The impact of output volatility on CO₂ emissions in Turkey: testing EKC hypothesis with Fourier stationarity test

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Abstract

This study uses the output volatility–augmented environmental Kuznets curve (EKC) model to determine the dynamic short- and long-term impacts of the volatility of economic growth (VOL) on carbon dioxide (CO₂) emissions in Turkey from 1980 to 2015. The results of the autoregressive distributed lag (ARDL) approach indicate that there is a long-run relationship between CO₂, per capita real GDP, per capita energy use, and VOL. The coefficients obtained from the ARDL estimation indicate that economic growth and energy use increase CO₂ emissions, while VOL decreases CO₂ emissions in the long run. Moreover, the coefficients obtained from the ARDL error correction model show that VOL decreases CO₂ emissions in the short run, as well. We also find that the EKC is valid in Turkey. This implies for the Turkish case that achieving macro-stability under a “just transition” is key for achieving both economic and environmental benefits from ratifying international agreements such as Paris Agreement and EU Green Deal.

Keywords Environmental Kuznets curve · CO₂ emissions · Output volatility

Introduction

Since developed countries started to identify a strong relationship between economic growth and environmental deterioration in the late 1960s, the relationship between economic growth and energy consumption has become an attractive research area (Beckerman 1992). With this heightened intellectual attention, the United Nations Conference on the Human Environment, along with the signing of the Stockholm Declaration, was held in 1972. This was the first effective

declaration to introduce the international shared responsibility for environmental problems. This Declaration identified the 26 common principles, such as poverty alleviation for protecting the environment, suggested by the environmental Kuznets curve (EKC) hypothesis. In the same year, the Club of Rome published a report titled “Limits to Growth,” and based on its early computer simulations, it suggested that economic growth would not continue indefinitely because of resource depletion (Meadows et al. 1972). The report increased public concern on growth and environmental issues in the 1970s oil crisis years. Thus, the scarcity of natural resources became a topic of interest and debate by many researchers. In 1987, the Brunnthal report brought the concept of sustainable development to the agenda.

The United Nations Environment and Development Conference held in Rio in 1992 was an important step towards sustainable development. After the Rio Conference, environmental issues became an important international agenda. The Kyoto Protocol held in 1997 was a significant turning point in reducing greenhouse gas (GHG) emissions through a strong public awareness of global warming (Bildirici and Gökmenoğlu 2017). These efforts gained further momentum with the introduction of the Millennium Development Goals (MDGs), which was an outcome of a series of meetings held by the UN and finalized in 2005 to tackle eight main goals;

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one of the MDGs is to “ensure environmental sustainability”. After a decade of introducing the MDGs, the global community has set a new and broader set of goals. The new goals, which was adopted in 2015 by all United Nations member states and comprising of 17 goals and 169 targets that pursue a highly ambitious agenda in which the environmental goals are divided into six explicitly defined goals, are labeled as the Sustainable Development Goals (SDGs) (see UN 2020). After the SDGs, the UNs Conference of the Parties (COP) gained more importance and most significantly, the 21st COP held in Paris (COP21-Paris Agreement) in 2015 marked a major milestone on climate change, especially carbon emission. The 21st COP steered the international community towards a strict climate agreement to keep global warming at 1.5–2°C and reduce GHG emissions by 2025–2030. Although it was widely supported, many countries did not ratify the Paris Agreement mainly because of concerns over growth and economic welfare, depending on their relative economic development level.

Because people are more interested in jobs and income than clean air and water, many countries polluted the environment during the first industrialization stage (Dasgupta et al. 2002). In the later stage of industrialization, as income rises, people tend to value the environment more, so regulatory institutions become more effective and pollution level declines (Dinda 2004). Many developed countries implement environmentally friendly economic growth policies in the later stage. EKC, which is based on the study of Kuznets (1955) that proposed a relationship between economic growth and income inequality, explains the inverted U-shaped relationship between income and environmental degradation. High-income level increases environmental degradation to its peak, and then it starts to decline after a threshold level of income has been reached. The EKC hypothesis was first estimated and tested by Grossman and Krueger (1991) and then many studies introduced other factors, such as scale, technological and composition effects, international trade, market mechanism, and regulation to the hypothesis (for the literature see Dinda 2004).

Numerous studies have tested the EKC hypothesis in Turkey. The findings of most of the studies support the EKC hypothesis (see Lise 2006; Yavuz 2014; Shahbaz et al. 2013; Tutulmaz 2015; Bölük and Mert 2015), whereas some of them do not support the EKC hypothesis (see Lise and Van Montfort 2007; Akbostancı et al. 2009; Ozturk and Acaravci 2010; Katircioglu and Katircioglu 2018). Aside from economic growth, a large part of the literature focuses on the relationship between carbon emission and other factors, such as agriculture (Dogan 2016), foreign direct investment (Balibey 2015; Seker et al. 2015; Gökmenoğlu and Taspinar 2016), tourism (Vita et al. 2015), trade openness (Halicioglu 2009; Ertugrul et al. 2016; Ozatac et al. 2017; Pata 2019), export product diversification (Gozgor and Can 2016), fiscal policy (Katircioglu and Katircioglu 2018), financial development

(Ozturk and Acaravci 2013; Katircioglu and Taspinar 2017), urbanization and industrialization (Pata 2018a, 2018b, 2018c), income inequality (Uzar and Eyuboglu 2019), shadow economy (Koksal et al. 2020), hydropower energy (Pata and Aydin 2020), renewable energy (Sharif et al. 2020), and information and communications technologies (Barış-Tüzemen et al. 2020). Moreover, the nexus between ecological or carbon footprint and economic growth especially from an industrialization perspective is thoroughly discussed for selected developing countries by Farhani and Ozturk (2015), Solarin et al. (2021), and Rehman et al. (2021).

