Validation of the environmental Kuznets curve hypothesis and role of carbon emission policies in the case of Russian Federation

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Abstract
Climate change currently observed and expected in the future is associated with risks to security and sustainable development and natural and irreversible consequences. To minimize these risks, it is necessary to adapt the public administration, economic sectors, and regional infrastructure to the changing climate conditions. This paper discovers the links between CO2 emissions and their key determinants such as economic growth, energy consumption, population, trade openness, and financial development including the period from 1990 to 2020 to test the environmental Kuznets curve (EKC) hypothesis by using ARDL bound test for the Russian Federation. Findings reveal that energy consumption and population have a positive impact on CO2 emissions, while economic growth, financial development, and trade openness have been found to decrease CO2 emissions in the long term. The results of this paper show that there is a “U”-shaped relationship between CO2 emissions and economic growth in the Russian Federation. This shows that EKC is valid up to a certain income level in the Russian Federation, and when this income level is exceeded, a positive relationship will begin between economic growth and environmental degradation. As a policy implementation, policymakers must implement clean energy technology policies to achieve the 2060 net zero carbon target. Policies such as fossil-based energy use and reducing energy intensity should be adopted.

Keywords  Environment Kuznets curve · Carbon emission · Economic growth · Energy consumption · Population · Trade openness · Financial development

Introduction
With the start of the industrial revolution, technological developments accelerated and investments increased and a growth in the income levels of the countries was observed. However, as a result of increasing energy use—especially the consumption of fossil fuels—environmental changes and degradations have started. Since the primary goal of the countries is economic growth and development, the negativities that have arisen have been ignored. Conversely, an increase in global warming and ecological pollution in the 1960s exposes the significance of this topic and principal to the questioning of the relationship between economy and ecological pollution (Balado-Naves, et al. 2018). Furthermore, energy is a strong input for enabling economic growth but it also exerts adverse environmental consequences. However, the use of renewable (including hydro) and clean energy resources is often linked with environmental improvement while fossil fuel consumption is usually alleged to hamper environmental well-being (Kanat et al., 2021).

Today, many countries are aware of issues such as climate change and sustainable development at the regional level and have signed a number of international conventions and protocols. For instance, the Sustainable Development Goals (SDGs), namely, the Agenda 2030 report, stated that the global economic models adopted by countries are responsible for the recent increase and continuation of climate disaster problems. For this reason, countries have focused on renewable energy solutions instead of fossil fuel consumption that harms the environment (Sinha et al. 2021). The United Nations has emphasized that a successful environmental protection strategy requires the equal and cooperative action of every nation in the world (Isik et al. 2017).
On the other hand, Anser et al. (2021) state that the quality of the environment can be strengthened by the efficient use of energy and sustainable development policies for growth because increased CO₂ emissions and other greenhouse gas (GHG) emissions produce extensive environmental impacts. These effects cause unexpected changes in weather conditions and increase in world temperatures and presented more serious hazards for ecosystems (Trisos et al. 2020). In the Paris Agreement, which was accepted by 195 member countries in 2015, global economies agreed to do their best for climate change mitigation and adaptation. Member countries have set international and national targets to limit global temperature rise to 2 °C (Ali et al. 2021; Ackah and Graham, 2021). It is also very important for countries to reach their net zero carbon targets within the scope of sustainable development policies. Herein lies the focus of this study.

The Russian Federation is the fourth country to contribute to carbon dioxide (CO₂) emissions in the entire world, after China, the United States (US), and India, respectively, although the Russian Federation has signed the Kyoto Protocol and adopted the Paris Agreement (Ketenci, 2018). In 2020, CO₂ emissions in the Russian Federation amounted to approximately 1.48 billion metric tons of CO₂, making a decrease relative to the previous year, but emissions of the Russian Federation are expected to continue rising until 2030 due to the geographical location and the characteristics of the climate, and fossil fuels still make up 90% of the Russian Federation energy mix (e.g., power, heat, transport). The Russian Federation’s emissions dropped by 41% between 1990 and 1998 but increased by 15% between 1998 and 2017 (Climate Transparency, 2020). The carbon zero target of the Russian Federation is 2060.

CO₂ emissions have been examined extensively at national and regional levels, with the majority of study focusing on the relationship between CO₂ emissions and potential effect factors such as economic growth, population, energy consumption, energy intensity, and industrial structures. While some researchers have studied national groups such as the Gulf Cooperation Council (GCC) countries (Ansari et al. 2020; Alsamara et al. 2018; Beck and Joshi, 2015; Salahuddin and Gow, 2014), Organisation for Economic Co-operation and Development (OECD) countries (Isik et al. 2021a, b, c; Leal and Marques, 2020; Iwata et al. 2012), and the Middle East and North Africa (MENA) countries (Cheikh et al. 2021; Gorus and Aslan, 2019; Abdalh and Abugamos, 2017; Al-Rawashdeh et al. 2014) and so on, some researchers also have investigated a specific country such as China, Turkey, and the US. Specifically, the link between economic growth and greenhouse gas emissions in the Russian Federation has rarely been studied. The Russian Federation is rich in natural resources, which has made the Russian Federation a typical resource-based economy country. In addition, there is a conflict between the Russian Federation’s economic development and greenhouse gas emission reduction (Yang, et al. 2017). Therefore, examining the relationship between greenhouse gas emissions related to the economy and gross domestic product (GDP) in the Russian Federation has important implications both in theory and in practice.

