



The impact of economic uncertainty, economic growth and energy consumption on environmental degradation in MENA countries: Fresh insights from multiple thresholds NARDL approach

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Abstract

This paper explores the influence of economic policy uncertainty on environmental quality in selected MENA countries depending on an augmented STIRPAT model over the period 1970–2020. ARDL model and its extensions like augmented ARDL, augmented NARDL, and MTNARDL models are applied to detect any possible effect from uncertainty index to carbon dioxide (CO₂) emissions. The empirical results reveal the validity of environmental Kuznet curve (EKC) curve in all the countries. Moreover, the results show that the uncertainty index enhances environmental degradation, especially in extremely large changes in Morocco, Turkey, and Iran. Besides, the findings reveal that energy consumption and population in the entire sample escalates CO₂ emissions over the study period. Consequently, policymakers in MENA countries should consider the economic uncertainty index, particularly in light of its recent rise, when developing any strategies and plans aimed at improving environmental standards, as well as the need to encourage the use of renewable energies in order to increase the percentage of their contribution to total energy consumption.

Keywords Environmental quality · Economic policy uncertainty · STIRPAT model · MTNARDL · MENA countries

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Introduction

Climate change and global warming have become one of humanity's most significant challenges in recent years (Jahanger et al. 2022a). The carbon dioxide (CO₂) levels in the atmosphere have risen in recent decades, coinciding with an increase in global average temperature (Jahanger et al. 2021a). In actual digit, the CO₂ levels in the atmosphere have increased by around 40% since the mid-nineteenth century, and our world is warming at a rate of 0.2° per decade (Cramer et al. 2018; Ahmad et al. 2022; Yang et al. 2022). Relayed to Solomon et al. (2007), increased greenhouse gas concentrations result in a 2 °C increase in global average temperature, as they suggest that our planet's average temperature could be between 2 and 9.7°F (1.1 to 5.4 °C) warmer in 2100 than it is today. It demonstrates that the Earth's climate warmed between 1880 and 2012 and that human activities that alter the atmosphere are likely to have played a pivotal role (Al-Ghussain 2019; Jahanger et al. 2021b; Khalid et al. 2021).

It is observed that the biodiversity damage was noticed at the level of ecosystems by the deforestation that has led to the loss of six million hectares per year of forest since 2000 (Laurent and Le Cacheaux 2012). This loss can provide a high cost for human development and the environment. In the past, this deterioration was mostly caused by natural phenomena, but now they are caused by anthropogenic factors (the result of human actions), such as the destruction of the environment of the species by the overexploitation of the resources, such as oil, coal, gold, and others (Sharif et al. 2019; Usman et al. 2021, 2022). Despite the fact that the conventions have been signed by the United Nations for environmental protection and against poverty in the world, the ruin of natural biodiversity and ecosystems continues its degradation and that getting worse and worse (Ramzan et al. 2022; Sharif et al. 2020a; Huang et al. 2022). According to Friedlingstein et al. (2010), they noticed that before 2100, the quantity of carbon will increase by 9 times than now and it is going to reach an unbelievable quantity of carbon that the atmosphere would not be able to support. Therefore, such outcomes push policymakers to search for solutions to the coming environmental disaster (Ke et al. 2022; Sari-Hassoun et al. 2019). The depletion of natural resources and pollution has become a severe issue that necessitates a rethinking of current government policy (Sharif et al. 2020b; Jahanger et al. 2022b; Usman and Balsalobre-Lorente 2022; Sari-Hassoun and Ayad 2020). Governments all across the world acknowledge that the existing growth model is unsustainable, and they are advocating for the environmental impact of economic expansion to be taken into account by proposing and implementing sustainable development as an integrated policy (Yang et al. 2021; Usman et al. 2020; Ramzan et al. 2021; Kamal et al. 2021).

Today's scholars admit that humans have a significant impact on the climate system, and the debate is whether the economic expansion will automatically result in increased carbon emissions or not. Thus, several researchers (Qader et al. 2021; Destek and Sarkodie 2019; Sadiq et al. 2022) pointed out that the investigation of the environmental Kuznets curve (EKC) hypothesis can give a holistic view of the link between economic growth and pollution. Kuznets (1955) studied several graphs of the economic inequality against per capita income over the economic development, but since then, Grossman and Krueger (1991) and Nemat (1994) have transferred the curve of Kuznets into a new model and new hypothesis, which is called the EKC. This hypothesis examines the association between pollution and economic growth (Sari-Hassoun et al. 2019). In the first period, the economic growth can escalate the rate of pollution the way of industry and chemical production, especially for the nations, which rely on fossil fuel production (Chen and Taylor 2020). In the second period, when the countries depend on cleaner industry and green production,

the economic factor can decrease the level of pollution (Dogan and Ozturk 2017; Usman and Radulescu 2022). Akalpler and Hove (2019) claimed that further economic expansion would degrade the ecology and ecosystem due to technological advances and the development of new unsafe products, resulting in demographic, social, and ecological concerns.

The last three decades have been marked by research into how different economic and social factors affect greenhouse gas emissions in all nations of the world in order to pinpoint the main reasons why environmental pollution has become a pressing issue that has to be addressed. Li et al. (2022) in the context of China as one of the top three emitter countries revealed that natural resources rent, financial development, and energy investment play a pivotal role in CO₂ emissions in all China provinces over the period of 1995–2017. Additionally, the authors showed that green investments could be effective in improving the environmental quality against the other determinants of CO₂ emissions, but these investments are still very limited. In addition, Liu et al. (2021) revealed that household consumption significantly increases carbon emissions, but that by using renewable energy sources, this consumption can become a key component in enhancing environmental circumstances. This finding is consistent with the study of Chica-Olmo et al. (2020) for the case of 26 European countries. Besides, Khan et al. (2022) exposed that energy efficiency and renewable electricity decrease the CO₂ emissions in the Next Eleven countries. In the long term, however, economic growth, financial inclusion, and trade openness are major factors influencing CO₂ emissions. Murshed et al. (2022) revealed that the G-7 countries' use of nuclear power has the potential to cut CO₂ emissions over the long term, whereas their use of renewable energy has the opposite effect. Besides, the economic complexity could be an important solution to reducing carbon footprint levels.

The classical study of decisions under uncertainty, on the other hand, stretches back to Savage (1954), but recent research began with Ellsberg's behavioral paradoxes (1961). Following that, this argument is expanded upon using Schmeidler's (1989) theoretical analysis, with some crucial ideas dating back to Keynes (1921, 1936). Arrow and Fisher (1974) and Henry (1974) developed new rational decision-making models for environmental economics, and several scholars followed suit with surveys of uncertainty in environmental economics. (Måler and Fisher 2005; Pindyck 2007; Aldy and Viscusi 2014; Usman et al. 2022). However, the COVID-19 pandemic that occurred in 2019 has generated huge economic policy uncertainty. Therefore, our focus here is on economic policy uncertainty (EPU), which is defined as the unpredictability of government regulatory, monetary, and fiscal policies that affect the economic agents' outputs and the environment in which they function.

It may also have environmental concerns with its economic ones (Wang et al. 2020; Li et al. 2022; Hussain et al. 2022). The EPU may encourage producers to use conventional, environmentally unfriendly procedures of manufacturing, resulting in higher carbon dioxide outputs (Anser et al. 2021a). On the other hand, EPU may have an impact on consumption and investment, resulting in lower CO₂ emissions (Liu and Zhang 2021). Furthermore, due to high EPU, reductions in R&D, innovation, and renewable energy usage could result in increased CO₂ emissions. As a result, the link between EPU and carbon emissions must be investigated to develop any environmental measures (Adedoyin and Zakari, 2020; Anser et al. 2021b; Balsalobre-Lorente et al. 2022).

