.456	-3.874***	-0.234	-6.089***	41.243	108.401***
GDP	-0.335	-2.364***	1.499	-2.303***	30.618	57.869***
RD	-2.586***	-6.813***	-1.240	-5.627***	50.350	102.079***
CO	-1.630**	-7.711***	-0.860	-8.039***	48.986**	117.539***
CR	-8.158***	-14.949	-4.581***	-9.589***	97.039***	129.337***
CE	-3.564	-5.679***	-1.965**	-4.866***	57.395**	87.737***
HY	-5.816***	-12.314***	-6.206***	-12.655***	116.344***	206.307***
ST	-0.718	-7.239***	-0.478	-5.363***	29.950	81.449***

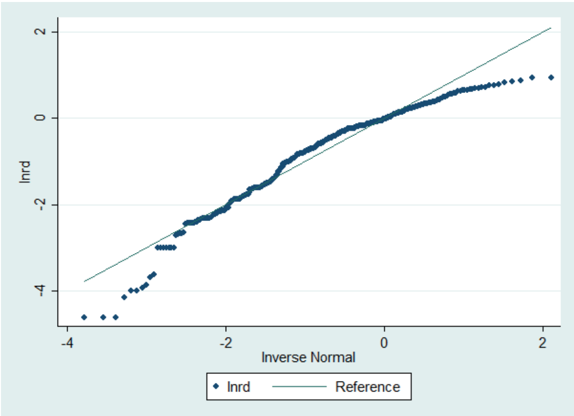
Note: ***, **, and * indicate significant p-values at the 1, 5, and 10% levels. Both a constant and a trend were used in the test.