The presented study aims to investigate empirical factors (population, GDP per capita, energy consumption, trade openness, and financial development) affecting CO₂ emissions per capita in the Russian Federation during the period of 1990–2020. Furthermore, this paper scrutinizes validation of the EKC hypothesis for the Russian Federation that contributes to CO₂ emission policies. The main reason for selecting the Russian Federation as this study’s sample country is twofold. First, the Russian Federation provides an interesting case study because the country plays a huge role in world oil markets. It is the world’s third largest oil producer after the US and Saudi Arabia, the world’s second largest exporter of crude oil, and the largest total exporter of oil and its products (IEA, 2022). Second, the Russian Federation’s CO₂ emission level in 2020 (11.64 tons per capita) is higher than other BRICS countries such as China (8.2), Brazil (2.1), South Africa (7.62), and India (1.74) (Xiang et al. 2021).

The contribution of the present paper to the previous literature is as follows. Firstly, this study is the first attempt, to the best of our knowledge, that analyzes the validity of the EKC hypothesis for a selected long-term dataset time interval (covering the period 1990–2020) and particular variables for the Russian Federation. Second, existing studies on the Russian Federation largely examined the impact of CO₂ emission (as an indicator of pollution) on the economic growth and energy consumption; the current paper also includes trade openness and financial development variables that are important for developing countries. Third, the current paper includes more recent and up-to-date observations compared to previous studies in the literature. Finally, the research results are predicted to be useful for policymakers as they formulate environmental policies targeting low-carbon growth strategies. The EKC hypothesis provides the determination of the low carbon turning point for the Russian Federation. In light of the aforementioned study expectations, the present paper is anticipated to minimize the gap in existing studies regarding the trade openness and financial development perspectives and the validity of the EKC hypothesis for the case of the Russian Federation (Sohag et al. 2021; Ketenci, 2018; Yang et al. 2017).

The rest of the current study is as follows: the next section examines empirical papers in the literature. The third section presents the methods applied in this paper and outlines empirical results as well. The discussion and conclusion on policy implications are performed in the last part.
Literature review

The reduction in emissions is explained by several factors, such as changes in household consumption, the effectiveness of environmental policies, and important changes in the economy resulting from technological modernization (Gavrilyeva et al. 2020). Therefore, the relationship between a nation’s economic development and its CO₂ emissions is regarded as empirically significant. There are several methods to scrutinize the link between economic growth and CO₂ emission. The EKC model, which is one of these methods, is well developed and widely used in investigating the economy-emissions relationship (Youssef et al. 2020; Brown and McDonough, 2016; Yang et al. 2015). In this study, unlike other studies, the EKC hypothesis was verified with more specific and extensive data, and the findings were compared with the EKC studies in the literature.

Generally, research shows that the inverse U-shaped link between economic growth and CO₂ is valid. From recent studies, Salari et al. (2021) assess the link between CO₂ emissions, energy consumption, and economic growth (GDP per capita) at the state level in the US between 1997 and 2016. The findings show an inverted U-shaped link between CO₂ emissions and GDP, providing sufficient evidence to confirm the EKC hypothesis across states. Similarly, AlZgool et al. (2020) display that the EKC hypothesis is effective for Bahrain as there is an encouraging link between economic growth and CO₂ emissions and the square of economic growth has an adverse impact on CO₂ emissions.

The EKC test for various countries and regions shows that this hypothesis is not always valid. To a large extent, this is determined by the length of time intervals analyzed and by national and regional characteristics (Friedl and Getzner, 2003). For example, calculations of Lantz and Feng (2006) over 30 years (1970–2000) revealed no correlation between emissions and GDP for the five Canadian regions. Similarly, Baek (2015) discovered that the EKC hypothesis was not acceptable for Arctic countries between 1960 and 2010. Economic growth only has a beneficial effect on the environment in some Arctic countries. Finally, energy consumption has been discovered to have a negative impact on CO₂ emissions in most countries.

In the Russian Federation, where the link between economic growth and greenhouse gas emissions is rarely examined, some studies found the EKC hypothesis valid, while others found it invalid. Of the studies that specifically investigated the Russian Federation, Yang, et al. (2017) tested the inverted U-shaped link between GDP per capita and greenhouse gas emissions linked to the economy per capita. The findings encouraged the EKC hypothesis for the Russian Federation. This result is also supported by Burakov (2019), Bass (2019), Ketenci (2018), and Rudenko and Skripnuk (2016); their results are coherent with the EKC hypothesis and valid for the Russian Federation. Differently, Pao et al. (2011) analyzed the inverse U-shaped relationship between CO₂ emissions, energy consumption, and economic growth in the Russian Federation from 1990 to 2007 and found that CO₂ emissions decrease as GDP increases when energy consumption is adjusted, and the EKC hypothesis is not acceptable for the Russian Federation. This idea is supported by Rustemoglu and Andrés (2016) in their study investigating the Russian Federation and Brazil; they indicated that changes in CO₂ emissions from 1992 to 2011 in the Russian Federation were affected by economic activities, but a decoupling also emerged between GDP and CO₂ emissions. In addition to these aforementioned studies, this paper has provided further detail for the literature review in the “Appendix” section, Table 9.