As seen from the literature, the relationship of CO₂ emissions with economic growth and other factors is well-examined. However, there is a gap in the literature about the relationship between output volatility and carbon emissions. The most rudimentary theoretical perception of the EKC hypothesis provides an intuitive nonlinear relation between a carbon-led output and per capita income. However, the proposed path towards a suggested inflection point is either assumed to be smooth or simply overlooked. In recent years, the literature has discussed the effect of the business cycle and financial crisis on carbon emission and the broad effect on the environment but mainly in the USA, China, or other developed economies. The data availability limits researchers to focus on the last five decades. Looking at this period, especially the last 30 years, there is an evident issue of macroeconomic instability for developing economies. This study seeks to augment the existing literature by introducing an additional axis of investigation in the form of output volatility, the single most important variable in assessing macroeconomic stability. This study focuses on the effect of output volatility on carbon emission in Turkey, which is a novel study in the literature. Turkey, as an upper-middle-income country that is yet to ratify the Paris Agreement, is an ideal economy for investigating the EKC hypothesis. Moreover, Turkey has experienced several episodes of macroeconomic shocks since the 1970s. Therefore, the findings of the model and inference will also be useful to similar economies.

The paper is organized as follows. The “**Output volatility and CO₂ emissions: theory and literature**” section reviews the theory and literature and constructs the theoretical foundations of the model. The “**Econometric model and data**” section presents the econometric model and data. The “**Empirical findings**” section discusses the empirical results and the main findings. Finally, the last section concludes.

Output volatility and CO₂ emissions: theory and literature

Prior to output volatility and CO₂ emissions literature, it is imperative to review the existing literature on growth and emissions. In a recent study, Joshua and Alola (2020) offer a

broad look at the literature and drive four main veins of theoretical approaches on coal usage and growth. The first two hypothesis stems from the conventional production function approach that stipulates a reduction in economic activity due to reduced coal usage. The traditional coal-based sectors, which are mainly classified as the industrial sector, have long been associated with development. However, while the first hypothesis claims that the availability of the energy source (coal) drives the economic growth, the latter hypothesis drives the causality in reverse order, claiming that the economic growth (i.e., demand for energy) pushes coal production (supply). While there are several studies that support the first view exists, several studies provide statistical evidence of the second view, such as Govindaraju and Tang (2013) and Reynolds and Kolodziej (2008) showing the increased economic activity driving further demand for energy. Joshua and Bekun (2020), on the other hand, propose a third view titled the feedback hypothesis, which states a two-way causality. Finally, there is the fourth view that focuses on the ambiguity of coal consumption and growth. The proponents of this view such as Wolde-Rufael (2010) present mixed evidence of causality for India, Japan, China, and South Korea.

Another important study from Farhani and Ozturk (2015) builds a stepwise augmentation to the conventional EKC hypothesis by incorporating additional variables that are highly associated with globalization and development. They built a progressive understanding of the issue by initially citing the nexus between quantities of energy used and the level of income. Then, by incorporating trade openness, the relation between foreign trade and development is considered accounting the evidence presented by Ang (2009). The model then expanded by urbanization measured as an urban population to total population, as an additional structural characteristic for development for newly industrialized countries. Finally, Farhani and Ozturk (2015) use a financial depth indicator (namely private credit to GDP ratio) to cover for financial development aspect of globalization. By this progressive approach, they built a comprehensive theoretical framework from economic activity to globalization and industrialization. Their findings support the significance of financial development and a monotonic relationship between real GDP and CO₂ emissions, disproving the EKC hypothesis.

While there is ample literature on output and pollution, the theoretical approaches to output volatility and environmental pollution area are relatively new. Geels (2013) distinguishes four main theoretical views on the impact of output volatility on environmental problems. The first three views, (1) a comprehensive transformation of the capitalist system, (2) a green Industrial Revolution, which is linked to the sixth Kondratieff cycle, and (3) green growth, show a positive impact of output volatility on environmental pollution. The (4) fourth view shows a negative impact since a financial/economic crisis weakens public, political, and business attention on environmental problems.

According to the first view, the relationship between economic growth, business cycles, and environmental pollution has deeper cultural and structural roots that emphasize high growth that brings modern societies into a “triple crisis.” Addison et al. (2011) defined the triple crisis as when global finance, climate change, and food crises coincide; in a broader sense, it is a financial, socio-economic, and environmental crisis. They described the first crisis as a reduction in capital flows and falling remittances. The second crisis, climate change, is when there is exceeding growth in the previous estimates of Greenhouse gas (GHG) emissions, and the concomitant rise in temperatures and sea level (see Sokolov et al. 2009). Lastly, malnutrition and hunger are the third crisis. The pursuit of higher growth rates, which only addresses growth in the real GDP, creates its internal conceptual crisis and eventually raises concerns about the type, nature, or definition of economic growth. The SDGs incorporated a broader perception of growth and development through 17 goals and 169 targets. These goals were solidified by the Sendai Framework for Disaster Risk Reduction, Addis Ababa Action Agenda on Financing for Development, and the Paris Agreement on Climate Change (see UN 2020). The 2008 global financial crisis was a profound shock not only to the developed economies but also to the least developed and developing countries; this made developing economies to abruptly contract international trade and capital flows and limit official development assistance. The economic crisis had a major impact and negative externalities on sustainable development, such as employment, social stability, health, education, and environment. This perspective is also evident in Farhani (2015).

The second view links the Kondratieff long cycles and environmental pollution. Kondratieff (1922, 1925, 1935) was the first economist to propose long cycles in economic life based on a statistical inquiry. Schumpeter (1939) named the long cycles as “Kondratieff waves” and explained these 40 to 60 years’ waves with his notion of “creative destruction.” He stated that technological innovations, such as railroads, steel, and electricity, leads to the Kondratieff waves of economic development (see Schumpeter 1967). Berry (1991) stated that the acceleration and deceleration phases of Kuznets growth cycles in Kondratieff waves result in technology, energy, and resource transitions to a sustainable economy. Some researchers have argued that we are in the sixth Kondratieff wave, which is mostly characterized by cybernetic revolution (Grinin et al. 2016), nano-revolution (Wonglimpiyarat 2005), smart cities (Batty 2016), and green revolution, such as renewable energy, resource efficiency, green nanotechnology, and green chemistry (Moody and Nogrady 2010; Gore 2010). Severe economic crises, such as the 2008 global crisis and COVID-19 pandemic, may have a positive effect on the environment by triggering a green revolution with more efficient use of technology, energy, and resource.