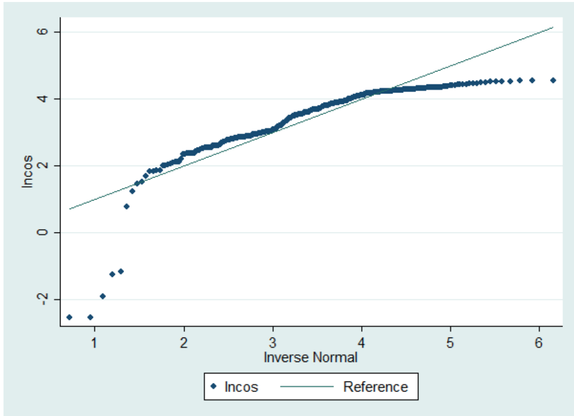
(a) EM



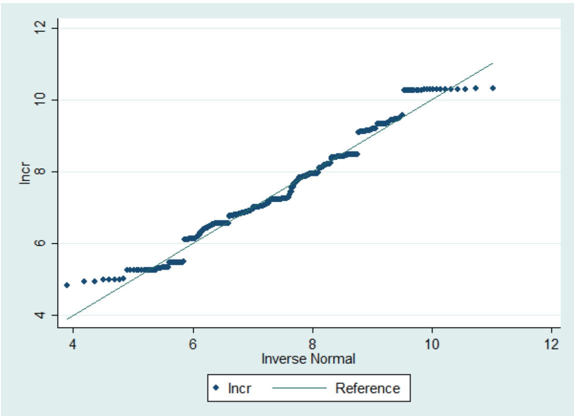
(b) GDP



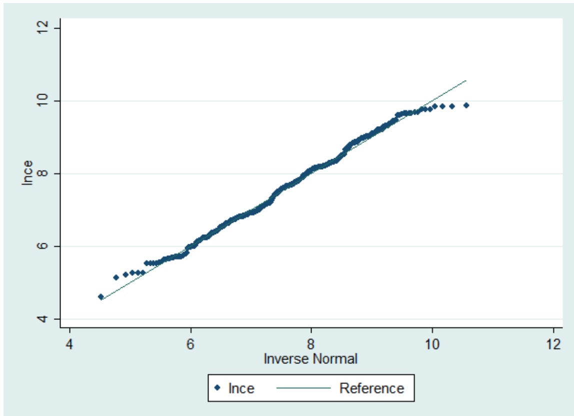
(c) RD



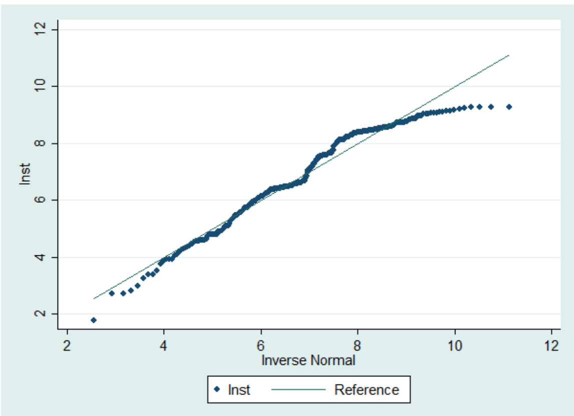
(d) CO



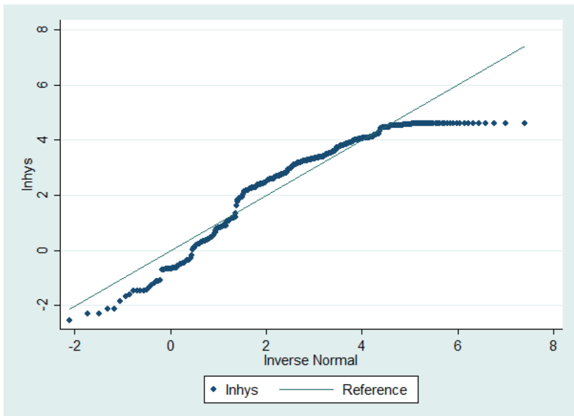
(e) CR



(f) CE



(g) ST



(h) HY

Fig. 1. The normal Q-Q plot for variables transformed by natural logarithm

The coefficients of GDP per capita on CO_2 emissions are negative from the 10th to the 30th quantile but significant only at the 10th quantile. This coefficient became positive and significant at the 70th, 80th, and 90th quantiles. Notably, the impact of GDP per capita on carbon emissions shows an increasing trend from the 50th to the 80th quantile. On the other hand, the impact of square GDP per capita on CO_2 is also heterogeneous, while the positive effect on carbon emissions is greater at the lower quantiles. The negative coefficient is recorded between the 50th and the 90th quantiles but is only statistically significant at the 70th and 80th quantile levels.

Thus, we provide evidence for the U-shaped environmental Kuznets curve for EE and CA countries with the lowest carbon footprint (related to the 10th quantile): a 1% increase in GDP per capita leads to a decrease of 4.34% in CO_2 emissions, while square GDP per capita records an increase of 0.26%. Our findings are in line with Wang et al. (2011) (for Chinese provinces), Destek and Sarkodie (2019) (for China, India, the Republic of Korea, Thailand and Turkey), Sarkodie and Strezov (2019) (for India and South Africa) and Simionescu et al. (2022) (for ten CEE and SEE countries).

In contrast, the countries with the highest emissions (the 70th and the 80th quantile of our sample) are characterized by the 'classical' inverted U-shaped relationship between GDP per capita and CO_2 emissions. For example, in the case of the 80th quantile, an increase of 1% in income results in carbon dioxide emissions increasing by 4.75%, while square GDP per capita records a decrease of 0.21%. So, for such countries, air pollution initially increases with income growth and then declines due to composition and technological effects. There are a lot of studies proving the validity of the inverted U-shaped EKC hypothesis for developed countries, including those from Europe, e.g. Atici (2009) (for Turkey and 3 CEE countries), Kasman and Duman (2015) (for 15 EU NMS and CC), Dogan and Seker (2016) (for EU-15), Shahnazi and Dehghan Shabani (2021) (for EU-28), Salahodjaev et al. (2022) (for 45 European and CA countries).

According to the IPCC classification, land use categories include cropland, grassland, wetland, forest land, and settlements. The change from one category to another refers to land-use change (LUC). Organic soils emit CO_2 when they are drained to be converted to cropland or grassland; the emissions of carbon dioxide, methane (CH_4) and nitrous oxide (N_2O) also happen as a result of human-induced fires. It is believed that soil contains twice as much carbon as the atmosphere. Conversion of forest land and grassland to cropland can lead to a 20-40% loss of the original soil carbon stocks because of CO_2 sinking.