Data and method

Data

In this paper, the acceptability of the EKC hypothesis in the Russian Federation was investigated by testing the time series analysis method for the period of 1990 to 2020. At this point, we would like to emphasize that with the disintegration of the Union of Soviet Socialist Republics (USSR) in 1991, the Russian Federation economy began a radical transformation. For the Russian Federation economy, which experienced an acute financial crisis in 1998, serious economic reforms have been made since the 2000s (Shumkov, 2010).

The variables used for analysis, as well as their definition, unit of measurement, and sources are presented in Table 1 and all variables are stated in natural logs.

CO₂ is the log of total CO₂ emission from the consumption of fossil-based sources such as oil, natural gas, and coal gas measured in tons CO₂ per capita. GDP is the log of the GDP measured in per capita as an indicator of economic development. Similarly, GDP² is the log of the square of the GDP measured in PPP (purchase power parity) current international dollar.

EC is the log of total energy consumption measured in per capita kilowatt hours. EC variable includes oil, coal, gas, renewable energy, and nuclear power generation. When the literature is reviewed, many studies certainly prefer the data of energy consumption to strengthen the EKC model (Amri, 2018; Shahbaz et al. 2013a), since a large proportion of total energy consumption is composed of fossil fuels, and its inclusion is not surprising given the
obvious harmful effects of fossil fuels on the environment. In addition, certain obstacles are also effective in high CO₂ emissions due to the incidence and surplus of energy consumption, particularly fossil-based energy resources. For instance, weather conditions in the Russian Federation are incomparable to many countries (e.g., many US states and EU countries, Turkey) because low air temperature is also effective in rising energy consumption (Cruz Rios et al. 2017). In addition, the Russian Federation ranks first in the world’s natural gas reserves (Marshintsev and Gadiyatov, 2021), and therefore, the government regulates the use of natural gas cheaply in the country. This is another important obstacle to the transition to zero CO₂ emission renewable energy sources.

TO is the log of the sum of export and imports of total goods and services as an indicator of the trade openness, which measures the balance of payment (BoP) in the current US dollar. Grossman and Krueger (1991) discuss that trade openness is linked to three main thoughts. These are scale effect, composition effect, and technical effect. The first two effects would be anticipated to have adverse impact on the environment in a developing country. The technical impact is assumed to contribute to the protection of the environment. The comparison of trade openness with the countries (China, Netherlands, and United Kingdom (UK)) to which the Russian Federation exports the most in 2020 is as in Fig. 1.

As seen in Fig. 1, the trade openness of China, the Russian Federation, and the UK is very similar and close, while the trade openness of the Netherlands is different from these countries. The reason for including trade openness in our variables is to reveal that trade openness increases or decreases environmental pollution for the Russian Federation. For instance, Aydin and Turan (2020) discover that trade openness reduces CO₂ emissions in China and India while increasing them in South Africa. Conversely, Jalil and Feridun (2011) find that trade openness has a growing effect on ecological pollution in China. Likewise, Farhani and Ozturk (2015) found that a 1% increase in trade openness promotes CO₂ emissions by 0.418% in the long run for Tunisia.

FD is a financial development measure and analyzes the factors enabling the development of the financial system. To represent which financial development, the financial development index created by Svirydenka (2016) within the International Monetary Fund was used. Financial development can have various effects on CO₂ emissions. Primarily, there is an evidence in the literature that financial development promotes to economic growth by increasing foreign direct investment (FDI) (Nasir et al. 2019) and improving
the equity and credit market (Hsu et al. 2014), which means easier access to credit for stockholders and customers (Zhang 2011). Increased economic expansion necessitates increased energy use, which contributes to CO₂ emissions (Pao and Tsai, 2011). Besides, financial development assists businesses in gaining access to additional capital to engage in environmentally friendly technology and projects that reduce CO₂ emissions (Shahbaz et al. 2013b). Haseeb et al. (2018) find that financial development plays a significant role in decreasing the level of CO₂ emissions in the Russian Federation. Similarly, Bass (2019) finds that the financial sector is an essential factor of CO₂ emissions in the Russian Federation. Therefore, including the financial development data in the model is essential to increase the validity of the EKC hypothesis for the Russian Federation. Furthermore, we would also like to emphasize that the Russian Federation has never been a popular foreign direct investment (FDI) destination by Western countries because the country has been sanctioned since 2014. The latest data show that FDI flows into the Russian Federation decreased from $32 billion in 2019 to $10 billion in 2020, down by 70%. One of the factors in this decline is the COVID-19 pandemic (UNCTAD World Investment Report, 2021).

POP is the log of the population measured in millions. Studies on population and EKC emphasize that population shifts the EKC curve upward, causing deforestation, and that the negative environmental impact is greater with population (Wang et al. 2015; Culas, 2007).

Largely, previous studies testing the EKC hypothesis have used only pollutant emissions, economic development, and energy consumption (Wen et al. 2021; Yusuf et al. 2020; Zhang et al. 2019; Alege et al. 2016; Ozcan, 2013; Pao and Tsai, 2010), while some studies have considered new variables such as electricity consumption (Saint Akadiri et al. 2020; Cowan et al. 2014; Akpan and Akpan, 2012), trade openness (Koc and Bulus, 2020; Mahmood et al. 2019; Ozatc et al. 2017), financial development (Amri, 2018; Jamel and Maktouf, 2017; Shahbaz et al. 2013a), renewable/non-renewable energy/electricity production (Chen et al. 2019; Bento and Moutinho, 2016), oil prices (Erdoğan et al. 2020; Balaguer and Cantavella, 2016), population (Liu et al. 2015; Begum et al. 2015), urbanization (Salim et al. 2019; Hanif, 2018; Pata, 2018), and corruption (Balsalobre-Lorente et al., 2019; Sekrafi and Sghaier, 2018).