The 2008 global crisis was a financial crisis, but the COVID-19 pandemic is an out-of-the-box crisis, which is a sudden powerful health crisis. Its impact on the global economy was simultaneous and immense, reducing both aggregate supply and demand. In addition to a sharp decrease in economic growth expectations, compared with the 2008 global financial crisis, the COVID-19 pandemic has had deeper negative effects on economies, especially on trade volume and the service sector (IMF 2020). Moreover, the COVID-19 pandemic has had a strong impact on social life, working life, education, pollution, and health because of the social distancing, lockdown, travel and transportation, and economic measures adopted (see Barkas et al. 2020; ILO 2020). The COVID-19 pandemic, as a multidimensional crisis, is an urgent call for all countries to follow more sustainable and inclusive development that is consistent with the SDGs. Understanding the triple crisis from the perspective of the COVID-19 pandemic is an opportunity to reassess the transition to a sustainable society, which requires fundamental solutions, such as a low, slow, or even de-growth economy, redistribution of work and time, redistribution of income and wealth, universal basic income, accessibility of health and social services, green growth, and beyond-GDP measures (Van Parijs 2004; Victor 2008; Jackson 2009; Gough 2010; Jackson and Victor 2011).

The third view explains the positive relationship between green growth and the environment (see Porter and Van der Linde 1995; Pollin et al. 2008; Lanoie et al. 2008; Bowen et al. 2009; Houser et al. 2009; Zenghelis 2012a, b; Lorek and Spangenberg 2014). Green growth, which is a result of sustainable development (see Jacobs 2012), claims that protecting the environment can yield better economic growth. Therefore, economic growth should be environmentally sustainable, be biodiverse, be climate-resilient, and have low carbon emissions. Initially, advocates of green growth highlighted the cost side of “ungreen” growth. Compared to the substantial effect on long-term growth, the cost of providing green growth is minimal (see Stern 2007; Kuik et al. 2009). By contrast, some researchers claim that only economic growth can provide advanced technology to adapt to or prevent global warming and environmental pollution (see Nordhaus 1974, 2007; Smulders 1999; Brock and Taylor 2005).

The fourth view emphasizes the uncertainty channel. Economic crisis and macroeconomic instability, such as an increase in output volatility, weakens the attention of economic agents on negative externalities of environmental problems (see Geels 2013). Moreover, economic volatility erodes investor confidence and discourages green investment. A credit crunch has many negative effects on the environment since it reduces investment in energy sectors and low-carbon projects, makes investors switch from conventional technologies to low-carbon and renewable energy technologies, weakens

the global carbon markets, and cuts funds to environmental institutions (see Huang 2012).

As a leading study on the business cycle and CO₂ emissions, Doda (2014) investigated business cycles in a cross-country panel using the Hodrick-Prescott (HP) filter to identify cyclical components of CO₂ emissions and output. The following four facts emerged from his statistical analysis. (i) Emissions are procyclical. (ii) Procyclicality of emissions is positively correlated with GDP per capita. (iii) Emissions are cyclically more volatile than GDP. (iv) Cyclical volatility of emissions is negatively correlated with GDP per capita.

Menyah and Wolde-Rufael (2010) found a positive short and long-run relationship between emissions and economic growth in South Africa from 1965 to 2006, using the bound test approach to cointegration. Using a dynamic stochastic general equilibrium model with persistent productivity shocks with monthly data on pollution externality in the US economy from 1981 to 2003, Heutel (2012) showed that optimal policy makes carbon emissions procyclical; that is, it increases during expansions and decreases during recessions. He also found that compared with an unregulated case, optimal policy mitigates the procyclicality of emissions. Solarin et al. (2021) utilize novel dynamic ARDL simulations for estimating the effects of economic growth and urbanization on ecological footprint.

Shahiduzzaman and Layton (2015) examined the asymmetry of changes in CO₂ emissions during recession and expansion periods in the US economy with 1949 yearly data and 1973 monthly data. The study suggested that emissions and emissions intensity reduce faster in recession and emissions per capita continued to decline in the post-global financial crisis expansion period. Sheldon (2017) investigated the asymmetric effects of the business cycle on CO₂ emissions in the US economy at a quarterly frequency from 1950 to 2011 using an asymmetric time series model. The empirical results suggest that the elasticity of emissions is not constant with the GDP; emissions fall more sharply when GDP declines, but when they rise, GDP partly increases due to a decrease in industrial energy intensity.

Khan et al. (2019) investigated the response of emissions to supply and demand shocks to GDP using structural vector autoregression SVAR models and quarterly US data from 1973 to 2016. They found that anticipated investment technology shocks, unanticipated technology shocks, and government spending and monetary policy shocks accounted for 25, 10, and 1% of the changes in emissions, respectively. Using the Markov-switching approach and monthly data from 1973 to 2015, Klarl (2020) showed that emissions are significantly more elastic during recessions than in normal times and the elasticity of emissions is above one in recession times and below one in normal times in the USA. Gozgor et al. (2019) found a significant dependence structure between business cycles and CO₂ emissions using the time-varying copula and

the Markov-switching models in the US economy from January 1973 to January 2017. Although there was a high dependence regime during the recession episodes up to 1982, the low dependence structure regime became prominent after 1983.