The main contributions of this paper can be summarized as follows. First, this paper is an attempt to compare the effects of economic uncertainty on CO₂ emissions in the Middle East and North Africa (MENA) countries, particularly those with very high carbon emissions from oil production (Algeria, Iran, and Saudi Arabia), as well as non-oil producer (Morocco, Egypt, and Turkey) countries. Second, this novel work adds to the body of literature by utilizing several autoregressive distributed lags (ARDL) methods to identify any potential impacts of uncertainty on carbon emissions. This study employs the augmented ARDL model to deal with the original series, in addition to nonlinear autoregressive distributed lags (augmented NARDL) presented by Sam et al. (2019) to detect the possible hidden co-integration proposed by Granger and Yoon (2002). Furthermore, as declared by Li and Guo (2022), the NARDL model with only one threshold is not flexible in detecting the different kinds of changes in the independent variable. In the light of this statement, this paper uses the multiple threshold nonlinear autoregressive distributed lag (MTNARDL) models, which allows us to use more than one threshold. The key improvement of such a model is when we are aware that changes in the uncertainty index are accompanied by various responses from other variables, as the rise or fall of uncertainty in tiny percentages does not have the same impact as the rise or fall in uncertainty in big percentages (Anser et al. 2021a). Hence, this study employs the modern ARDL model with multiple thresholds presented by Pal and Mitra (2015) to examine and even the extremely small and large changes effects of uncertainty on carbon emissions. Moreover, the most significant additional benefit of this methodology is that it enables decision-makers to deal with any type of shocks or changes that occur in economic uncertainty, allowing them to create different and flexible policies that can deal with different levels of uncertainty and avoid using conventional methods to deal with economic variables. In other words, decision-makers can select from a range of tactics and techniques to manage any potential imbalance by applying different

thresholds when using the MTNARDL model estimation. Thirdly, this study compares these nations in the context of the environmental Kuznets curve to investigate the relationship between economic growth and environmental quality and to determine whether a turning point exists in order to calculate the ideal rates of economic growth to reduce carbon emissions.

The paper is structured into five sections: the introduction, which covers a basic overview of climate change, economic growth, energy, and uncertainty, is the first section. The second section includes a review of the literature, and the third section includes data and methods. The model and empirical results are presented in the fourth section, while discussion and policy implications are presented in the fifth section.

Literature review

Literature on EKC hypothesis

The environmental Kuznets curve (EKC) hypothesis is based on the finding that economic development is linked to an increase in environmental destruction up to a certain level, after which environmental quality starts to recover. Several empirical investigations looking into the EKC hypothesis employed polynomial regression (inverted *U*-shape, *N*-shape, and *M*-shaped EKC) (Ozokcu and Özdemir 2017; Balsalobre-Lorente et al. 2022). These shapes (*U* with one turning point, *N* with two points, and *M* with three points) may be analyzed sequentially in determining the best-fit curve to see if an inverse trend suggesting less environmental deterioration emerges when wealth rises above a specific level. It is possible for a cubic function to increase quicker than falls or vice versa (Lieb 2003).

Jalil and Mahmud (2009) studied the relationship between gross domestic product (GDP) and CO₂ emissions in China over the period from 1975 to 2005. They suggest that CO₂ emissions and economic growth association take the inverted *U* shape under the EKC hypothesis. Shahbaz et al. (2014) analyzed the EKC hypothesis in addition to a causality analysis among CO₂ emission, GDP per capita, energy use, and trade openness in Tunisia using ARDL procedure and innovative accounting approach over the period of 1971–2010. They found evidence of the EKC hypothesis with an inverted *U* shape. Dogan and Ozturk (2017) examined the EKC hypothesis in the USA over the period from 1980 to 2014. They used the variables of CO₂ emissions, GDP, square of GDP (GDPsq), renewable, and non-renewable energy consumption. They established that the EKC hypothesis is not valid, because the expansion in production level will not stop the USA's growth and will create a collapse in the environment. Sari-Hassoun et al. (2019) investigated the link between fossil energy,

renewable energy, carbon dioxide emissions, and economic growth in Algeria during the period of 1995–2016. To analyze the influence in the short and long term, they used Granger causality and the vector error correction model (VECM). The authors concluded that an increase in economic growth, fossil energy production, and consumption will result in an increase in carbon dioxide emissions, but an increase in renewable energy consumption will result in a decrease in income growth and carbon dioxide emissions, confirming that the EKC hypothesis is not supported in Algeria. They came to the conclusion that there is short-term unidirectional causation going from renewable energy use to carbon dioxide emissions and bidirectional causality between carbon dioxide emissions and economic growth. Moreover, Murshed et al. (2021) examined the EKC hypothesis in Bangladesh using Maki co-integration and ARDL framework over the period 1980–2015. Clearly, the results exposed the existence of the EKC hypothesis showing that Bangladesh is still in the development phase of the relationship between economic growth and CO₂ emissions. Finally, In South Asia countries, Murshed (2021) revealed the presence of the EKC hypothesis in India, Bhutan, Bangladesh, and Sri Lanka.

Economic policy uncertainty

Existing literature attempts to characterize uncertainty by pointing to several measurements of uncertainty, but in this study, we shall focus on economic policy uncertainty only. Tiwari, Jana, and Roubaud (2019) said that the economic policy uncertainty affects the economic agents' behavior such as consumption and investment decisions, and it is relating to monetary, fiscal, trade, and other interrelated policies. Moreover, the worldwide financial issues caused by the global financial crisis of 2007–2009, US and European taxation, the European debt crisis, the US–China trade war, Brexit, and other events have made the economic policy uncertainty gain more attention, according to Al-Thaqeb and Algharabali (2019). The EPU influences the government's regulatory, monetary, and fiscal policies that change the situation in which people and businesses function. Higher EPU could affect several macroeconomic indicators (economic growth, investment, financial development, trade, tourism, oil prices, and innovation) at the company levels such as national and international markets and activities (Pirgaip and Dinçergök, 2020).

Using the dynamic ARDL simulations model, Bhowmik et al. (2022) examined the environmental Phillips curve (EPC) hypothesis between unemployment and CO₂ emissions in the USA as well as the impact of several uncertainty indexes (monetary, fiscal, and trade uncertainties) on environmental degradation. The findings demonstrated the long-term validity of the EPC hypothesis. Additionally, the findings revealed a positive association between monetary

policy uncertainty and CO₂ emissions, whereas fiscal policy uncertainty causes emissions to decline. Contrarily, the results showed that trade policy uncertainty might not have any effect at all on emissions. Similarly, depending on the bootstrap ARDL model, Syed and Bouri (2021) investigated the impact of EPU on CO₂ emissions in the USA from January 1985 to December 2019. The results showed diverse outcomes in the short and long term. On the one hand, it is evident that EPU increases CO₂ emissions in the short run, which causes more environmental damage. On the other hand, EPU decreases emissions, which improves the quality of the environment. Moreover, Syed et al. (2022) studied the impact of EPU and geopolitical risk on CO₂ emissions in BRICST countries (Brazil, Russia, India, China, South Africa, and Turkey) over the period 1990–2015 using quantile regressions. The results revealed that EPU decreases CO₂ emissions in both lower and middle quantiles in contrast to higher quantiles where the EPU increases the emissions. Conversely, the geopolitical risk upsurges the emissions in the lower quantiles and drops the emissions in both middle and higher quantiles. In the same frame, Anser et al. (2021a, b) dealt with the same topic as Syed et al. (2022), but in a group of emerging countries (Mexico, China, Brazil, and Colombia) over the period 1995–2015. The findings showed clearly that EPU and energy use escalate CO₂ emissions in contrary to geopolitical risk and renewable energy use.