**Method**

The EKC hypothesis suggests that environmental pollution grows in the initial periods of economic development. According to the EKC hypothesis, it assumes that as the welfare level of a country increases, environmental pollution will increase and after a certain income, income increase will contribute positively to environmental quality (Karaca, 2012). The current study scrutinizes the link between ecological pollution and economic development in the Russian Federation including the period from 1990 to 2020, and the basic EKC hypothesis is formulated as follows (Eq. (1)):

\[
CO_{2t} = f(GDP_t, GDP_t^2, EC_t, TO_t, FD_t, POP_t)
\] (1)

In Eq. (1), CO₂t states the CO₂ emission per capita and GDPt, GDPt² states GDP per capita and its square, respectively. ECt states energy consumption, TOt states trade openness, FDt states financial development, and POPt indicates population. All data used in the study are at the annual frequency and all are included in the analysis in logarithmic form. Thus, the log linear-quadratic model formulated is shown in Eq. (2).

\[
lnCO_{2t} = \beta_0 + \beta_1lnGDP_t + \beta_2ln(GDP_t^2) + \beta_3lnEC_t + \beta_4lnTO_t + \beta_5lnFD_t + \beta_6lnPOP_t + \epsilon_t
\] (2)

According to Eq. (2), t denotes time and means that the natural logarithm of the relevant variable is taken. The possible results of the model expressed in Eq. 2 within the scope of EKC are as follows (Dinda, 2004).

I. \( \beta_1 = \beta_2 = 0 \), there is no link between CO₂ and income.
II. \( \beta_1 > 0 \) and \( \beta_2 = 0 \), the link between CO₂ and income is linear.
III. \( \beta_1 < 0 \) and \( \beta_2 = 0 \), the link between CO₂ and income is negative.
IV. \( \beta_1 > 0 \) and \( \beta_2 < 0 \), the link between CO₂ and income is “inverted U” and the EKC is acceptable.

For the EKC to be valid, there must be an “inverted U” link between CO₂ and economic growth (Allard et al. 2018: 5848). Following the approval of the EKC theory, the turning point in which environmental pollution decreases, the level of GDP per capita, GDP*, is \(-\beta_1/2\beta_2\) and the turning point is the monetary value representing that point. However, Iwata et al. (2012) argued that the turning points of developing countries can be outside the sample period and that environmental pollution continues to increase with economic growth in developing countries.

Cointegration tests are performed to examine the long-term relationship between the variables. For cointegration, the Engle and Granger (1987) and Johansen and Juselius (1990) tests are pioneering and frequently used. However, an important limitation of these tests is that the variables must be equally stationary. Therefore, this paper was conducted by Pesaran et al. (2001); ARDL bound test approach has been applied, and this approach allows to determine the cointegration relationship between variables with different levels of stationarity. The ARDL bound test was performed using Eq. (3), which shows the unbounded error correction model (UECM) by applying the Wald test.
\[ \Delta \ln \text{CO}_2_t = \beta_0 + \sum_{i=1}^{d} \beta_i \Delta \ln \text{CO}_2_{t-i} + \sum_{i=0}^{a} \rho_i \Delta \ln \text{GDP}_{t-i} + \sum_{i=0}^{b} \gamma_i \Delta \ln \text{FD}_{t-i} + \sum_{i=0}^{c} \alpha_i \Delta \ln \text{TO}_{t-i} + \sum_{i=0}^{m} \omega_i \Delta \ln \text{POP}_{t-i} + \delta_i \ln \text{EC}_{t-i} + \varepsilon_t \]  

(3)

In Eq. (3), \( \beta_0 \) denotes the constant term; \( \Delta \) denotes the difference operator, \( u_t \) denotes the error term, \( \beta_1 \ldots \beta_7 \) denote the short-term coefficient, and \( \delta_1 \ldots \delta_7 \) denote long-term coefficient. The letters \( a, b, \ldots, g \) denote the optimal lag lengths. The model allows the determination of separate lag lengths for each variable, and the null hypothesis \( (H_0): \beta_0 = \delta_1 = \cdots = \delta_7 = 0 \) stating that there is no cointegration link between the variables and the alternative \( (H_1): \beta_0 \neq \delta_1 \neq \cdots \neq \delta_7 \neq 0 \) is being created.