Many authors use data on agriculture value-added, which cannot be applied to carbon dioxide emissions: while crop and livestock production is responsible for direct emissions of CH_4 and N_2O, they do not contribute to CO_2 emissions. For example, N_2O emissions come from using fertilizers, the cultivation of organic soils, and the decomposition of crop residues, while CH_4 is emitted due to enteric fermentation in ruminants and anaerobic digestion of manure. In general, direct emissions of greenhouse gases from agricultural production were estimated to be 5.0-5.8 $GtCO_2e$ per year in 2000-10, whereas indirect emissions from land use and land-use change were 4.3-5.5 $GtCO_2e$ per year (IPCC 2014).

The total cropland area of our sample countries exceeds 82 million ha (they would only be ahead of India, USA, China and Russia on a global scale). According to our calculations, the coefficients of cropland expansion are negative and non-significant from the 10th to the 30th quantile. Subsequently, this coefficient becomes positive, showing high statistical significance only at the 80th quantile (a 1% increase in cropland use leads to CO_2 emissions increase by 0.28%). This variable has a heterogeneous impact on emissions across different quantiles (it is higher at lower quantiles). Our findings are in line with Zaman and Abd-el Moemen (2017), Spawn et al. (2019) and Magazzino et al. (2023).

The energy system of the vast majority of sample countries is largely based on the extraction and consumption of bituminous coal and lignite. As of 2022, EE countries (especially Poland, Czech Republic, Serbia and Bulgaria) produced 55 million tons of hard coal and 185 million tons of lignite – 99% and 63% of total European extraction. The biggest coal producer in CA is Kazakhstan

Table 6. Panel quantile regression results

Variable	10th	20th	30th	40th	50th	60th	70th	80th	90th
GDP	-4.340** (2.140)	-1.515 (1.845)	-2.280 (1.657)	0.194 (1.714)	1.005 (1.302)	2.248 (2.165)	4.337** (1.991)	4.745*** (1.815)	3.628* (2.189)
GDP2	0.258** (0.107)	0.106 (0.093)	0.141* (0.082)	0.019 (0.085)	-0.021 (0.064)	-0.082 (0.106)	-0.185* (0.098)	-0.210** (0.092)	-0.159 (0.112)
CR	-0.212 (0.184)	-0.120 (0.155)	-0.038 (0.151)	0.023 (0.177)	0.067 (0.195)	0.129 (0.198)	0.106 (0.171)	0.283*** (0.102)	0.175 (0.142)
CO	0.110** (0.048)	0.119* (0.069)	0.083 (0.059)	0.108** (0.045)	0.097** (0.041)	0.127*** (0.044)	0.096* (0.053)	0.144*** (0.055)	0.204*** (0.056)
CE	0.004 (0.049)	0.019 (0.052)	0.016 (0.042)	0.00003 (0.033)	0.029 (0.029)	0.032 (0.031)	0.038 (0.030)	0.032 (0.028)	0.019 (0.047)
ST	0.060** (0.030)	0.053* (0.029)	0.065*** (0.020)	0.069*** (0.016)	0.064*** (0.015)	0.057*** (0.017)	0.058*** (0.021)	0.072** (0.032)	0.045 (0.033)
HY	-0.051 (0.032)	-0.060* (0.035)	-0.072*** (0.023)	-0.062*** (0.014)	-0.052*** (0.013)	-0.035** (0.017)	-0.040** (0.017)	-0.027 (0.020)	-0.014 (0.021)
Intercept	-0.084*** (0.007)	-0.056*** (0.007	-0.038*** (0.007)	-0.029*** (0.005)	-0.022*** (0.003)	-0.012** (0.005)	-0.004 (0.007)	0.015* (0.009)	0.038*** (0.009)

Note: Bootstrapped standard errors are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10%, respectively.
Source: authors' calculations

(90 million tons annually). The share of coal-fired electricity generation is usually decreasing but still significant in the energy balance of many countries: the maximum values during the study period (2000-20) reached 95% in Poland, 87% in North Macedonia, 80% in Kazakhstan, 75% in Serbia and Bosnia and Herzegovina, 72% in the Czech Republic, and 55% in Bulgaria and Montenegro. As we expected, the relationship between electricity production from coal and carbon footprint is positive and significant at all quantiles (with the exception of the 30th quantile); a 1% increase leads to CO_2 emissions increasing by 0.08-0.20%. These findings are consistent with the conclusions about environmental degradation due to the burning of fossil fuels by Al-Mulali (2014), Güney (2022), Raihan and Tuspekova (2022).