Jiang et al. (2019) used the Granger causality in quantiles to analyze the causal link between EPU and CO₂ emissions (both its growth rate and uncertainty index) on both aggregate and sectoral levels in the USA for the period from January 1985 to August 2017. They established that there is a unidirectional causal link running from EPU to CO₂ emissions in both high and low quintiles. Adedoyin and Zakari (2020) used ARDL and Granger causality to examine the contribution of EPU in the relationship between CO₂ emissions, GDP, and energy use in the UK for the period 1985–2017. They found that the economic policy uncertainties reduce the level of CO₂ emissions in the short run, however, in the long run; it needs relevant policies to reduce the rise of carbon emissions according to the positive effect of EPU on CO₂ emissions. The causality results show the existence of unidirectional causality running from energy use to CO₂ emissions, from CO₂ emissions to EPU, and from energy use to EPU as well. Pirgaip and Dinçergök (2020) studied the causal link between EPU, energy consumption, and carbon emissions using Konya's panel causality in the context of G-7 countries from 1998 to 2018. The results revealed the existence of Granger causal link from EPU to CO₂ emissions in the USA, Germany, and Canada; however, there is a unidirectional causality running from CO₂ emissions to EPU in Italy. Furthermore, their findings explore that policies promoting reduced energy consumption and CO₂ emissions, as well as the use of

Table 1 Data sources and abbreviations

Variables	Variable description	Measurement	Data source
CO ₂	Carbon dioxide emissions	Metric tons	WDI
GDP	GDP per capita	Constant 2015 US\$	WDI
ENE	Energy consumption	Oil equivalent	WDI
POP	Population	Total population	WDI
WUI	World uncertainty index	Index	Ahir et al. (2022)

alternative energy sources, should be implemented in G-7 countries to help mitigate the impact of EPU to improve the environment quality. Danish et al. (2020) analyzed the role of EPU on CO₂ emissions in the USA over the period from 1985 to 2017. They concluded with dynamic ARDL simulations that EPU increases the level of carbon dioxide with a fundamental role in environmental humiliation. Amin and Dogan (2021) investigated the impact of EPU on the energy-CO₂ emissions connection in China from 1980 to 2016. They used the recent ARDL model presented by Jordan and Philips (2018) examined the effect of EPU shocks on energy use and CO₂ emissions depending on dynamic simulations, the results showed that EPU has a significant and positive impact on CO₂ emissions, showing that high economic policy uncertainty, real income growth, and energy intensity increase highly the emissions of carbon. However, renewable energies play an important role in mitigating CO₂ emissions that can be a determinant solution to avoid environmental degradation in the long run.

Furthermore, Abbasi and Adedoyin (2021) employed a dynamic ARDL simulation approach to examine the shocks of energy use, EPU, and real income growth, on carbon dioxide emissions during the period from 1970 to 2018 in China. The findings show that both energy use and real income growth have positive and significant coefficients, while the sign EPU coefficient was positive but insignificant. Zakari et al. (2021) examined the influence of real income growth, energy use, and EPU on carbon dioxide emissions in 22 Organisation for Economic Co-operation and Development (OECD) countries during the period of 1985–2017. They employed the methodology of PMG-ARDL (Pooled Mean Group ARDL) and they found that EPU, real income growth, and energy use have a positive and statistically accept coefficient, leading to an increase in the level of CO₂ emissions in such countries.

EKC hypothesis and economic policy uncertainty

Several studies examine the hypothesis of EKC under the effect of the EPU on the energy use CO₂ emissions nexus. Adams et al. (2020) considered the relationship between EPU and CO₂ emissions in the presence of both energy consumption, and geopolitical risk for 10 resource-rich countries over the period of 1996–2017. They found with the

PMG-ARDL model that EPU, income growth, and energy use contribute positively and significantly to the raised CO₂ emissions, in the long run, this result, therefore, stimulates the environmental pollution in such countries. Furthermore, the results demonstrated the existence of U shapes EKC in the short run, but on the other hand, they proved that EKC is constant in the long run. Wang et al. (2020) studied the impact of real income growth, energy prices, and the World Uncertainty index on CO₂ emissions in the USA spanning the period 1960–2016 depending on the ARDL model. The results explored a positive effect from EPU on CO₂ emissions through two channels, which are the consumption, and the investment effects. The first suggests that EPU can decrease energy consumption as a response to a rise in EPU, thus CO₂ emissions decline. The second effect suggests that high EPU can harm renewable energy investments; thus, CO₂ emissions increase automatically using non-renewable energies. Therefore, they proposed developing stable and transparent policies in order to minimize these effects and improve environmental quality. Furthermore, they validated also the EKC hypothesis in the USA. Anser et al. (2021a) employed the CO₂ and Anser et al. (2021b) emissions, real income growth, energy consumption, total population, and the world uncertainty index (as a proxy of Economic Policy Uncertainty) to analyze the influence of economic policy uncertainty on CO₂ emissions. The authors used PMG-ARDL modeling for the top 10 carbon emitter countries, which are China, the USA, India, Russia, Japan, Germany, Iran, Saudi Arabia, South Korea, and Canada during the period 1990–2015. They found that the world uncertainty index influence positively and significantly the emissions of CO₂, and there is evidence of the EKC hypothesis for these countries.

Moreover, Liu and Zhang (2021) analyzed the instruments of how EPU influences carbons emissions and its role in controlling the environmental regulation–CO₂ emissions nexus for 30 provinces of China during the period from 2003 to 2017. The authors employed a fixed-effects panel model and linear regression with Driscoll-Kraay standard errors. They used CO₂ emissions as a dependent variable, followed by independent variables GDP, GDPsq, energy consumption, environment regulation (ER), economic policy uncertainty (EPU), and they introduced the concept of (EPU*ER) to establish the moderating role of EPU on

Table 2 Descriptive statistics

Variables	CO ₂	WUI	ENE	GDP	POP
Algeria					
Mean	4.882076	0.030706	2.407497	3.320116	7.414975
Maximum	5.221784	0.305590	2.848214	3.747584	7.625605
Minimum	4.177795	0.000000	1.564133	2.526630	7.148039
Std. dev	0.236570	0.047459	0.331443	0.296440	0.140080
Jarque-Berra	9.471998	1059.074	12.09305	7.077352	3.516880
Probability	0.008774	0.000000	0.002366	0.029052	0.172314
Saudi Arabia					
Mean	8.390452	0.087548	3.010720	4.324529	7.216817
Maximum	8.829225	0.256045	3.486491	4.576815	7.534895
Minimum	7.655631	0.000000	2.403568	4.179827	6.766144
Std. dev	0.295983	0.059446	0.343419	0.116170	0.227362
Jarque-Berra	2.084889	4.303609	3.011698	10.49980	3.616427
Probability	0.352592	0.116274	0.221829	0.005248	0.163947
Morocco					
Mean	7.423852	0.062676	1.991121	3.272816	7.407290
Maximum	7.833890	0.311055	2.420973	3.532473	7.561957
Minimum	6.862252	0.000000	1.478653	3.008282	7.204248
Std. dev	0.274077	0.068804	0.263342	0.157192	0.105534
Jarque-Berra	2.742235	49.93353	2.490448	2.704183	3.471427
Probability	0.253823	0.000000	0.287876	0.258699	0.176274
Egypt					
Mean	7.956833	0.087089	2.611459	3.328744	7.778616
Maximum	8.398989	0.704506	3.036700	3.598242	8.001682
Minimum	7.335538	0.000000	1.957085	2.983228	7.537993
Std. dev	0.318362	0.114461	0.324012	0.184978	0.137895
Jarque-Berra	3.154639	610.9941	3.546504	3.065762	3.043837
Probability	0.206528	0.000000	0.169780	0.215913	0.218293
Turkey					
Mean	8.209184	0.209933	2.788912	3.777712	7.751320
Maximum	8.628725	0.722115	3.255959	4.079340	7.921320
Minimum	7.629198	0.000000	2.164564	3.523290	7.542530
Std. dev	0.290104	0.148794	0.309853	0.163032	0.109698
Jarque-Berra	3.361596	13.71205	2.842273	3.082764	2.946293
Probability	0.186225	0.001053	0.241440	0.214085	0.229203
Iran					
Mean	8.435705	0.117915	2.996919	3.664509	7.738538
Maximum	8.865321	0.419369	3.535150	3.916407	7.918627
Minimum	7.962783	0.000000	2.225617	3.467298	7.455056
Std. dev	0.276845	0.111464	0.373877	0.113467	0.141600
Jarque-Berra	4.150008	8.919352	2.934487	2.275142	5.150512
Probability	0.125556	0.011566	0.230560	0.320597	0.076134

the environmental regulation–carbon emissions nexus. The findings show that there is a negative impact of EPU on carbon emissions, while the other variables have a positive influence on carbon emissions. Also, the interactive term (EPU*ER) has a positive and significant coefficient, confirming that environmental regulations have significantly

promoted carbon emissions (evidence of green paradox), and it implies that EPU has a positive impact on the environment regulation-carbon emissions nexus. This study confirmed the evidence of the EKC hypothesis in the eastern and central regions.