The ARDL method gives better results with small sample sizes when compared to other traditional cointegration tests (Nkor and Uko, 2016). The state of the cointegration link between the variables is interpreted by comparing the F test statistic with the critical values. The presence of cointegration is shown by a F statistic more than the upper critical value, and the absence of cointegration is indicated by a F statistic smaller than the lower critical value. The short-term dynamics are determined by Eq. (4), which is established after the determination of the cointegration relationship.

\[ \Delta \ln \text{CO}_2_t = \lambda_0 + \sum_{i=1}^{d} \lambda_i \Delta \ln \text{CO}_2_{t-i} + \sum_{i=0}^{a} \lambda_i \Delta \ln \text{GDP}_{t-i} + \sum_{i=0}^{b} \lambda_i \Delta \ln \text{FD}_{t-i} + \sum_{i=0}^{c} \lambda_i \Delta \ln \text{TO}_{t-i} + \sum_{i=0}^{m} \lambda_i \Delta \ln \text{POP}_{t-i} + \tau \ln \text{ECT}_{t-i} + u_t \]  

(4)

In Eq. (4), \( \lambda_0 \) represents the constant term, \( \lambda_1 \ldots \lambda_7 \) represents the short-term coefficient, and \( \tau \) shows the coefficient of the error correction term (ECT). If the ECT coefficient is between 0 and −1, there is a direct convergence to the long-term equilibrium value. If the ECT coefficient is between −1 and 2, it is interpreted that the error correction process proceeds in the form of decreasing fluctuations around the long-term balance. If the coefficient is positive or greater than −2, it indicates that the equilibrium has been moved away (Alam and Quazi, 2003; Narayan and Smyth, 2006). Lastly, Brown et al. (1975) advised that the model’s stability be tested using the CUSUM and CUSUMSQ tests. The CUSUM and CUSUMSQ tests are suitable for time series data and can be utilized when a structural break is occurred (Yoo, 2005).

**Empirical findings**

Firstly, the augmented Dickey-Fuller (ADF) test developed by Dickey and Fuller (1979) and Philips Perron (PP) test are used to check the stationarity of the variables. In addition, the unit root test developed by Zivot and Andrews (2002) was used to determine the stationarity of the variables more reliably, which stated that the ADF test would give more reliable results with a single internal structural break. Unit root tests were applied to the level and first difference values of each variable, respectively. The findings are presented in Tables 2 and 3.

According to the ADF and PP unit root test findings in Table 2, it is seen that the variables are stationary at different degrees. The CO2 and energy consumption variables were proven to be stationary at the level by both unit root tests, while the other variables were stationary at the first difference. Since the variables are stationary at different levels, it is appropriate to use the ARDL bounds test to find long-run relationships.

As seen in the ZA test results, it was concluded that while the CO2 and energy consumption (EC) variables were stationary I(1), the GDP, GDP², trade openness, financial development, and population variables were stationary I(0)) at the level. It has been determined that model C is suitable for CO2 and GDP variables and model A is

### Table 2 ADF and PP unit root test results

| Variables | ADF | PP |
|-----------|-----|----|
|           | I(0) | I(1) | I(0) | I(1) |
|           | Constant | Constant + Trend | Constant | Constant + Trend | Constant | Constant + Trend |
| GDP       | 0.4107 | −3.9186** | −2.7030** | −2.5984*** | −0.1417 | −2.4388 |
| GDP²      | 0.4466 | −3.8688** | −2.7598* | −2.6567 | −0.0961 | −2.4365 |
| EC        | −2.9282* | −2.8560 | −2.6426** | −2.6180** | −2.7430* | −2.8560 |
| TO        | −1.8565 | −0.7233 | −4.7548*** | −5.2334*** | −2.0015 | −0.9470 |
| FD        | −1.6406 | −2.0084 | −6.0588*** | −5.8867*** | −1.6690 | −2.1201 |
| POP       | −0.2562 | −3.3983* | −2.9821** | −2.1362** | −1.1787 | −0.9557 |
| CO₂       | −5.0405*** | −4.5341*** | −3.7833*** | −4.5330*** | −4.6747*** | −5.6063*** |

***, **, and * indicate 1%, 5%, and 10% significance levels, correspondingly.

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suitable for GDP, TO, FD, POP, and EC variables. The fact that the test statistic is greater than the critical values means that the H0 hypothesis, which argues that the series contains a unit root without a structural break, is rejected. Therefore, the break dates do not have a permanent effect on the relevant variables.

In the study, a randomly selected lag interval containing the selected variables to determine the lag delay interval, and a vector auto-regressive (VAR) model to scrutinize the lag interval were determined. The lag interval test results obtained are shown in Table 4.

As seen in Table 4, the appropriate lag length to be used to test the cointegration was chosen as VAR = 2, because the appropriate lag length was decided as 2 since three different criteria point in this direction. In addition, AIC (Akaike information criteria), SC (Schwartz’s criterion), and HQC (Hannan-Quinn information criterion) information criteria were used to find the optimal lag lengths for the ARDL bound test used for the cointegration connection between the 6 variables contained in the study. AIC helps in selecting the maximum possible delay length, while SBC assists in selecting the minimum possible delay length. Table 5 shows the model summaries in the lag order selection criteria.

As shown in Table 5, the lag length was selected as model 2, 2, 2, 2, 2, 2 because it had the lowest AIC and HQC
values. The bound test results for the long-term relationship are presented in Table 6.

According to Table 6, the estimated F statistics for the selected model are significant at the 1% significance level for cases II and III. The null hypothesis is rejected, and cointegration is proven because the F statistic is greater than the low critical values. The estimated long-term coefficients are displayed in Table 7.