The process of substitution of non-renewable energy sources by wind, solar, or biomass is in its initial stages in most of the selected countries. The share of them up to the mid-2010s is too insignificant for a relevant assessment of the impact on emissions in the 21st century. In this regard, we use data on hydropower as a traditional type of renewable energy for EE and CA: in 2022 its share in total energy production was 90-99% in Albania, Kyrgyzstan, and Tajikistan; 55% in Latvia; 40-45% in Croatia and Montenegro; and circa 25-30% in Romania, Bosnia and Herzegovina, North Macedonia, Serbia, and Slovenia. According to our calculations, the impact of hydroelectricity on CO_2 emissions is negative and significant at conventional levels from the 20th to the 70th quantile (a 1% increase in hydropower generation results in a decrease of emissions by 0.04-0.07%). Our findings are also confirmed by Al-Mulali et al. (2015), Solarin et al. (2017) and Bilgili et al. (2021).

Using aggregate data on industrial value-added to assess the industry's carbon footprint is simpler in terms of data searching, but methodologically it is not entirely correct. Products with the maximum carbon footprint are produced by only a few industries (cast iron and steel, aluminium, cement, ammonia), the share of which in the structure of industrial value-added may be quite small. Our analysis of UNFCCC data shows that the share of the steel and cement industries in the structure of industrial CO_2 emissions in 2021 in Poland was 8% and 63%, respectively; in the Czech Republic – 54% and 29%, in Romania – 37% and 46%, in Kazakhstan – 44% and 36%. Thus, using these two variables as proxies of industrial development could provide interesting conclusions. To our knowledge, earlier papers have not proposed such a combination of dependent variables.

The coefficient of steel production is positive and significant in all quantile levels except the 90th quantile (highly significant from the 30th to the 70th quantile); a 1% increase in the output of steel products results in a growth in carbon emissions of 0.05-0.07%. The coefficients for cement production on emissions tend to be notably higher at elevated quantiles, even though this relationship is not statistically significant.