Jalles and Ge (2020) studied the emissions and economic development of 46 commodity-exporting countries from 1990 to 2014 using time series and panel data techniques. The empirical results suggest that the environmental Okun's law that suggests a cyclical relationship between emissions and output is strong in some countries, which is as expected, but negative in others, which supports the successful transition to a low-carbon path. Jalles (2020) evaluated the effect of different types of financial crises on emissions using panel data of 55 developing countries from 1980 to 2012. The empirical results show that financial crises reduce CO₂ emissions. Azami and Angazbani (2020) examined CO₂ response to business cycles of six large CO₂-emitting countries, China, India, Japan, Iran, Saudi Arabia, and South Korea, using Markov-switching autoregressive models. They found that the elasticity of the emission to GDP significantly depends on regimes. For example, the elasticity of CO₂ emissions during expansions is significantly larger than during recessions in Japan and South Korea, but in Iran and Saudi Arabia, CO₂ emissions' response to GDP during recessions is significantly larger than during expansions. The empirical results imply that the optimal response of pollution abatement costs varies in the countries. In a very recent study, Rehman et al. (2021) analyze the CO₂ emissions interaction to industrialization, energy imports, carbon intensity, economic progress, and fixed investment expenditure using quantile regression analysis, finding evidence for higher pollution stemming from the increased economic activity for Pakistan. This study adds to the recent literature regarding growth, economic activity on environmental degradation by considering macroeconomic stability in the form of output volatility in Turkey.

Econometric model and data

Following the empirical literature in energy economics, the output volatility-augmented EKC model can be expressed in Equation (1):

$$\ln CO_{2t} = \alpha_0 + \alpha_1 \ln Y_t + \alpha_2 \ln Y_t^2 + \alpha_3 \ln EN_t + \alpha_4 \ln VOL_t + \varepsilon_t \quad (1)$$

where $\ln CO_{2t}$ is the log of the per capita CO₂ emissions (metric tons); $\ln Y_t$ is the log of the per capita real GDP (2010 constant \$); $\ln Y_t^2$ is the square of the log of per capita real GDP; $\ln EN_t$ is energy use (kg of oil equivalent per capita), $\ln VOL_t$ denotes the log of output volatility and measured as

the five years moving average of the standard deviation of the per capita growth rate. ε_t is the white noise error term. α_1 , α_2 , α_3 , and α_4 are the long-run elasticities of CO₂ emissions with respect to the real GDP, the square of real GDP, energy use, and output volatility, respectively. Under the EKC hypothesis, the coefficients of α_1 are expected to be positive as a result of higher output lead to higher CO₂ emissions; the coefficients of α_2 are expected to be negative to ensure that an inversely U-shaped curve relationship between CO₂ emissions and output. The expected sign of the coefficients of α_3 is positive since an increase in energy use enhances the CO₂ emissions. Furthermore, the model tests the effect of output volatility on CO₂ with the coefficient of α_4 . The annual data from 1980 to 2015 used in this study are from the World Bank's Development Indicators online database.

Unit root test

In this study, the stationarity of the variables was tested using Fourier Augmented Dickey-Fuller (ADF) test developed by Christopoulos and León-Ledesma (2010).

The standard unit root tests were biased towards non-rejection of the unit root in the presence of a structural break in the time series. The importance of structural breaks in unit root tests was first emphasized by Perron (1989), who suggested that the structural break date is exogenously determined and known ex ante. However, Zivot and Andrews (1992) proposed that the structural break date should be endogenous when testing for unit root. Lumsdaine and Papell (1997) allowed for two endogenous breaks under the alternative hypothesis. Lee and Strazichich (2003) showed that spurious rejection problems may arise when breaks are absent in the null hypothesis. There may be a tendency for endogenous break tests to suggest evidence of stationary with breaks. Schmidt and Phillips (1992) used the Lagrange multipliers (LM) test, which allows single and double breaks, to eliminate this problem. Another approach to test unit roots with breaks is the Fourier Kwiatkowski, Phillips, Schmidt and Shin (KPSS) test developed by Becker et al. (2006). According to the Fourier KPSS test, it is not necessary to determine the number and date of structural breaks when using Fourier functions. The Fourier KPSS test is estimated as follows:

$$y_t = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + e_t \quad (2)$$

where π , k , t , and T denote pi, frequency, trend, and the number of observations, respectively. Equation (2) is used to estimate the frequency from 1 to 5 with the ordinary least squares OLS to reach the minimum sum of squared residuals (SSRs) to determine the optimal frequency. The statistical

significance of the trigonometric coefficients, γ_1 and γ_2 , are determined by the F test. If γ_1 and γ_2 are statistically insignificant, the standard KPSS test is conducted; otherwise, Fourier KPSS test is used (Becker et al. 2006: 391). The group significance of the trigonometric coefficients tested using the F test is as follows:

$$F_{\tau}(k) = \frac{(SSR_0 - SSR_1(k))/2}{(SSR_1(k)/(T-q))} \quad (3)$$

where τ denotes the model with the trend; SSR_1 is the sum of the squared residuals of the unrestricted equation; that is, Equation (2) is estimated using the least square method for k optimal frequency; SSR_0 is the SSRs of the restricted equation, that is, Equation (2) without trigonometric coefficients, implying that γ_1 and γ_2 are zero; T denotes the number of observations, and q is the number of variables. If the F statistics is bigger than the critical values of the Becker et al. (2006) table, the null hypothesis is rejected, implying that the trigonometric values are statistically significant, and the Fourier KPSS test is valid. Christopoulos and León-Ledesma (2010) proposed a Fourier ADF test that uses the same procedure as the Fourier KPSS test. In the Fourier ADF test, the residuals obtained from Equation (2) are used to test the stationary in the standard ADF test.