In the long-term ARDL model estimated in Table 7, energy consumption and population raise CO₂ emissions, while GDP, financial development, and trade openness decrease CO₂ emissions in the long run. Additionally, the GDP coefficient was found to be −1.7596 in the model and \( \beta_1 > 0 \). The GDP² coefficient was 0.2879, and according to the EKC hypothesis, \( \beta_1 < 0 \). This indicates that the EKC is valid up to a certain income level in the Russian Federation, and when this income level is exceeded, a positive relationship will emerge between economic growth and environmental degradation. The turning point level of the EKC can be calculated by this “GDP* = -a1/2a2, and exp (GDP*)” formula. From the formula, the paper can obtain a turning point at GDP* = 9.50, indicating that value of 13.360$.

As seen in Table 7, it has been revealed that there is a positive relationship between energy consumption and population and environmental pollution. A 1% increase in energy consumption and population increases environmental pollution by 1.06% and 4.23%, respectively. This result is in line with a study by Katircioglu (2014) that finds a positive and significant relationship between energy consumption and carbon emissions for Turkey. Similarly, Rafindadi et al. (2018) find that there is a cointegration between CO₂ emissions and energy consumption for GCC countries. In addition, there is a negative relationship between financial development and trade openness on environmental pollution. A 1% increase in financial development and trade openness reduces environmental pollution by 0.02% and 0.71%, respectively. Our finding is consistent with Zhao et al. (2021) for China and Sadorsky (2010) for emerging economies. They emphasize the negative effects of financial development on the environment. Likewise, the result of trade openness is in line with some studies in the literature. For instance, Sun et al. (2019) discover an inverse and statistically significant relationship between trade openness and carbon emissions for Europeans.

Two lag lengths are used in the estimated ARDL model. The Breusch-Godfrey Serial Correlation LM Test determined the autocorrelation problem, and the Ramsey-Reset test verified that the model had a suitable functional form. The error terms are typically distributed, according to the Jarque–Bera test. Another step related to the ARDL cointegration test is the short-term analysis of the established model and the values related to the created model are reported in Tables 8.

As seen in Table 8, it is seen that the test statistics for the model are appropriate. An important issue in short-term analysis is the error correction term. The error correction term should generally have a statistical value

### Table 7 Long-term coefficients for the ARDL model

| Variables | Coefficient  | t statistics | Diagnostic test | F statistics | P value |
|-----------|--------------|--------------|-----------------|--------------|---------|
| InGDP     | -1.7596**    | -3.1083      | BG-LM test      | 0.9349       | 0.4531  |
| InGDP²    | 0.2879**     | -3.1342      | Ramsey reset test | 0.0852       | 0.7743  |
| InEC      | 1.0657***    | 6.5665       | F statistics    | 4.9112       | 0.003   |
| InTO      | 0.7163***    | -2.2967      | Jarque–Bera test | 0.3208       | 0.851   |
| InFD      | -0.0220***   | -3.4218      | White test      | 1.344051     | 0.3616  |
| InPOP     | 4.2365**     | 2.0389       | Model standard deviation | 0.0284   |
| C         | 0.0024       | 0.6024       | Durbin Watson value | 1.9597     |         |
| R²        |              |              |                 | 0.7660       |         |

***, **, and * indicate 1%, 5%, and 10% significance levels, correspondingly.

### Table 8 Short-term ARDL error correction model

| Variables | Coefficient  | t statistics | Variables | Coefficient  | t statistics |
|-----------|--------------|--------------|-----------|--------------|--------------|
| ΔInGDP    | -5.2290**    | -4.1147      | ΔInFD     | 0.0323       | 0.7586       |
| ΔInGDP₂   | 2.7458**     | 3.5028       | ΔInFD₂   | 0.1315**     | 3.0008       |
| ΔInGDP₃   | 0.2751**     | 4.1839       | ΔInTO     | -0.0505**    | -4.1040      |
| ΔInGDP₄   | -0.1398**    | -3.4958      | ΔInTO₂   | 0.02839*     | 3.2787       |
| ΔlnEC     | 0.8514***    | 6.9870       | ΔInPOP   | -15.1608     | -2.2284      |
| ΔlnEC₂   | -1.1929***   | -3.6214      | ΔInPOP₂ | 23.0065**    | 3.0630       |
| ECT       | -0.7682***   | -6.6183      | R² | 0.97         |

***, **, and * denote 1%, 5%, and 10% significance levels, correspondingly.
between “0” and “−1.” The error correction term of the established model is statistically significant and was found to be −0.7682. In other words, 97% of short-term deviations are corrected in the next period.

Finally, the ARDL model’s stability was tested using CUSUM and CUSUMQ tests and its long-run coefficients, in other words, to provide information about the incidence of structural breaks in the data set in general. CUSUM test indicates whether there is a structural break or not and CUSUMQ indicates the period of the break (Doguwa et al., 2014). The interpretation of the related tests is that the curves obtained with the error terms test statistics are within the critical limits, and if they are, the estimated parameters are stable. Figure 2 shows the CUSUM and CUSUMQ test charts.

As seen in the CUSUM and CUSUMQ graphs, the fact that the curves are within the critical value band at the 5% significance level indicates that there are no structural breaks in the determined long-term relationship, and it can be interpreted that the parameters are significant. Furthermore, the outcomes of the CUSUM and CUSUMSQ tests show that the coefficients in the two ARDL models are stable.