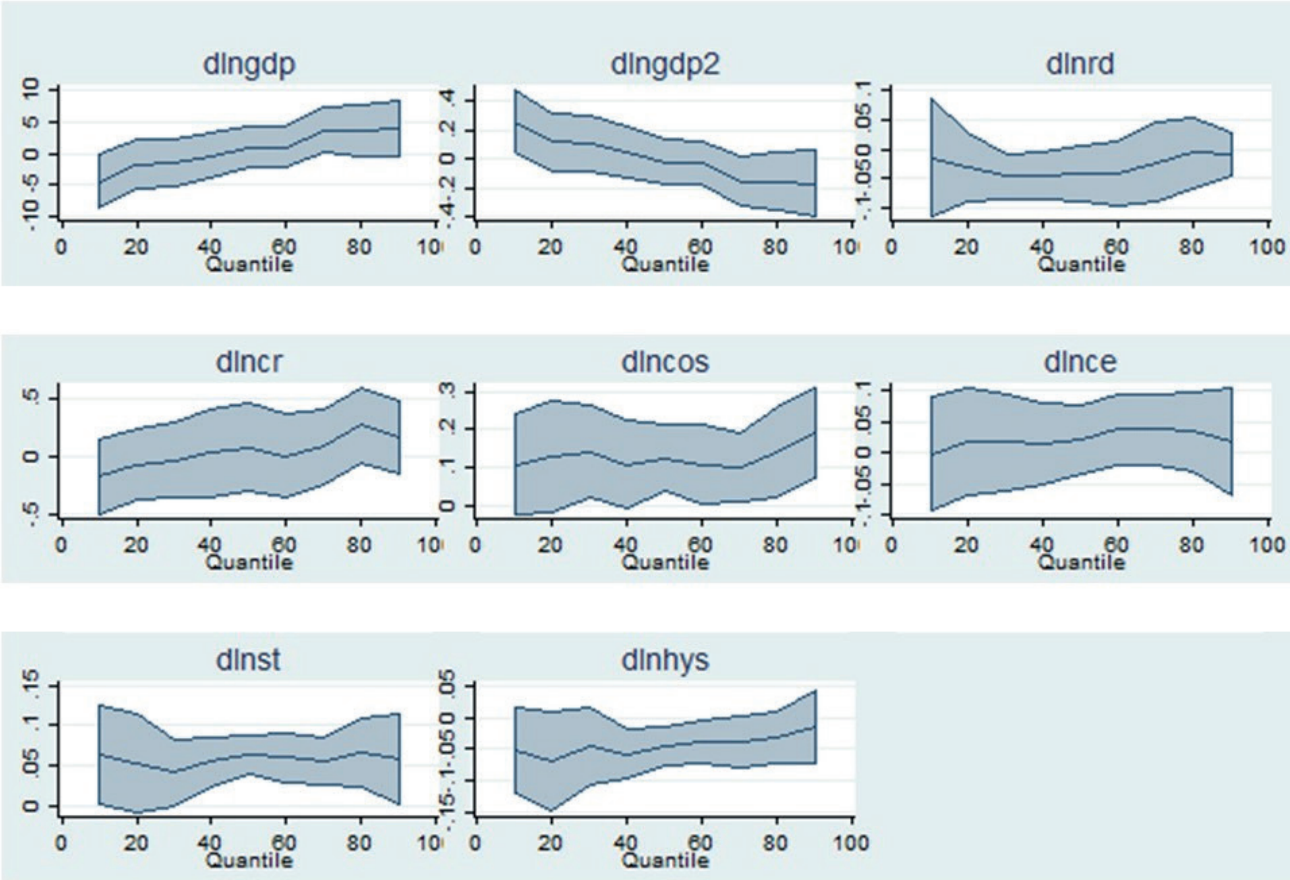
In order to test the robustness, we conducted the quantile regression analysis by including the RD variable. The effect of R&D on carbon emissions is negative, and only at the 40th and the 50th quantile levels has low statistical significance. EE and CA countries adhere to an imitation model of technological development, particularly relying on importing know-how to reduce anthropogenic emissions into the atmosphere. With this approach, the level of R&D expenditures (like any other indicator of technological development) cannot be sensitive to the dynamics of greenhouse gas emissions. Petrović and Lobanov (2020) find that the effect of R&D expenditure growth rates on CO_2 emissions in OECD countries could be positive, negative, and neutral (insignificant) for many years – the relationship between these two variables is country-specific. The coefficients of other regression variables do not change notably, so we conclude that our panel quantile model is robust.

Additionally, we present the quantile regression results in Fig. 2. The effect of GDP per capita has an increasing trend at all selected quantiles, while the square of GDP per capita has a diminishing effect on ecological deterioration. All of our key independent variables have a heterogeneous impact on CO_2 in its condition distribution.

Table 7. Panel quantile regression results (robustness check – with RD)