ARDL bounds testing approach

ARDL bounds testing approach is a cointegration method developed by Pesaran et al. (2001) to test the presence of a long-term relationship between variables. In contrast with the cointegration methods proposed by Engle and Granger (1987) and Johansen and Juselius (1990), the ARDL bounds test has been used when the series integration of different orders is less than $I(2)$. However, the ARDL bounds test produces efficient results in small samples. The approach has both short- and long-run dynamics and is shown as an unrestricted error correction model as follows:

$$\begin{aligned} \Delta \ln CO_{2t} = & \beta_0 + \omega_1 D2001 + \sum_{i=1}^l \beta_i \Delta \ln CO_{2t-i} \\ & + \sum_{i=0}^m \delta_i \Delta \ln Y_{t-i} + \sum_{i=0}^n \alpha_i \Delta (\ln Y_{t-i})^2 \\ & + \sum_{i=0}^p \varnothing_i \Delta \ln EN_{t-i} + \sum_{i=0}^r \gamma_i \Delta \ln VOL_{t-i} \\ & + \vartheta_1 \ln CO_{2t-1} + \mu_1 \ln Y_{t-1} + \sigma_1 (\ln Y_{t-1})^2 \\ & + \pi_1 \ln EN_{t-1} + \tau_1 \ln VOL_{t-1} + u_t \end{aligned} \quad (4)$$

where β_0 is the constant term; β , ω , δ , α , $\varnothing$, γ , ϑ , μ , σ , π and, τ are the coefficient of the variables; l , m , n , p , and r are

the optimal lag lengths, Δ is the first difference, and u is the white noise error term. Following Pata (2019), we added the 2001 dummy variable to catch up with the structural change in the 2001 crisis, which has enormous effect on output and carbon emission in Turkey. We perform the bound test for Equation (4) after determining the optimal lag length using Akaike information criteria (AIC), Schwartz information criteria (SIC), and the Hannan-Quinn information criterion (HQ). The null hypothesis is $\vartheta = \mu = \sigma = \pi = \tau = 0$ and shows that there is no cointegration relationship between the variables, whereas the alternative hypothesis is $\vartheta \neq \mu \neq \sigma \neq \pi \neq \tau \neq 0$ and indicates that there is cointegration between the variables. If the F test statistics is greater than the upper bound critical values of Pesaran et al. (2001) and Narayan (2005), the null hypothesis is rejected, and there is cointegration relationship. If the null hypothesis is rejected, “there is no long-term cointegration relationship,” so we can estimate the long-term “levels model” presented in Equation (5) and separate the “restricted” ECM to measure the short-term dynamic effects in Equation (6). The ARDL model presents the long-term coefficients as follows:

$$\begin{aligned} \ln CO_{2t} = & \beta_0 + \omega_1 D2001 + \sum_{i=1}^l \beta_i \ln CO_{2t-i} + \sum_{i=0}^m \delta_i \ln Y_{t-i} \\ & + \sum_{i=0}^n \alpha_i (\ln Y_{t-i})^2 + \sum_{i=0}^p \varnothing_i \ln EN_{t-i} \\ & + \sum_{i=0}^r \gamma_i \ln VOL_{t-i} + u_t \end{aligned} \quad (5)$$

where β_0 is the constant term; ω_1 refers the dummy variable for 2001 crisis in Turkey, β , δ , α , $\varnothing$, and γ denote the long-term coefficient; l , m , n , p , and r denote the optimal lag length; Δ is the first difference, and u represents the white noise error terms. After estimating ARDL (l , m , n , p , r) model and obtaining the long-term coefficient, we can perform the restricted error correction model (ECM) to determine the short-term coefficients.

$$\begin{aligned} \Delta \ln CO_{2t} = & \beta_0 + \omega_1 D2001 + \sum_{i=1}^l \beta_i \Delta \ln CO_{2t-i} \\ & + \sum_{i=0}^m \delta_i \Delta \ln Y_{t-i} + \sum_{i=0}^n \alpha_i \Delta (\ln Y_{t-i})^2 \\ & + \sum_{i=0}^p \varnothing_i \Delta \ln EN_{t-i} + \sum_{i=0}^r \gamma_i \Delta \ln VOL_{t-i} \\ & + \mu ECT_{t-1} + u_t \end{aligned} \quad (6)$$

where ECT is the error correction term and represents the error term of the long-term coefficient calculated with Equation (5); μ is the coefficient of the ECT, which shows how quickly the variables attain a long-run equilibrium. The

expected value of this coefficient is between 0 and -1 , and it is also expected to be significant.

Fourier Toda-Yamamoto Granger causality test

Enders and Jones (2016) claimed that ignoring the structural breaks in a VAR model creates a bias towards a rejection of the null hypothesis of non-causality for the Granger causality tests. They offer a flexible Fourier form of Granger causality test for smooth structural change in a VAR model. Nazlioglu et al. (2016) propose a Toda-Yamamoto (TY) causality test method with a Fourier approximation. Fourier TY Granger causality test is capable of capturing gradual or smooth shifts without requiring prior knowledge such as the number, dates, and form of structural breaks for the series. In order to account for structural shifts, Nazlioglu et al. (2016) modified the TY causality test by relaxing the assumption of constant intercept term over time as presented in Equation (7):

$$y_t = \alpha(t) + \beta_1 y_{t-1} + \dots + \beta_{p+d\max} y_{t-(p+d\max)} + \varepsilon_t \quad (7)$$

where $\alpha(t)$ shows the constant term as a function of time (t), and y_t represents all endogenous variables. In this study, y_t denotes per capita CO₂ emissions, per capita real GDP, per capita energy use, and output volatility. The Fourier transformation of the constant term can be shown in Equation (8):

$$\alpha(t) \cong \alpha_0 + \sum_{k=1}^n \gamma_{1k} \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^n \gamma_{2k} \cos\left(\frac{2\pi kt}{T}\right) \quad (8)$$

where n denotes the number of frequencies, γ_{1k} and γ_{2k} measure the amplitude and displacement of the frequency, respectively. π is the pi value, and k shows the optimal frequency selected by ensuring the smallest value of the sum of squared residuals. Following Becker et al. (2006), Nazlioglu et al. (2016) used a single-frequency component to tackling over fitting problem caused by large number of n . The modified version of Equation (8) is as follows:

$$\alpha(t) \cong \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) \quad (9)$$

By substituting Equation (9) in Equation (7), we can obtain a Fourier TY Granger causality test. Equation (10) shows this test:

$$y_t = \alpha_0 + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \beta_1 y_{t-1} + \dots + \beta_{p+d\max} y_{t-(p+d\max)} + \varepsilon_t \quad (10)$$

For Equation (10) where the null hypothesis of Fourier TY Granger causality test is based on zero restriction on p parameters, $H_0 = \beta_1 = \dots = \beta_p = 0$. Nazlioglu et al. (2016) compared the effectiveness of TY, Fourier TY with a single frequency,

and Fourier TY with cumulative frequencies tests. The authors offer a TY test for small samples such as 25 observations, Fourier TY test with single frequency for larger samples, and Fourier TY causality test with cumulative frequencies for observations over 250.