### Conclusion and policy implications

In this study, the acceptability of the EKC for the economy of the Russian Federation was tested with the 1990–2020 period data. In this framework, the ARDL cointegration test was applied within the framework of a quadric model. It was determined that the coefficients of the GDP and GDP² variables, which were taken into account to test the EKC hypothesis, were statistically significant.

According to findings, energy consumption, financial development, trade openness, population, and GDP and its square are the most significant indicators of CO₂ emissions in the long term. A 1% growth in energy consumption and population increases CO₂ emissions by 1.0657% and 4.2365%, correspondingly. A 1% increase in GDP, financial development, and trade openness decreases CO₂ emissions by 1.7596%, 0.0220%, and 0.7163%, correspondingly.

The analysis findings of the study showed the existence of a U-shaped link between economic development and CO₂ emissions, which does not approve the acceptability of the EKC hypothesis in the long term for the Russian Federation. It was determined that the coefficients of the GDP and GDP² variables, which were taken into account to test the EKC hypothesis, were statistically significant. However, it is seen that the relevant variables are marked (−) and (+), respectively. This situation is not in line with the EKC and expresses a “U” link between the environment and economic growth. The same findings were obtained by Gavrilyeva et al. (2020), indicating that EKC hypothesis is not acceptable for the Russian Federation. Furthermore, Rudenko and Skripnik (2016) indicate a little evidence to support the existence of EKC for the Russian Arctic areas. The contrary of a finding of Sohag et al. (2021), Burakov (2019), Bass (2019), Ketenci (2018), and Yang et al. (2017) find that EKC is valid for the Russian Federation. Among the studies conducted for BRICS countries, Aydin and Turan (2020) found that the EKC hypothesis is not valid for the Russian Federation, but Ummalla and Goyari (2021), Ferreira et al. (2021), and Erataş and Uysal (2014) find that EKC is acceptable for BRICS countries and for Russian Federation as well.

The EKC hypothesis is valid up to a certain income level in the Russian Federation. A positive association between economic growth and environmental deterioration is projected when this income level is exceeded. While this is a promising sign for the early phases of economic development, it is an unacceptable result for the advanced stages of economic growth within the framework of the EKC hypothesis. In the short-term relationship of the model established for the analysis, it is seen that the error correction mechanism

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**Fig. 2** CUSUM and CUSUMQ plots for the ARDL model
works and its coefficient is statistically significant. Most of the short-term deviations are corrected in the next period.

The other independent variable used in the study, energy consumption, has a significant effect on the findings. There is a positive and strong relationship between CO₂ emissions and energy consumption. The growth in energy consumption increases CO₂ emissions. While fossil-based energy sources are mostly used in energy consumption for the Russian Federation, the use of renewable energy is very limited.

In the scope of the obtained findings, some policy recommendations can be made for the Russian Federation. The Russian Federation can prefer the use of clean energy (renewable, nuclear, etc.) instead of fossil energy resources to decrease CO₂ emissions. In addition, various energy sources should be used in order to expand the share of energy sources that do not emit carbon in total energy consumption and to increase energy use efficiency through advanced technologies. There is strong evidence that energy use has a devastating impact on CO₂ emissions, and financial development encouragingly influences ecological quality in the long term. Thus, policymakers should apply appropriate strategies concerning financial development. Based on the empirical results, future policy recommendations in the perspective of COVID-19 in the context of open economies are also suggested. Razzaq et al. (2020) noted that the asymmetrical link between COVID-19 and pollution is recognized by the depth and breadth of different quarantine measures. This could mean that tackling air pollution will be an important part of easing quarantine to face the socioeconomic challenges arising from stalled economic activity due to the pandemic.

The current study is important both in terms of national economy and environmental quality. Therefore, in future studies, it is essential to evaluate the issue from different dimensions with additional variables or to compare the current situation with other countries in order to reveal the effects of the policy applied and the changes made for the geography.

Furthermore, EKC hypothesis concentrated on the rise in the production level due to the economies of scale, together with the economic development, causes fast ecological pollution. When the income reaches a certain point, the process enters the recovery process (Dinda, 2004). However, this study found the relationship between CO₂ and income in a “U” shape. Therefore, future studies can focus on the question of “What needs to be done for the EKC hypothesis to be valid for the Russian Federation?”.
### Appendix