Variable	10th	20th	30th	40th	50th	60th	70th	80th	90th
GDP	-4.353** (2.169)	-1.687 (1.524)	-1.510 (1.571)	-0.342 (1.681)	0.989 (1.739)	1.051 (2.073)	3.666* (1.929)	3.603* (2.029)	3.849* (2.229)
GDP2	0.259** (0.109)	0.113 (0.079)	0.103 (0.080)	0.046 (0.083)	-0.023 (0.084)	-0.024 (0.101)	-0.154* (0.093)	-0.153 (0.102)	-0.172 (0.117)
RD	-0.015 (0.054)	-0.029 (0.044)	-0.046 (0.029)	-0.044* (0.024)	-0.041* (0.257)	-0.042 (0.032)	-0.022 (0.034)	-0.006 (0.032)	-0.008 (0.015)
CR	-0.177 (0.235)	-0.069 (0.136)	-0.029 (0.161)	0.032 (0.174)	0.079 (0.185)	0.003 (0.174)	0.085 (0.172)	0.277 (0.179)	0.167 (0.201)
CO	0.108 (0.086)	0.129** (0.064)	0.142** (0.058)	0.108* (0.059)	0.124** (0.056)	0.108** (0.052)	0.099* (0.051)	0.141** (0.058)	0.190*** (0.058)
CE	-0.0008 (0.041)	0.017 (0.040)	0.017 (0.036)	0.014 (0.032)	0.023 (0.028)	0.038* (0.022)	0.037 (0.024)	0.034 (0.029)	0.017 (0.040)
ST	0.063* (0.033)	0.052 (0.032)	0.041* (0.022)	0.055*** (0.018)	0.063*** (0.016)	0.059*** (0.016)	0.054*** (0.016)	0.067*** (0.023)	0.058* (0.031)
HY	-0.052 (0.036)	-0.068** (0.033)	-0.045* (0.024)	-0.057*** (0.019)	-0.043** (0.019)	-0.037* (0.022)	-0.038 (0.024)	-0.031 (0.028)	-0.015 (0.028)
Constant	-0.084*** (0.009)	-0.053*** (0.011)	-0.036*** (0.009)	-0.027*** (0.007)	-0.019*** (0.005)	-0.010* (0.005)	-0.002 (0.006)	0.015* (0.007)	0.040*** (0.011)

Note: Bootstrapped standard errors are in parentheses. ***, **, and * indicate significance at the 1%, 5%, and 10%, respectively.
Source: authors' calculations



Note: The labels represent the first difference of the variables (dlngdp – GDP per capita, dlngdp2 – the square value of GDP per capita, dlnrd – the R&D expenditure, dlncr –the cropland, dlncos – the electricity production from coal, dlnce – the cement production, dlnst – the crude steel production, dlnhys – hydroelectricity production).

Fig, 2. Change in the panel quantile regression coefficients based on Table 7

CONCLUSIONS

In this paper, we study the impact of the energy sector (coal-based electricity and hydroelectricity generation), the manufacturing industry (steel and cement production) and agriculture (cropland area change) on CO_2 emissions in 16 Eastern European and 4 Central Asian countries for the period from 2000 to 2020. In addition, the relationship between the carbon footprint and income and the level of technological development is considered.

First, the relationship between air pollution and income (using GDP per capita PPP as a proxy) is explored in order to confirm or reject the EKC hypothesis. We find evidence for a U-shaped environmental Kuznets curve for EE and CA countries with the lower carbon footprint: in particular, for the 10^{th} quantile, a 1% increase in GDP results in a 4.34% drop in CO_2 emissions, while square GDP per capita is associated with a 0.26% increase in emissions. Less economically developed countries with low pollution levels (Albania, North Macedonia, Montenegro in the Balkans, Tajikistan and Kyrgyzstan in CA) are before the turning point of the U-curve: implementation of green transition policies is still not dampening economic growth, but later the progress in the economy will lead to increased emissions due to a deficit in technology and a qualified labor force.

It is important to note that some of these energy-intensive economies are based on the use of renewables, so emissions with increasing income are still minimal (non-fossil energy generation makes up 90-99% in Albania, Kyrgyzstan, and Tajikistan). On the other side, economically developed countries with low emissions (three Baltic states – Estonia, Latvia, and Lithuania) may face a slowdown in economic growth as they combat air pollution. Interestingly, we cannot confirm the pollution haven hypothesis, which is often associated with the U-shaped EKC. None of the countries mentioned are examples of relocation of carbon-intensive industries from developed countries with stringent environmental policies.

In contrast, the countries with the highest emissions (the 70^{th} and 80^{th} quantile) are found to have an inverted U-shaped relationship between GDP per capita and CO_2 emissions (for the 80^{th} quantile, an increase of 1% in income results in emissions increasing by 4.75%, while square GDP per capita records a decrease of 0.21%). Energy-intensive economic growth in high-emitting countries like Kazakhstan or Uzbekistan is directly connected with environmental degradation (fossil energy generation makes up 90% of total, heavy industry is almost not equipped with emission-reducing equipment, etc.). On the other hand, more economically developed large emitters of greenhouse gases (e.g., Poland and the Czech Republic) are beginning to reduce their carbon footprint because of the structural (economic composition) and technological effects linked to the inverted U-shaped EKC, as well as due to the environmental awareness of the wealthier population.