Data, model construction, and methodological framework

Data and model construction

Our analysis is mainly based on Dietz and Rosa (1994) model named STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) model which examines the effect of socioeconomic factors on environmental quality including technology, affluence, and population. Thus, our STIRPAT model can be written as follows:

$$(CO_{2,t}) = \varphi POP_t^\alpha GDP_t^\beta ENE_t^\gamma \varepsilon_t \tag{1}$$

where CO₂ shows the carbon dioxide emissions, POP illustrates the population growth, GDP denotes the gross domestic product per capita, and ENE represents energy consumption. Moreover, to avoid the issue of heterogeneity, we transform our STIPRAT model into logarithmic form following Usman and Hammar (2021) and Yang et al. (2022) as follows:

$$\log(CO_{2,t}) = \varphi + \alpha(\log POP_t) + \beta(\log GDP_t) + \gamma(\log ENE_t) + \varepsilon_t \tag{2}$$

As stated previously, we aim in this paper to investigate the effect of uncertainty on CO₂ emissions using the World Uncertainty Index (WUI) presented by Ahir et al. (2022); therefore, we introduce the WUI variable into our STIRPAT model. In addition, the authors incorporate the GDP square (GDPsq) variable into the model with the GDP variable to test the EKC hypothesis with the expectation of positive and negative effects of GDP and GDPsq on CO₂ emissions respectively, following Apergis and Ozturk (2015). Finally, our empirical model used is as follows:

$$\begin{aligned} \log(CO_{2,t}) = & \varphi_1 + \beta_1(\log GDP_t) + \beta_2(\log GDPsq_t) \\ & + \beta_3(\log ENE_t) + \beta_4(\log POP_t) \\ & + \beta_5(\log WUI_t) + \varepsilon_t \end{aligned} \tag{3}$$

Moreover, our analysis uses annual data for six selected MENA countries depending on availability data (Algeria, Egypt, Iran, Morocco, Saudi Arabia, and Turkey) spanning the period 1970–2020. Noteworthy, the WUI index is available only on quarterly bases, for this reason, and following Anser et al. (2021a), we convert the quarterly data into yearly data by calculating the average of four quarters for

each year. The descriptions of all variables are reported in Table 1.

Descriptive statistics of the variables are presented in Table 2. Remarkably, all the series in most cases are normally distributed except WUI and GDP for Algeria and Saudi Arabia. Besides, it is important to shed light on maximum and minimum values of GDP, whereas, we will need it in the comment on the threshold of the EKC curve. For the correlations matrix, the energy consumption and CO₂ emissions in all countries except Iran are positively and significantly correlated, showing that ENE is a fundamental explanation for CO₂ emissions. In juxtaposing, the same result is achieved with population-CO₂, and GDP-CO₂ emissions relationships (except in Saudi Arabia where there is a negative association).

Methodology

Since Pesaran et al. (2001), the ARDL bounds test approach has become widely used in economic studies. Whereas traditional tests like Engel Granger and Johansen tests require all series to be of type I (1), the ARDL methodology, which allows for a mixture of type I (0), and I (1) variables, is the best option for researchers to study the co-integration relationship between their variables, given that no variable is of type I (2). Furthermore, the typical ARDL model established three key assumptions: first, the independent variables

must be exogenous, second, the dependent variable must be integrated into order one I (1), and third, there must be no degenerate cases (McNown et al. 2018). As a result, according to Sam et al. (2019), many papers and researchers have neglected these assumptions, resulting in ambiguous results. Moreover, the ARDL approach suggested two tests to examine the cointegration relationships, one for the lagged level variables (LLV) named the overall *F* test, and the second for the lagged level of the dependent variable (LLDV) named the *t*-test. However, in order to avoid the degenerate instances indicated above for the third assumption of the ARDL model, these two tests require the dependent variable to be an I (1) series as a strong assumption. On one hand, the acceptance of the significance of the overall *F* test means that the lagged level of all variables is together significant; on the other hand, the *t*-test allows us to avoid the degenerate lagged dependent variable described by McNown et al. (2018). This last suggests that the significance of the overall *F* test can be due to the significance of LLDV or the lagged level of independent variables (LLIV) solely. Resultantly, if only the LLDV is significant, we get the Dickey-Fuller equation and the dependent variable is the I (0) series.

For all these reasons, McNown et al (2018) proposed a third test to examine the significance of LLIV to eliminate the I (1) assumption for the dependent variable. To get a clear idea about the three hypotheses, we introduce our ARDL model in this study as follows:

$$\Delta \ln \text{CO}_{2,t} = \varphi_1 + \beta_1 \text{CO}_{2,t-1} + \beta_2 \text{GDP}_{t-1} + \beta_3 \text{GDPsq}_{t-1} + \beta_4 \text{ENE}_{t-1} + \beta_5 \text{POP}_{t-1} + \beta_6 \text{WUI}_{t-1} + \sum_{i=1}^p \gamma_{1i} \Delta \text{CO}_{2,t-i} + \sum_{i=0}^p \gamma_{2i} \Delta \text{GDP}_{t-i} + \sum_{i=0}^p \gamma_{3i} \Delta \text{GDPsq}_{t-i} + \sum_{i=0}^p \gamma_{4i} \Delta \text{ENE}_{t-i} + \sum_{i=0}^p \gamma_{5i} \Delta \text{POP}_{t-i} + \sum_{i=0}^p \gamma_{6i} \Delta \text{WUI}_{t-i} + \varepsilon_t \quad (4)$$

where φ_1 is the intercept of the model; γ_{ji} represents the short run estimators; β_j indicates the long run estimators; and ε_t is the white noise of estimation while Δ represents the first difference operator, in addition. Thus, the three hypotheses are as follows:

Overall *F* test on LLV is presented as $H_{0A} : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$;

The *t*-test on LLDV is presented as: $H_{0B} : \beta_1 = 0$

F test on LLIV is presented as: $H_{0A} : \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = 0$

As a result, the AARDL model (augmented ARDL model) provides two sets of critical values: I (0) critical values are lower bounds achieved when variables are completely I (0), while I (1) critical values are upper bounds in the case of all variables are purely I (1). Therefore, on the one hand, the null hypothesis will be rejected only if the test statistic exceeds the upper critical value; on the

other hand, the null hypothesis cannot be rejected if the test statistic is below the lower bounds. Notably, if the test statistic falls between the upper and lower boundaries, the test will be indecisive; for this reason, they applied a bootstrapping technique to get new critical values to avoid this situation.

On the other extreme, since Granger and Yoon (2002) work, the hidden cointegration concept has become very important in time series analysis. According to Stock and Watson (1988), variables are co-integrated when they respond to the same shocks together and are not co-integrated when they respond to the same shocks separately. Going further, Granger and Yoon (2002) showed that some series could move together only in the case of the positive shock but not with negative ones or vice versa. For this reason, they suggested a new procedure to put a threshold at zero to get positive and negative sums to

detect independently both appreciations and depreciations of independent variables’ effects on dependent variables. Therefore, in this paper, we aim to examine the asymmetric effects of uncertainty on CO₂ emissions by decomposing the WUI variable into its positive and negative changes as follows:

$$WUI_t^+ = \sum_{j=1}^t \Delta WUI_j^+ = \sum_{j=1}^t \max(\Delta WUI_j, 0) \tag{5}$$

$$WUI_t^- = \sum_{j=1}^t \Delta WUI_j^- = \sum_{j=1}^t \min(\Delta WUI_j, 0) \tag{6}$$

where $WUI_t = WUI_0 + WUI_t^+ + WUI_t^-$. Consequently, the NARDL model following Shin et al. (2014) can be written as follows:

$$\begin{aligned} \Delta \ln CO_{2,t} = & \varphi_1 + \beta_1 CO_{2,t-1} + \beta_2 GDP_{t-1} + \beta_3 GDPsq_{t-1} + \beta_4 ENE_{t-1} + \beta_5 POP_{t-1} \\ & + \beta_6 WUI_{t-1}^+ + \beta_7 WUI_{t-1}^- + \sum_{i=1}^p \gamma_{1i} \Delta CO_{2,t-i} + \sum_{i=0}^p \gamma_{2i} \Delta GDP_{t-i} \\ & + \sum_{i=0}^p \gamma_{3i} \Delta GDPsq_{t-i} + \sum_{i=0}^p \gamma_{4i} \Delta ENE_{t-i} + \sum_{i=0}^p \gamma_{5i} \Delta POP_{t-i} \\ & + \sum_{i=0}^p \gamma_{6i} \Delta WUI_{t-i}^+ + \sum_{i=0}^p \gamma_{7i} \Delta WUI_{t-i}^- + \varepsilon_t \end{aligned} \tag{7}$$

where WUI_t^+ and WUI_t^- are positive and negative changes of the WUI variable respectively. Thus, the co-integration nexus in Eq. 5 can be verified due to the null hypothesis proposed by Shin et al. (2014) using Pesaran et al. (2001) and Narayan (2005) critical values depending on standard bounds tests, which is $H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6 = \beta_7 = 0$. Besides, this allows us to test the asymmetric behavior in the long-run term by setting $(\beta_6 / -\beta_1 = \beta_7 / -\beta_1)$ along with short-run asymmetry by setting $(\sum_{i=0}^{p-1} \gamma_{6i} = \sum_{i=0}^{p-1} \gamma_{7i})$, according to normal Wald test.

Additionally, to confirm the long-term link between the variables, the augmented NARDL model can be examined utilizing the three hypotheses in line with Sam et al. (2019) work on the ARDL model. Furthermore, Pal and Mitra (2015) have introduced the MTNARDL model, which is an extension of the NARDL framework with multiple thresholds instead of a single threshold. Thus, using several partial sums, we can determine the impact of extremely small and large changes in independent variables on the dependent variable. Therefore, in this paper, we will use an MTNARDL model with three thresholds denoted by τ_{25} , τ_{50} , and τ_{75} to get partial sum series in quintiles 25th, 50th, and 75th respectively given that $WUI_t^i = WUI_0^i + WUI_t^i(\omega_1) + WUI_t^i(\omega_2) + WUI_t^i(\omega_3) + WUI_t^i(\omega_4)$ calculated as given:

$$WUI_t^i(\omega_1) = \sum_{j=1}^t \Delta WUI_j^i(\omega_1) = \sum_{j=1}^t \Delta WUI_j^i I \left\{ \Delta WUI_j^i < \tau_{25} \right\} \tag{8}$$

$$WUI_t^i(\omega_2) = \sum_{j=1}^t \Delta WUI_j^i(\omega_2) = \sum_{j=1}^t \Delta WUI_j^i I \left\{ \tau_{25} < \Delta Q_j^i < \tau_{50} \right\} \tag{9}$$

$$WUI_t^i(\omega_3) = \sum_{j=1}^t \Delta WUI_j^i(\omega_3) = \sum_{j=1}^t \Delta WUI_j^i I \left\{ \tau_{50} < \Delta Q_j^i < \tau_{75} \right\} \tag{10}$$

$$WUI_t^i(\omega_4) = \sum_{j=1}^t \Delta WUI_j^i(\omega_4) = \sum_{j=1}^t \Delta WUI_j^i I \left\{ \tau_{75} \leq \Delta Q_j^i \right\} \tag{11}$$

where $I\{T\}$ is an indicator function with the value one if the condition T is satisfied and zero value if not? Hence, our MTNARDL model will be:

$$\begin{aligned} \Delta \ln CO_{2,t} = & \varphi_1 + \beta_1 CO_{2,t-1} + \beta_2 GDP_{t-1} + \beta_3 GDPsq_{t-1} + \beta_4 ENE_{t-1} + \beta_5 POP_{t-1} \\ & + \sum_{k=1}^4 \beta_k WUI_{t-1}^i(\omega_k) + \sum_{i=1}^p \gamma_{1i} \Delta CO_{2,t-i} + \sum_{i=0}^p \gamma_{2i} \Delta GDP_{t-i} \\ & + \sum_{i=0}^p \gamma_{3i} \Delta GDPsq_{t-i} + \sum_{i=0}^p \gamma_{4i} \Delta ENE_{t-i} + \sum_{i=0}^p \gamma_{5i} \Delta POP_{t-i} \\ & + \sum_{i=1}^4 \sum_{i=0}^p \gamma_{ki} WUI_{t-i}^i(\omega_k) + \varepsilon_t \end{aligned} \tag{12}$$

$$H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = \beta_5 = \beta_6$$

where the null hypothesis is $\beta_7 = \beta_8 = \beta_9 = \beta_{10} = 0$, which is tested by standard critical values suggested by Pesaran et al. (2001). Returning to the Sam et al. (2019) publication, it is evident that there are no critical values for more than six independent variables; nevertheless, since our models contain more than seven independent variables, we are unable to apply the Augmented MTNARDL model.

Results and discussion

Unit root tests results

Generally, the first step in time series analysis is the unit root test to detect the integration order of the series to avoid spurious regressions and results. Additionally, the ARDL procedure and its extensions are used in this article, and this procedure demands that all series must be in order I (0) or I (1), with no I (2) series. For this reason, we use three tests to ensure that there is no I (2) series among our variables, the tests are augmented Dickey-Fuller (ADF) and Phillips Perron (PP) tests for traditional unit root tests and Zivot-Andrews (ZA) test to deal with structural breaks in the series. Table 3 demonstrates that all variables, with the exception of WUI, which is stationary at the level, are I (1) series for all of our samples employing the three tests. Resultantly, the study variables have no I (2) series, thus, we can use the ARDL equations to look at the long-run

Table 3 Unit root tests results

Variables	Algeria				Saudi Arabia				Morocco			
	ADF		PP		ADF		PP		ADF		PP	
	Statistic	Break	Statistic	Break	Statistic	Break	Statistic	Break	Statistic	Break	Statistic	Break
CO ₂	-4.511***	1999	-4.647***	1999	-3.733**	1999	-3.733**	1999	-2.635	1995	-2.515	2004
Δ (CO ₂)	-6.170***	1976	-9.321***	1976	-6.593***	1976	-6.593***	2000	-9.055***	2000	-9.593***	2004
ENE	-3.287*	1978	-2.474	1978	-1.677	1978	-1.531	1995	-3.482*	1995	-3.456*	2004
Δ (ENE)	-5.467***	1983	-6.811***	1983	-8.365***	1983	-8.413***	2008	-7.689***	2008	-7.690***	2014
GDP	-2.111	2004	-2.228	2004	-2.361	2004	-2.139	1982	-2.749	1982	-2.963	1992
Δ (GDP)	-5.238***	1996	-5.699***	1996	-5.104***	1996	-5.026***	1984	-10.33***	1984	-9.968***	2006
GDPsq	-1.792	2004	-2.026	2004	-2.335	2004	-2.151	1982	-2.506	1982	-2.781	1992
Δ (GDPsq)	-5.380***	2003	-5.612***	2003	-5.078***	2003	-5.001***	1986	-10.17***	1986	-9.842***	2001
POP	-2.481	1990	-1.390	1990	-2.369	1990	-1.199	2003	-2.434	2003	-1.338	1988
Δ (POP)	-5.283***	1994	-5.129***	1994	-5.708***	1994	-4.652***	2006	-4.621***	2006	-4.583***	1992
WUI	2.868	2010	-3.380**	2010	-5.244***	2010	-5.022***	2012	-4.718***	2012	-4.668***	1982
Δ (WUI)	-10.35***	1995	-11.70***	1995	-7.846***	1995	-17.23***	1977	7.997***	1977	-16.63***	2004
Egypt												
Turkey												
CO ₂	-0.994	2005	-0.701	2005	-1.701	2005	-1.823	1978	-2.187	1978	-2.356	1986
Δ (CO ₂)	-8.834***	2003	-9.122***	2003	-6.265***	2003	-6.320***	2015	-5.507***	2015	-6.117***	1982
ENE	-1.618	1991	-1.066	1991	-2.964	1991	-2.962	2001	-2.755	2001	-2.752	1993
Δ (ENE)	-5.809***	2006	-5.854***	2006	-7.282***	2006	-7.330***	1999	-4.847***	1999	-6.160***	2010
GDP	-2.625	1991	-1.369	1991	-2.138	1991	-2.223	1999	-1.868	1999	-1.448	1978
Δ (GDP)	-4.431***	2011	-4.201***	2011	-6.696***	2011	-6.689***	2011	-4.766***	2011	-4.673***	1981
GDPsq	-2.789	1980	-1.492	1980	-1.953	1980	-1.953	1999	-1.885	1999	-1.510	1984
Δ (GDPsq)	-4.422***	1985	-4.219***	1985	-6.688***	1985	-6.681***	2011	-4.729***	2011	-4.660***	1981
POP	-1.435	2005	-1.008	2005	-3.728**	2005	-2.752	2003	-2.081	2003	-0.820	1993
Δ (POP)	-3.916**	1995	-4.878***	1995	-5.027***	1995	-5.919***	1988	-4.292***	1988	-4.879***	1988
WUI	-3.835**	2011	-3.940**	2011	-5.178***	2011	-5.182***	2015	-3.743**	2015	-3.694**	2006
Δ (WUI)	-7.422***	2013	-8.033***	2013	-7.822***	2013	-14.93***	2015	-9.709***	2015	-11.90***	2012