#### Table 9  Summary of recent literature

| Author(s)          | Location                  | Period      | Method                          | Results                                                                                                                                 |
|--------------------|---------------------------|-------------|---------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|
| Wang et al. (2022) | 134 Countries            | 1996–2015   | Threshold regression model      | There is a positive relationship between urbanization, economy, carbon emissions, and ecological footprint. In addition, the coefficient of the lower middle-income group is in an inverted U shape. |
| Frodyma et al. (2022) | European Union Countries | 1970–2017   | ARDL testing bound approach     | The findings show that in most countries, EKC models fail to explain the relationship between income and output-based emissions over the period 1970–2017. Similarly, the results obtained for consumption-based emissions do not confirm the EKC hypothesis. |
| Zhong (2022)      | China Provinces          | 2011–2015   | Panel regression model          | This study confirms the EKC hypothesis for China provinces. Digital finance can alleviate income inequality and promote green industrial structure, thereby indirectly reducing pollution, but the scale effect of income growth outweighs the technological impact that indirectly increases pollution. |
| Agboola et al. (2021) | Saudi Arabia             | 1971–2016   | Pesaran bound test              | The findings show that a 1% increase in energy consumption increases environmental pollution by 0.360% and 0.983% in both the short and long term, respectively. |
| Gyamfi et al. (2021a) | E7 Countries             | 1995–2018   | PMG-ARDL model                  | Long-term results confirm the existence of an N-shaped EKC in 7 developing countries. For E7 countries, there is an inverted U-shaped EKC. |
| Gyamfi et al. (2021b) | Sub-Saharan Africa Countries | 1990–2016   | Panel quantile regression       | The findings confirm the pollution haven hypothesis for both oil and non-oil countries. This indicates that FDI inflows have a negative impact on the host country. |
| Gyamfi et al. (2021c) | Mediterranean region     | 1995–2016   | Mediterranean region            | The study found the EKC hypothesis for the Mediterranean region to be inverted U-shaped. While both financial development and renewable energy show a negative relationship with CO₂ emissions, fossil fuel has a positive relationship with emissions. |
| Bekun et al. (2021a) | EU-27 Countries          | 1990–2017   | Cointegration test technique and Granger causality | The findings confirm the correctness of the EKC hypothesis for EU-27 countries. Environmental quality is based on GDP growth. |
| Bekun et al. (2021b) | E7 Countries             | 1995–2016   | Panel causality analysis        | The results confirm the EKC hypothesis for E7 countries. The study emphasizes the importance of economic expansion in the quality of the environment. |
| Aziz et al. (2021) | MINT Countries           | 1995–2018   | Moments Quantile Regression     | The findings confirm the EKC curve between economic growth and carbon emissions for these countries. |
| Isik et al. (2021a, b, c) | 8 OECD Countries        | 1962–2015   | Fixed-effect regression model   | The empirical findings support the EKC hypothesis for 4 out of 8 countries of the model with an undecomposed series of GDP per capita. |
| Ahmad et al. (2021) | 31 Chinese provinces    | 2004–2017   | STIRPAT model                   | The intensity of non-renewable energy use with economic development is found to be inverted U-shaped. |
| Isik et al. (2021a, b, c) | 50 US States            | 1990–2017   | Armey curve model               | The results show that it has the ability to test the EKC hypothesis for 7 US states. |
| Adebayo et al. (2021) | MINT Countries           | 1990–2018   | Moments quantile regression     | The study found an inverted U-shaped correlation between economic growth and CO₂ emissions for MINT countries. Thus, the EKC hypothesis was confirmed. |
| Isik et al. (2021a, b, c) | USMCA Countries          | 1961–2016   | Threshold autoregressive panel unit root test | Empirical findings show that there is convergence of ecological footprint in the second regime, representing 48.08%, and difference in the first. |
| Gyamfi et al. (2020) | G7 Countries             | 1980–2018   | Kao cointegration test          | While the study confirms the EKC hypothesis in the short term, there is no statistical evidence of EKC in the long term. |
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Table 9 (continued)

| Author(s)          | Location              | Period      | Method                          | Results                                                                                                                                                                                                 |
|--------------------|-----------------------|-------------|---------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dogan et al. (2020) | BRICS Countries       | 1980–2014   | STIRPAT model                   | It has been determined that the EKC hypothesis is not valid for BRICS countries. In addition, it has been determined that energy density and energy structure are important determinants of environmental degradation |
| Isik et al. (2020)  | G7 Countries          | 1995–2015   | Panel bootstrap cointegration test | The tourism-based EKC hypothesis has been found to be valid in France. The negative (decreasing) impact of increased renewable energy consumption on CO2 emissions has been discovered in France, Italy, the UK, and the US |
| Godil et al. (2020) | US                    | 2000–2019   | Quantile autoregressive distributed lag (QARDL) approach | Empirical evidence suggests that the transport system (both passenger and freight) is negatively associated with carbon emissions |
| Sharif et al. (2020)| Malaysia              | 1995–2018   | ARDL method                      | The findings confirm the existence of an inverted U-shaped curve for the Malaysian economy |
| Aziz et al. (2020a, b) | Pakistan            | 1990–2018   | Quantile autoregressive distributed lag (QARDL) approach | The study confirms the EKC hypothesis for Pakistan |
| Aziz et al. (2020a, b) | BRICS Countries      | 1995–2018   | Moments quantile regression      | The findings show that an inverted U-shaped EKC curve is evident in all quantities except the 10th and 20th quantities |
| Suki et al. (2020)  | Malaysia              | 1970–2018   | Quantile autoregressive distributed lag (QARDL) approach | The results confirmed the existence of an inverted U-shaped curve in the Malaysian economy |
| Bekun et al. (2020) | Nigeria               | 1971–2015   | ARDL bounds test                 | In the study, the EKC hypothesis is confirmed for Nigeria |
| Isik et al. (2019)  | US States             | 1980–2015   | Panel unit root test            | The EKC (inverted U-shaped) hypothesis only applies to Florida, Illinois, Michigan, New York, and Ohio. The adverse effects of fossil energy consumption on CO2 emission levels in Texas have not been identified |
| Agboola and Bekun (2019) | Nigeria         | 1981–2014   | Classical linear regression model | This study confirms the inverted U-shaped model of EKC in the Nigerian sample. It confirms that Nigeria’s growth trajectory remains in the scale effect phase |
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