Empirical findings

The findings of the ADF and Fourier ADF unit root test

The ADF (Dickey and Fuller 1981) and Fourier ADF (Christopoulos and León-Ledesma 2010) unit root tests are used to determine the stationary level of $\ln CO_2$, $\ln Y$, $(\ln Y)^2$, $\ln EN$, and $\ln VOL$. As mentioned in the “Unit root test” section, the Fourier ADF test is a two-step test. In the first step, Equation (1) is used to estimate the optimal frequency by providing the minimum SSR. In the second step, the ADF test is conducted on the residuals of Equation (1) with the optimal frequency, and if the nonlinear trend coefficients, γ_1 and γ_2 , are insignificant in Equation (1), the standard ADF test is valid. The results of the unit root test are presented in the fourth and sixth columns of Table 1.

The second, third, fourth, fifth, and last columns of Table 1 present the minimum SSR, optimal frequency, Fourier ADF test statistics, F statistics, and ADF test statistics, respectively. Table 1 indicates that all variables are stationary at the first difference except VOL, which is stationary at level, as expected. We performed the ARDL bounds test since the dependent variable of the model, CO₂, is stationary at the first difference level, but independent variable output volatility, VOL, is stationary at a level based on the Fourier ADF test statistics.

The findings of the ARDL bounds test

$\ln CO_2$, $\ln Y$, $(\ln Y)^2$, and $\ln EN$ are stationary at the first difference level but $\ln VOL$ is stationary at level. Then, we perform the ARDL model to determine the cointegration relationship. The findings of the ARDL bounds test are presented in Table 2.

Since the F -stat (4.92) is higher than the critical values for Pesaran et al. (2001) at 1% significance level and Narayan (2005) at 5% significance level, the null hypothesis, having no cointegration relationship, is rejected. After identifying the cointegration relationship between the variables, we use the ARDL model to measure the short- and long-run relationships. Based on the AIC criteria, the best model for Equation (5) is the ARDL (1,3,2,3,1) model. The results of the model are shown in Table 3.

The long-term coefficients of the ARDL (1,3,2,3,1) model are presented in Table 4. The coefficient of Y is positive and significant at 1% level, and the coefficient of Y^2 is negative

Table 1 ADF and Fourier ADF Unit root tests

Series	MinSSR	<i>k</i>	Fourier ADF	<i>F</i> (<i>k</i>)	ADF
$\ln CO_2$	1.366832	1	−1.636344 (0)	15.97438***	−1.666084 (0)
$\ln Y$	1.437425	1	−1.002257 (2)	17.49546***	0.265129 (0)
$\ln Y^2$	467.7724	1	−0.985900 (2)	17.45677***	0.415521 (0)
$\ln EN$	1.032791	1	−0.990409 (0)	18.14562***	−0.584365 (0)
$\ln VOL$	5.227717	1	−4.151515** (4)	6.259998**	−2.668018* (0)
$\Delta \ln CO_2$	0.068102	4	−7.151969*** (0)		−6.551303*** (0)
$\Delta \ln Y$	0.049182	4	−7.711134*** (0)		−6.206260*** (0)
$\Delta \ln Y^2$	16.04037	4	−7.597941*** (0)		−6.109369*** (0)
$\Delta \ln EN$	0.048932	4	−6.163601*** (1)		−6.591397*** (0)
$\Delta \ln VOL$	4.388613	5	−7.102889*** (0)		−5.809669*** (0)

Notes: ***, **, and *, respectively, represent 1%, 5%, and 10% significance level. The values in the parentheses refer to the optimum lag lengths over a maximum of nine lag length

and significant at 1% level, implying that the EKC hypothesis is valid in Turkey and consistent with the findings of the studies of Lise (2006), Shahbaz et al. (2013), Yavuz (2014), Tutulmaz (2015), and Bölük and Mert (2015). The coefficient of EN is positive as expected and significant at the 1% level. The dummy variable is negative and statistically significant at a 5% level, which indicates that the 2001 crisis has a decreasing effect on CO₂ emissions. The long-term coefficient of output volatility is −0.04 and significant at the 1% level, which indicates that an increase in output volatility decreases CO₂ emissions in the long run. This negative relationship between output volatility and CO₂ emissions supports the first three theoretical views mentioned in the previous section.

The first view is about the transformation of the capitalist system, the second view focuses on the sixth Kondratieff wave, and the third view is related to green growth. Following the literature on Turkey that used various factors, such as financial development (Ozturk and Acaravci 2013; Katircioğlu and Taşpinar 2017), urbanization and industrialization (Pata 2018a, 2018b, 2018c), income inequality (Uzar and Eyuboglu 2019), shadow economy (Koksall et al. 2020), hydropower energy (Pata and Aydin 2020), renewable energy (Sharif et al. 2020), and information and communications technologies (Barış-Tüzemen et al. 2020), we add output volatility as another factor and find evidence in favor of the EKC hypothesis. After determining the long-run relationship

between output volatility and CO₂, we run the restricted ECM to measure the short-run relationship using the ARDL (2,1,1,4) model.