***, ** and * denote the significance level at 1%, 5%, and 10% respectively

relationship between them, as well as the long-run and short-run impacts.

Augmented ARDL model estimation results

As previously stated, we use the modern augmented ARDL (AARDL) model presented by McNown et al. (2018) instead of the standard ARDL model proposed by Pesaran et al (2001). The results are presented in Table 4, which clearly showed that the three null hypotheses of no co-integration are all rejected at the 1% significance level, with the exception of Iran. Additionally, the results demonstrated that all error correction terms (ECT) are statistically significant at the 1% level, with negative coefficients indicating that all models include a long-run adjustment. As a result, Algeria, Saudi Arabia, and Iran adjust more than 40% of variations from long-run equilibrium each year (the three oil producers). However, when compared to Morocco and Egypt, it is evident from the ECT coefficient that this case’s rate of adjustment

is extremely rapid, with an annual adjustment rate of more than 80%. According to Narayan (2005), the ECT coefficient between -1 and -2 that shows dampened fluctuations in the equilibrium path; however, the ECT coefficient in Turkey is -1.082 , which is lower than -1 . We suggest relating to the coefficient (-1.082) that the error correction process varies around the long-run value in a dampening way rather than monotonically converging to the equilibrium path straight. The convergence to the equilibrium path, however, happens quickly once this process is over. Moreover, the diagnostic tests indicated that there is no problem with estimation models with any autocorrelation of errors, high R -squared, no auto-regressive conditionally heteroscedasticity (ARCH) behavior, and the estimators are stable overtime except in Algeria and Iran. However, the findings revealed clearly that the uncertainty index affects the CO_2 emissions neither in long-run nor in the short-run terms with the exception of Saudi Arabia and Turkey but at only a 10% significance level with a positive association.

Table 4 Augmented ARDL results

Variables	Algeria	Saudi Arabia	Morocco	Egypt	Turkey	Iran
Long-run effects						
ENE	0.405***	1.875**	0.747***	0.961**	0.373***	0.206
GDP	2.285***	34.023**	-0.645	-1.389	5.590***	-1.404
GDPsq	-0.287***	-3.845**	0.019	0.178	-0.674***	0.291
POP	2.114***	4.671**	1.192***	0.244	0.711***	1.439
WUI	-0.089	0.474*	0.004	0.022	0.035*	0.044
Short-run effects						
ECT	-0.428***	-0.451***	-0.902***	-0.801***	-1.082***	-0.530***
Δ ENE	0.580**	0.846***	0.674***	0.770***	0.404**	0.109
Δ ENE (-1)	0.236	0.377*	-----	-----	-----	0.493**
Δ GDP	3.265**	15.354**	-6.154	-1.112	6.050**	-0.745
Δ GDP (-1)	-----	-2.292	-12.936**	-----	-----	-----
Δ GDPsq	-0.411**	-1.735**	0.979	0.143	-0.729***	0.154
Δ GDPsq (-1)	-----	0.037*	2.055**	-----	-----	-----
Δ POP	3.020***	2.108***	57.606**	29.233	0.770***	0.763*
Δ POP (-1)	-194.871***	13.493***	-50.707**	-42.850**	8.486	-1.967
Δ WUI	-0.128	-0.358	0.003	0.017	0.038	0.023
Δ WUI (-1)	-----	-----	-----	-----	0.007	-----
Constant	-20.596***	-43.005**	-2.957	5.087	-10.556**	-1.091
Diagnostics tests						
F test overall	10.172***	5.233**	13.532***	6.950***	15.940***	5.498**
t -test-dependent	-6.396***	-4.322**	-7.588***	-4.882***	-9.147***	-3.821
F test-independent	8.903***	6.279***	13.587***	6.132***	17.838***	6.342***
LM test	2.596*	1.299	0.012	0.244	0.029	0.785
ARCH test	0.076	0.706	0.876	4.219**	0.119	0.243
Adjusted R -squared	0.945	0.983	0.997	0.994	0.997	0.993
CUSUM	S	S	S	S	S	S
CUSUMSQ	N	S	S	S	S	N

***, ** and * denote the significance level at 1%, 5%, and 10% respectively

The environmental Kuznets curve also exists in the cases of Algeria, Saudi Arabia, and Turkey because the GDPsq coefficient is significant and negative while the GDP coefficient is significant and positive. This suggests that an inverse *U*-shaped curve exists in the relationship between GDP and CO₂ emissions in the three countries (return points are 3.98, 4.42, and 4.14, respectively). These findings are in line with the conclusion of earlier studies (Intisar et al. 2022; Wan et al. 2022; Usman and Jahanger 2021; Usman and Hammar 2021; Sadiq et al. 2022). On the other hand, the outcomes exposed that population growth plays a pivotal role in CO₂ emissions in Algeria, Saudi Arabia, Morocco, and Turkey in both long-run and short-run

terms, especially in Saudi Arabia where a 1% increase in population increases CO₂ emissions by 4.67% in the long-run term (2.11% in Algeria, 1.19% in Morocco, and 0.71% in Turkey). Furthermore, the energy coefficient has a positive impact on CO₂ emissions in all country's samples, implying that energy consumption upsurges CO₂ emissions in the long and short run.

Augmented NARDL model estimation results

Returning to Granger and Yoon (2002), we see that the concept of hidden co-integration has gained a lot of traction in the economic literature up until Shin et al. (2014) paper, in