According to popular belief, the level of technological development is inversely correlated with environmental pollution. However, most innovation indicators show a general picture and are not directly related to the spread of green technologies and, therefore, are insensitive to data on greenhouse gas emissions. For instance, less air pollution can be achieved by implementing imported green technologies and know-how, so the national data on R&D expenditure or patent applications is not important in this case. We find that the effect of R&D on carbon emissions is negative but only statistically significant at the 40th and 50th quantiles. This proves that given countries, firstly, may differ in the method of collecting statistical data, and secondly, import green technologies as part of a more general model of technological imitation.

There is a consensus in the literature on the impact of thermal energy on air pollution, but the use of data on coal-based electricity generation is very rare. We find that the relationship between electricity production from coal and CO_2 emissions is positive and significant at almost all quantiles (a 1% increase leads to CO_2 emissions increasing by 0.08-0.20%). The EE and CA countries are traditionally large producers of coal (together more than 330 million tons in 2022) and still widely use it in power generation, although the share of this non-renewable is declining (65-70% in Poland, Kazakhstan, Serbia, Bosnia and Herzegovina, 45-50% in Czech Republic, North Macedonia, Montenegro, Bulgaria). At the same time, the installed capacity of coal-fired thermal power plants is practically not reduced in some countries (Poland, Bulgaria, and Serbia), and even new power units are being commissioned (Kazakhstan). The persistence of coal generation is primarily due to the affordability of brown and steam hard coal and the lack of political will or finance for the transition to low-carbon (natural gas) or carbon-free energy. The implementation of carbon capture and storage technologies (CCS) is critical to reducing emissions.

We choose hydropower to discover the role of non-fossil electricity generation in EE and CA because, in most of the countries, it remains the key type of renewable energy in conditions of the still limited use of wind, solar, and biomass. In 11 of 20 selected countries, the share of hydropower exceeds ¼ in the energy consumption structure; in Albania, Kyrgyzstan, and Tajikistan, it makes 90-99%. We find that the impact of hydroelectricity on CO_2 emissions is negative and significant from the 20th to the 70th quantile (a 1% increase in hydropower generation results in a decrease of emissions by 0.04-0.07%). In the case of key hydropower producers, one can find that they continue to expand their installed capacity: for example, in Romania in the 21st century, it was increased by 7%, in Tajikistan by 30%, and in Kazakhstan by 24%. A strategy to strengthen the role of hydropower will positively contribute to reducing the carbon footprint (except for emissions due to decomposition of aquatic biomass). However, we should not forget the negative consequences of constructing hydroelectric power stations and damming rivers, such as changing the natural course of rivers and their physical conditions, rising risks for upstream and downstream wildlife habitat, microclimate changing, and flooding of agricultural lands and settlements.

The change in cropland area, crude steel and cement production are chosen to examine the impact of industry and agriculture on CO_2 emissions. As far as we know, this combination of these dependent variables has not previously been considered in studies. The use of aggregated data for this purpose (agriculture or industry value-added / value-added per capita / share in GDP) has no theoretical or practical significance, since almost all carbon dioxide emissions in the industry are associated with the activities of 3-4 branches, and in agriculture – only with land-use change in favor of croplands (organic soils emit CO_2 when they are drained to be converted to cropland). More to say, the data on agriculture value-added used by many authors cannot be used in relation to carbon footprint: crop and livestock production is responsible for direct emissions of CH_4 and N_2O, but not CO_2.

We assumed that cropland area change could be one of the key factors in explaining the dynamics of carbon emissions in EE and CA countries. The total cropland area of our sample countries exceeds 82 million ha (they would only be ahead of India, USA, China, and Russia on a global scale). In 2020, compared to the early 2000s, the cropland area in Kazakhstan, rich in fertile chernozem and kastanozem soils, grew by 4%; in Serbia and Bulgaria – by 6% and 8%, respectively; in Tajikistan – by 19%, in the Baltic States – by 30-45%. Our hypothesis is confirmed, but only for the 80th quantile: a 1% increase in cropland use leads to CO_2 emissions increasing by 0.28%.