The results of the short-run estimation are shown in Table 5. The coefficient of the error correction term is negative and significant, as expected. The EC term measures the speed of adjustment towards the long-run equilibrium. This term is −0.89 and considerably close to 1. This indicates that annually, the system corrects its previous period disequilibrium at a speed of 89.15%. Hence, the full convergence to the equilibrium level takes about 1.12 years. The error correction model also proves the short-run effect of output volatility on carbon emission. The effect of the $\Delta \ln VOL$ coefficient, −0.017, is negative as the same sign with the long-run model. These findings point to the nature of volatility in a developing economy. The volatility of output in these economies is usually associated with economic and financial crises. Hence, this points to adverse shocks to both aggregate demand and supply. Thus, the fourth view which emphasizes the uncertainty channel by Geels (2013) does not hold. For uncertainty channels to operate, macroeconomic and financial stability should be maintained for a prolonged period to make way for a shift in investment decisions towards greener production. However, the type of volatility experienced by Turkey (and for the majority of small open developing economies)

Table 2 ARDL bound test

Model	<i>k</i>	<i>F</i> statistic	Critical values	Critical values Pesaran et al. (2001)		Critical values Narayan (2005)	
				Lower bound <i>I</i> (0)	Upper bound <i>I</i> (1)	Lower bound <i>I</i> (0)	Upper bound <i>I</i> (1)
$CO_2 = f(Y, Y^2, EN, VOL)$	4	4.921526	10%	2.20	3.09	2.460	3.460
			5%	2.56	3.49	2.947	4.088
			1%	3.29	4.37	4.093	5.532

Table 3 The ARDL (1,3,2,3,1) model

Variable	Coefficient	Std. error	t-statistic
$\ln CO_{2t-1}$	0.096477	0.218214	0.442122
$\ln Y$	-1.06384	4.293228	-0.24779
$\ln Y_{t-1}$	1.86609	4.890105	0.381605
$\ln Y_{t-2}$	4.953974	3.680872	1.34587
$\ln Y_{t-3}$	0.409187**	0.164115	2.493298
$\ln Y^2$	0.068705	0.235707	0.291484
$\ln Y^2_{t-1}$	-0.09749	0.269799	-0.36134
$\ln Y^2_{t-2}$	-0.30299	0.203616	-1.48804
$\ln EN_t$	0.838316***	0.173926	4.819971
$\ln EN_{t-1}$	-0.35466	0.307554	-1.15318
$\ln EN_{t-2}$	0.60094**	0.188951	3.180395
$\ln EN_{t-3}$	-0.30513*	0.166875	-1.82849
$\ln VOL$	-0.01722	0.011513	-1.49538
$\ln VOL_{t-1}$	-0.02169*	0.012352	-1.75579
$D2001$	-0.02308*	0.011538	-2.00057
Constant	-33.1461***	9.098493	-3.64303
Breusch-Godfrey serial correlation LM test statistic: 0.342382 (0.5585)			
Breusch-Pagan-Godfrey heteroskedasticity test statistic: 14.49974 (0.4880)			
White heteroskedasticity test statistic: 15.06304 (0.4469)			
ARCH heteroskedasticity test statistic: 0.066836 (0.7960)			
Jarque-Bera normality test statistic: 0.517775 (0.771810)			

Notes: ***, **, and * represent 1%, 5%, and 10% significance level, respectively. The values in the parentheses refer to the probability of the statistics

can be classified as rather abrupt shocks to the economy, where short- and long-run impacts are hard to differentiate as evident from the adjustment coefficient. At this stage of economic activity, output volatility may also weaken the public attention on environmental issues, erode investor confidence, and stall green transmission if not discourage.

Finally, diagnostic tests are conducted to ensure the model's stability. The diagnostic test statistics do not suggest the presence of any serial correlation and heteroskedasticity. The estimated model also passes the diagnostic tests of functional form specification and

Table 4 Long-run coefficients of ARDL (1,3,2,3,1)

Variable	Coefficient	Std. error	t-statistic
$\ln Y_t$	6.82375***	1.778788	3.83618
$\ln Y^2_t$	-0.3672***	0.088716	-4.13904
$\ln EN_t$	0.862693***	0.271861	3.173291
$\ln VOL_t$	-0.04306***	0.014694	-2.93036
$D2001$	-0.02555**	0.011419	-2.23713
Constant	-36.6854***	7.341512	-4.99698

Notes: *** and **, respectively, represent 1% and 5% significance level

Table 5 The results of the ARDL (1,3,2,3,1) error correction model

Variable	Coefficient	Std. error	t-statistic
$\Delta \ln Y_t$	-0.90363	2.429756	-0.3719
$\Delta \ln Y_{t-1}$	-5.4452*	2.667827	-2.04106
$\Delta \ln Y_{t-2}$	-0.40757***	0.09549	-4.26817
$\Delta \ln Y^2_t$	0.059737	0.133209	0.448441
$\Delta \ln Y^2_{t-1}$	0.307346*	0.146597	2.096541
$\Delta \ln EN_t$	0.823522***	0.121133	6.798477
$\Delta \ln EN_{t-1}$	-0.27612*	0.131315	-2.10274
$\Delta \ln EN_{t-2}$	0.301**	0.107421	2.802047
$\Delta \ln VOL_t$	-0.01762**	0.008167	-2.15772
$\Delta D2001$	-0.03331**	0.015752	-2.11495
ECT_{t-1}	-0.8915***	0.144031	-6.18963

Notes: *** and **, respectively, represent 1% and 5% significance level

normality. Moreover, the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) test developed by Brown et al. (1975) are used to determine the stability of the coefficients of the ARDL error correction model. The results of the tests are presented in Figure 1. As shown in Figure 1, the results of the CUSUM and CUSUMSQ tests do not exceed the critical values at the 5% significance level, implying that all the estimated coefficients of the ARDL error correction model are stable.