Table 5 Augmented NARDL model results

Variables	Algeria	Saudi Arabia	Morocco	Egypt	Turkey	Iran
Long-run effects						
ENE	0.407***	2.002*	0.382**	0.891**	0.340**	0.422*
GDP	2.291***	34.737**	-0.962	-1.657	6.101***	-8.191**
GDPsq	-0.288**	-3.931**	0.034	0.168	-0.724***	1.157**
POP	2.128***	4.759***	1.499***	1.230	0.816***	-0.194
WUI+	-0.090	0.505	-0.091	-0.084	0.040	0.072
WUI-	-0.078	0.442	-0.347***	0.012	0.062**	-0.175*
Short-run effects						
ECT	-0.429***	-0.444***	-0.780***	-0.796***	-1.112***	-0.906***
ΔCO ₂	-0.129	0.555***	0.219	0.203	0.095	0.497***
ΔCO ₂ (-1)	-0.300**	-----	-----	-----	-0.208*	-0.403**
ΔENE	0.236	0.370	0.651***	0.710**	0.378**	0.382*
ΔENE (-1)	-0.819*	-0.123	-0.352*	-----	-----	-----
ΔGDP	3.274**	-2.148	-10.424*	-1.320	12.652***	1.205
ΔGDP (-1)	-----	17.593**	-4.497	-----	-5.863	-8.630**
ΔGDPsq	-0.412**	0.373	1.565*	0.252	-1.592***	-0.109
ΔGDPsq (-1)	-----	-2.083***	0.663	-0.117	0.786	1.127**
ΔPOP	-193.989***	13.458***	39.313*	39.510*	18.487*	-5.031*
ΔPOP (-1)	419.346***	-11.341***	-81.550*	-79.758*	-45.689**	4.855**
ΔWUI+	-0.128	0.224*	0.129**	-0.067	-0.036	0.230***
ΔWUI+(-1)	-----	-----	-0.200**	-----	0.081**	-0.164*
ΔWUI-	-0.112	0.196	-0.194**	-0.037	0.070**	-0.104
ΔWUI-(-1)	-----	-----	0.058	0.140**	-----	-0.054
Constant	-20.755	-43.159**	-1.390	-0.178	-12.989	20.815**
Diagnostics tests						
<i>F</i> test overall	8.484***	4.366**	7.029***	5.928***	6.568***	5.089**
<i>t</i> -test-dependent	-6.305***	-3.966	-5.022***	-4.733**	-6.417***	-5.221***
<i>F</i> test-independent	7.219***	5.094**	5.377***	5.476**	7.033***	5.741***
Wald SR	0.001	0.032	7.622***	1.233	1.575	7.778***
Wald LR	0.001	0.031	7.242**	1.234	1.542	8.957***
LM test	2.737*	1.395	2.633*	0.607	0.668	0.219
ARCH test	0.073	0.688	0.072	0.750	0.305	0.040
Adjusted <i>R</i> -squared	0.944	0.983	0.998	0.994	0.997	0.993
CUSUM	S	S	S	S	S	S
CUSUMSQ	N	S	S	S	S	N

***, ** and * denote the significance level at 1%, 5%, and 10% respectively

which they applied the Granger and Yoon methodology to the ARDL equation by dividing the independent variable to its positive and negative partial sums. Additionally, in order to confirm the long-term relationships between the variables, we rely on the augmented NARDL model to test the three hypotheses. Table 5 displays the outcomes of the augmented NARDL calculation, and the conclusions are summarized as follows: we found that all nations except Saudi Arabia accept the null hypothesis that there is no co-integration between negative and positive changes, as well as other factors. Furthermore, in both short- and long-run terms, the Wald test for asymmetric behavior rejects the symmetric impact of WUI on CO₂ emissions only in Morocco and Iran, showing that WUI affects CO₂ emissions asymmetrically and exclusively the negative changes. Thus, in the long run, a 1% reduction in WUI reduces CO₂ emissions by 0.34 and 0.17% in Morocco and Iran, respectively. In juxtaposing, the uncertainty coefficient is significant only in the Turkey equation with negative changes but with a positive association, the decrease in WUI in Turkey by 1% leads to an upsurge in CO₂ emissions by 0.06% in the long-run term. Furthermore, the results of the environmental Kuznets curve, population, and energy use are the same for ARDL estimation. Observably, in the case of Iran, the results revealed a *U* shape curve of the environmental Kuznets curve (the return point is 3.54) with a negative effect from GDP to CO₂ emissions and a positive effect from GDPsq, these results indicate that GDP is higher than 3.54 in Iran improves the environmental quality in the long run term.

MTNARDL model estimation results

Table 6 presents the multinomial threshold NARDL (MTNARDL) findings. To obtain more reliable results, we used Pal and Mitra's (2015) ARDL model with multiple thresholds, by decomposing the WUI variable into four partial sums based on three thresholds at 25, 50, and 75 quintiles. As a result, we can detect the impact of extremely small and large changes in WUI on CO₂ emissions using this decomposition. The outcomes show that a co-integration relationship among the partial sums of WUI and other variables exists in the entire sample excluding Saudi Arabia. Besides, the Wald test shows that the asymmetric effect of WUI on CO₂ emissions exists only in Morocco, Egypt, Turkey, and Iran. Therefore, in Turkey and Iran, both small and large changes affect positively WUI in both long- and short-run terms. In Iran on one hand, a 1% change in the second quintile (ω_2) surges the CO₂ emissions by 1.44 and 1.51% in the long run and short run respectively; on the other hand, a 1% change in large changes (fourth quintile ω_4) increases CO₂ emissions by 0.15% and 0.28% respectively. In the case of Turkey, the results indicate that a 1% change in extremely small changes (first quintile (ω_1)) rises CO₂

emissions by 0.03 and 0.06% in the long run and short run respectively, while a 1% change in extremely large changes (fourth quintile ω_4) rises CO₂ emissions by 0.05 and 0.09%. In addition, in Morocco, WUI affect CO₂ emissions only with large changes (ω_3) where any change in large changes by 1% increases CO₂ emissions by 0.9 and 0.84% in the long run and short run respectively. In the case of Egypt, at a 10% significance level, the small changes (ω_2) negatively affect carbon emissions in the long-run term. Contrariwise, the uncertainty index in Algeria and Saudi Arabia affects CO₂ emissions neither in long-run nor in short-run terms.

The inverse *U* shape of the EKC is consistently present in the whole sample. In contrast, in Iran at 5% and Egypt at 10% significance levels, the results revealed the *U*-shaped of EKC. Furthermore, the findings show that energy consumption worsens the environment in all countries. Population growth, on the other extreme, is a significant factor in environmental deterioration in Algeria, Saudi Arabia, and Turkey, but not in Morocco, Egypt, or Iran. Noteworthy, GDP is the major factor in CO₂ emissions in Saudi Arabia, any rise in GDP of 1% increases CO₂ emissions by 24.70% and 15.02% in the long and short run, respectively.

Discussion

Clearly, over the last 50 years, climate change has been a major impediment to economic and social activities. For this reason, we attempted to examine the socioeconomic determinants of CO₂ emissions in selected MENA countries from 1970 to 2020 in this paper. We specifically sought to detect the impact of EPU on CO₂ emissions as an important key factor of environmental quality over the last 10 years, particularly following the 2008 crisis. As previously discussed, the association between EPU and CO₂ emissions must be tested and explored before proposing any climate change policies (Anser et al. 2021b). To achieve this goal, we use various econometric estimation methods to ensure the results. For example, because our dependent variable was integrated with order 0 in some countries (Algeria and Saudi Arabia), we used the augmented ARDL model presented by McNown et al. (2018) instead of the standard ARDL model, which requires that the dependent variable must be an I (1) variable. Furthermore, we use both augmented NARDL and MTNARDL models to detect any possible asymmetric effects from uncertainty to CO₂ emissions. On the one hand, based on our findings, we will concentrate our discussions on the augmented ARDL results for Algeria and Saudi Arabia, as there is no evidence of asymmetric effects from WUI on CO₂ emissions. On the other hand, due to the asymmetric impacts detected, we will discuss the MTNARDL results for Morocco, Egypt, Turkey, and Iran.

Particularly, the findings led to several disparate conclusions, which can be summarized as follows. First, the