Thus, the EE and CA countries need to be attentive to environmental degradation caused by various forms of land-use change. The main goal is to make land serve more as a carbon sink, not a carbon source, which is achievable when the storage capacity of carbon in soil and biomass exceeds the emissions from deforestation and organic soil conversion. To preserve carbon sink, the measures of sustainable land use and improved agronomic practices are required: 1) to introduce "carbon farming" (soil carbon sequestration) when CO_2 is removed from the atmosphere and absorbed by the soil (e.g. switching from tillage (including grassland ploughing) by no-till or low-till methods that not disturbing the soil, rotational grazing of livestock, changing planting schedules and using cover crops); 2) to reduce deforestation and promote afforestation and reforestation; 3) to combat wildfires; 4) to develop agroforestry; 5) to rewet drained peatlands. The EE and CA countries can develop appropriate measures within the framework of international agreements, for example, the Glasgow Declaration on Forests (COP26) or the recently revised EU's Regulation on land use, land use change, and forestry.

Enterprises producing cement, cast iron, and steel are the main industrial air pollutants of carbon dioxide (for example, their total share in the Czech Republic, Romania, and Kazakhstan exceeds 80%, in Poland – 70%). Therefore, using aggregate data on industrial value-added to assess the carbon footprint of manufacturing instead of steel and cement industry data is not methodologically correct. We find that the coefficient of steel production is positive and significant from the 10th to 80th quantile levels: a 1% increase in production at the 20th and 80th quantiles leads to 0.05% and 0.07% rise in emissions, respectively. Thus, technological modernization of ferrous metallurgy will be the most important factor in reducing industrial greenhouse gas emissions in EE and CA countries, which together produce 30-35 million tons of crude steel annually (which is comparable to the production of Germany or Brazil).

There are two basic routes to produce steel – by integrated blast furnace-basic oxygen furnace (BF-BOF) and electric arc furnace (EAF). Carbon dioxide emissions are due to the use of BF-BOF: 80-90% of them are associated with the first stage since coal serves as a reducing agent to extract iron from iron ore in a blast furnace (in the second stage the basic oxygen converter turns carbon-rich pig iron, with some scrap added, into crude steel). Depending on the quality of carbon-containing reducing agents (coke), CO_2 emissions from BF-BOF may account for 1.4-1.9 tCO_2/t steel (estimates of World Steel Association and IEA). In contrast, the carbon footprint of EAF route, mostly using scrap, is about 0.3-0.4 tCO_2/t steel, so these furnaces need to be introduced more actively. Generally, the use of secondary metallurgy will reduce the need for primary metals and lead to a reduction in emissions. It is also possible to develop direct reduction of iron (DRI) from ore or ore concentrate without melting by using solid carbon or a reducing gas, for example, hydrogen.

We prove that cement production positively influences CO_2 emissions, though this relationship is not statistically significant. Interestingly, quantile regression analysis that takes into account the R&D variable shows that for the 60^{th} quantile, the coefficient of cement production is not just positive but also statistically significant. The countries of EE and CA are dynamically expanding cement production: in 2000-2020, it increased by almost 80% – from 48 to 86 million tons (for comparison, the USA, which is in 4^{th} place in the world, produces 95 million tons). There are wet and dry processes of cement production – the first of them is more energy- and source-intensive. In the first stage of the wet method, limestone, clay, and other raw materials are mixed with water in a ball mill, making slurry. After adding various compounds in storage tanks, the slurry goes to a rotary kiln and then transforms into cement clinker – the process is energy-intensive and links to high emissions of CO_2. Depending on the fuels used and clinker/cement ratio the carbon footprint of wet and dry methods is about 0.7-1.0 and 0.5-0.7 tCO_2/t cement, respectively. In order to reduce the carbon footprint of cement production, the following measures can be taken: to capture CO_2 emissions from the calcination of limestone in clinker production (carbon capture and storage, CCS), to reduce clinker-to-cement ratio (via adoption of supplementary cement materials, SCMs), to use more low-carbon fuels (like bioenergy and waste) instead of fossil fuels, and to develop innovative electric kilns. ■

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