Finally, the direction of causality among real GDP, energy use, output volatility, and CO₂ emissions is investigated with TY and Fourier TY causality tests. The results of the TY and Fourier TY causality test are reported in Table 6. Both causality tests results indicate that there is a one-directional causality from energy use and real GDP to output volatility. Fourier TY causality test and TY causality test shows that there is a unidirectional causal relationship from energy use to volatility at the 1% and 10% levels, respectively. In addition, there is a unidirectional causal relationship from real GDP to output volatility at the 1% level for Fourier TY causality test and 5% level for TY causality test.

Conclusion

There is an increasing interest in the relationship between economic growth and SDGs. Eisenmenger et al. (2020) criticize the SDGs for putting growth and economic well-being before ecological integrity. Moreover, the broadened scope of SDGs compared to millennium development goals, which focused specifically in the developing world, caused a lack of emphasis on the challenges faced by developing economies. Meantime since 2015, the accelerated efforts for controlling climate change introduce new challenges for developing economies. Hence, for many developing economies, researchers and policymakers are

Figure 1 CUSUM and CUSUMSQ test results

increasingly interested in the nexus between growth and environmental degradation.

This study investigates the relationship between output volatility while considering long-term cycles of the economy and CO₂ emission for Turkey. Turkey is an open economy, which is classified as an upper-middle-income economy by the World Bank and as a developing economy by the UN. Moreover, the Turkish economy is an emerging market economy, a member of G20, and an EU candidate country. Turkey also faces pressures to ratify the Paris (Climate) Agreement and the EU Green Deal. These qualities make Turkey a highly appropriate model to analyze.

Even though Turkey has enjoyed a robust growth rate in the last four decades, the growth path was not smooth. Turkey experienced several economic and financial crises stemming from both external and domestic imbalances. This study incorporates output volatility to analyze the

validity of transformational power of prolonged reduced uncertainty over volatility as an indicator of macroeconomic instability. During this period, Turkey's main exports shifted from the textiles to the automotive, household appliances, and consumer electronics industries, indicating a transformation in technology and factor intensity, whereas the share of the services sector constantly increased in GDP in comparison to both agriculture and the industrial value added. However, increased volatility of output is mainly associated with severe economic down turns clamping any long-term transformation towards a greener production.

The ARDL estimation method provides a suitable tool to test the dynamic short- and long-term impacts of the output volatility on CO₂ emissions while considering the EKC hypothesis. The empirical results also show that the EKC hypothesis is valid in Turkey. One important finding of the model comes from the

Table 6 The results of Fourier TY and TY causality tests

Results of Fourier TY					Results of TY		
Null hypothesis	Wald statistics	<i>p</i> value	<i>p</i>	<i>k</i>	Wald statistics	<i>p</i> value	<i>p</i>
$EN \neq > CO_2$	0.080	0.7814	1	3	0.057	0.8121	1
$GDP \neq > CO_2$	0.143	0.6902	1	3	0.007	0.9349	1
$VOL \neq > CO_2$	0.085	0.7738	1	3	0.101	0.7505	1
$CO_2 \neq > EN$	1.123	0.3012	1	3	0.536	0.4643	1
$GDP \neq > EN$	0.004	0.9508	1	3	0.340	0.5598	1
$VOL \neq > EN$	0.569	0.4462	1	3	0.345	0.5567	1
$CO_2 \neq > GDP$	0.121	0.7174	1	3	0.118	0.7318	1
$EN \neq > GDP$	0.037	0.8452	1	3	0.050	0.8230	1
$VOL \neq > GDP$	1.040	0.3252	1	3	0.788	0.3748	1
$CO_2 \neq > VOL$	1.769	0.1910	1	3	0.417	0.5184	1
$EN \neq > VOL$	8.277***	0.0094	1	3	3.643*	0.0563	1
$GDP \neq > VOL$	11.763***	0.0024	1	3	6.367**	0.0116	1

Notes: ***, **, and * represent 1%, 5%, and 10% significance levels, respectively. Optimal lag lengths selected by SIC and the number of bootstrap replications are 5000

estimated short-term and long-term coefficients of output volatility. Even though the EKC hypothesis is valid for Turkey, our findings suggest that an increase in output volatility decreases CO₂ emission both in the short and long terms. The results of the ARDL estimation indicate that a 1% increase in output volatility leads a 0.04% decrease in CO₂ emissions in the long run. The error correction model also proves the short-run effect of output volatility on carbon emission. The effect of the $\Delta \ln \text{VOL}$ coefficient, -0.017 , is negative as the same sign with the long-run model. This implies that macroeconomic stability still pushes conventional energy demand and use further and still far away from providing an adequate investment horizon for green transformation in Turkey. This is also supported by the speed of adjustment coefficient—the error correction term. This term is estimated as -0.89 and a shock to long-run equilibrium corrects in about 1.12 years.

Changes in technology or technological innovations tend to support greener growth, along with heightened environmental awareness that affects the markets. Also, this transformation is likely to be realized with sustained macroeconomic stability and increased investor confidence. Our result suggests that Turkey is still at a stage of development where a lasting period of macroeconomic stability is essential to achieve positive environmental gains.

Ratifying agreements such as Paris Agreement and EU Green Deal offer several opportunities to countries such as Turkey. There are qualitative returns like better air quality and mitigated energy risk. Also, there are opportunities to lower investment costs and mobilize funds, towards achieving 2030 and 2050 targets, which would simultaneously help transform the economy as well. However, as evident from this study, attained output stability would initially put pressure on CO₂ emissions, thus requiring a strong just and fair transitioning position is going to be vital. So, for the Turkish case, achieving macro-stability under a just transition is key. Under those conditions, the benefits are expected to multiply and this would reveal the results of the EKC hypothesis, and virtuous cycle of stability, investment, and greening of the economy would be initiated.

Availability of data and materials The datasets generated and/or analyzed during the current study are available in the [World Bank Open Data] repository [<https://data.worldbank.org/>].

Author contribution AE and BS analyzed and interpreted the literature and theory section. AE and MCG performed the empirical models. All authors have contributed to the conclusion and introduction sections and read and approved the final manuscript.

Declarations

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