Table 6 MTNARDL model results

Variables	Algeria	Saudi Arabia	Morocco	Egypt	Turkey	Iran
Long-run effects						
ENE	0.444***	0.389	0.941***	1.009**	0.020**	0.403**
GDP	2.268***	24.707***	2.825**	-5.218*	7.623***	-7.523**
GDPsq	-0.285***	-2.768**	-0.492**	0.779*	-0.878***	1.074**
POP	2.654***	3.105***	0.178	-0.470	0.845**	0.326
WUI ω 1	0.105	0.477	-0.005	0.006	0.039**	-0.058
WUI ω 2	1.030	1.309	0.182	-0.854*	-0.214	1.441***
WUI ω 3	-1.087	-1.177	0.903***	0.298	-0.083	0.134
WUI ω 4	-0.101	0.426	0.059	-0.052	0.054**	0.155**
Short-run effects						
ECT	-0.421***	-0.441***	-0.933***	-0.779***	-1.515***	-1.049***
Δ CO ₂	-0.140	0.558***	0.066	0.220	-0.160	0.456***
Δ CO ₂ (-1)	-0.281*	-----	-----	-----	-0.354*	-0.505***
Δ ENE	0.194	0.171	0.878***	0.787***	0.030	0.423*
Δ ENE (-1)	-0.825*	-----	-----	-----	-----	-----
Δ GDP	3.225**	-4.109	2.637**	-4.067*	11.552***	-2.162
Δ GDP (-1)	-----	15.019**	-----	-----	-----	-6.026*
Δ GDPsq	-0.406**	0.587	-0.460**	0.607*	-1.404***	0.345
Δ GDPsq (-1)	-----	-1.779**	-----	-----	0.040	0.782
Δ POP	-184.477**	9.887***	0.166	-0.367	34.372**	7.282
Δ POP (-1)	401.425***	-8.516***	-----	-----	-90.867**	-26.328
Δ WUI ω 1	0.150	0.210	-0.118	-0.033	0.060*	-0.061
Δ WUI ω 1 (-1)	-----	-----	0.113**	-0.079	-----	-----
Δ WUI ω 2	1.465	0.578	0.170	0.129	-0.144	0.002
Δ WUI ω 2 (-1)	-----	-----	-----	-0.795**	-0.181	1.511***
Δ WUI ω 3	-1.545	0.687	0.843***	-0.579	-0.090	0.141
Δ WUI ω 3 (-1)	-----	-1.207*	-----	0.812*	0.166	-----
Δ WUI ω 4	-0.143	0.188	0.132***	-0.040	-0.011	0.286***
Δ WUI ω 4 (-1)	-----	-----	-0.130**	-----	0.093**	-0.194*
Constant	-25.862	-30.008*	0.156	13.703**	-22.087**	18.732
Diagnostics tests						
Fisher Bound test	6.433***	3.044	20.432***	4.445***	8.949***	5.723***
Student Bound test	-5.983***	-3.855	-10.653***	-4.223***	-6.293***	-6.165***
Wald SR	0.220	1.475	9.460***	4.356**	9.444***	4.818***
Wald LR	0.214	1.155	13.959***	3.595**	15.377***	4.426**
LM test	2.006	0.428	0.028	0.520	2.948*	0.723
ARCH test	0.061	0.009	0.070	0.907	0.107	0.379
Adjusted R-squared	0.942	0.982	0.998	0.993	0.998	0.996
CUSUM	S	S	S	S	S	S
CUSUMSQ	N	S	S	S	S	S

***, ** and * denote the significance level at 1%, 5%, and 10% respectively

uncertainty index WUI has no impact on CO₂ emissions in any estimation model for Algeria and Saudi Arabia, two of the major oil producers and carbon emitters in the world. This outcome is consistent with those of the Abbasi and Adedoyin (2021) study, which showed that EPU has no short- or long-term influence on carbon emissions. However, this result can be explained by the two countries' total reliance on oil exports. Whereas uncertainty in both countries

is largely related to global oil prices, and whether prices rise or fall, both countries will continue in the same context and export direction of oil exportation to avoid external shocks, which is what isolates the hydrocarbon sector from economic uncertainty. Consequently, despite external and internal shocks, carbon emissions will not change in the long run due to the stability of their economic situation (Sadiq et al. 2022).

Second, depending on MTNARDL results, the WUI index affects positively the CO₂ emissions in Morocco, Turkey, and Iran in the long run confirming the results of Zakari et al. (2021), and Atsu and Adams (2021). In Iran, average (second quantile) and extremely large (fourth quantile) changes in WUI increase CO₂ emissions by 1.44% and 0.15%, respectively. Notably, the effect of average changes in WUI is greater than the effect of large changes. Accordingly, the higher Iran's uncertainty index, the lower the impact on carbon emissions, and vice versa. Therefore, while it is critical for Iran to take advantage of high levels of uncertainty in order to reduce carbon emissions, the Iranian government should tread carefully when uncertainty decreases by limiting non-environmentally friendly activities, for example, by imposing taxes on these activities, to avoid exacerbating long-term carbon emissions. Conversely, it is clear in the Turkish case that the WUI affects CO₂ emissions positively in both extremely small (first quantile) and extremely large (fourth quintile). However, the effect of extremely large changes is greater than the effect of extremely small changes. This means that Turkey's high economic uncertainty index worsens the country's climatic situation. Thus, this result can be explained by the hustle of Turkish institutions to boost their industrial activities by relying on cheap production methods that depend primarily on oil products to reduce losses caused by uncertainty. Furthermore, in a state of economic uncertainty, these companies and firms largely avoid using renewable energies because of their high costs. In the same line, in the context of Morocco, the rise in the third quantile (average changes) of WUI by a 1% increase will lead to increase the CO₂ emissions by 0.90% in the long term. Hence, this result means that Moroccan companies, in light of high economic uncertainty, tend to reduce their losses and mitigate the effects of any expected shocks by reducing production costs this is done by using low-cost methods, and the latter are often unfriendly to the environment. Therefore, this situation increases carbon emissions and exacerbates the climate situation in the long term.

Third, moving to the EKC hypothesis, the findings showed that Algeria, Saudi Arabia, Morocco, and Turkey accomplished the EKC's inverted *U*-shape curve. These results are consistent with the investigations of (Amri 2017; Bouznit and Pablo-Romero 2016; Touitou and Langarita 2021) for Algeria. Alshehry and Belloumi (2017) and Samargandi (2017) confirmed the result for Saudi Arabia. Kharbach and Chfadi (2017), Sghaier et al. (2019), and Bouyghrissi et al. (2022) established the outcomes for Morocco, while Bölük and Mert (2015) and Pata (2018) for Turkey. Therefore, this means that economic growth has a positive impact on carbon emissions until a certain threshold is reached, after which the effect becomes negative. Exceeding this threshold of economic growth will allow these countries to implement new economic measures that

help improve the quality of the climate, and these thresholds are estimated to be 3.98, 4.42, 2.87, and 4.34 (in logarithmic form), respectively. Nevertheless, both Algeria and Turkey were unable to cross this threshold during the study period, indicating that the effect is positive and economic growth contributes to an increase in environmental deterioration, while Saudi Arabia and Morocco have crossed this threshold on very rare occasions, indicating that economic growth contributes to an increase in carbon emissions most of the time. Contrariwise, the results showed that Iran achieved the *U*-shape of the EKC curve validating the results of Moghadam and Dehbashi (2018) and Asghari (2012), which means that economic growth has an inverse effect on carbon emissions until a certain threshold is reached, which was estimated to be 3.49. However, Iran never achieved a growth rate below this threshold during the study period, implying that economic growth contributed to an increase in carbon emissions.

Fourth, the results revealed logically that energy consumption is a key factor determinant of environmental degradation in these countries. Whereas, it is clear the biggest effect of ENE on CO₂ emissions is in the Saudi Arabia case confirming the results of Raggad (2020) and, Agboola et al. (2021) results, where the increase in ENE by 1% increases CO₂ emissions by 1.87% and 0.84% in the long and short run respectively. Hence, Saudi Arabia is one of the top three exporter countries in the world with its huge company ARAMCO. Because the Kingdom's consumption of energy for oil extraction has increased significantly in recent years, and the use of renewable energies remains very low in comparison to widely accessible and cheaper fuels, energy consumption in Saudi Arabia is regarded as one of the major contributors to rising carbon emissions and environmental deterioration. The same result is held in all other countries, this means that these countries rely heavily on cheap and non-renewable energy sources to boost their economic growth, which exacerbates environmental degradation.

Finally, it is clear that population growth in Algeria, Saudi Arabia, and Turkey contributes significantly to environmental descent as Mahmood et al. (2020) exposed in Algeria and Saudi Arabia respectively, where a 1% increase in population leads to a 4.76% increase in carbon emissions (2.11% in Algeria and 0.84% in Turkey). This result can be explained by stating that population growth puts additional pressure on energy demand and consumption in the long run, resulting in an increase in carbon emissions.

Conclusion and policy implications

In recent years, the concept of economic uncertainty has gained popularity among researchers and policymakers, particularly in the aftermath of the 2008 financial crisis, which

resulted in a state of doubt and mistrust in the global economy, as well as the dire consequences for the global economy for several years. For this reason, this paper explored the effect of economic policy uncertainty (measured by the World Uncertainty Index (WUI) proposed by Ahir et al. (2022) on environmental quality (measured by carbon dioxide emissions (CO₂) in selected MENA countries (Algeria, Saudi Arabia, Egypt, Morocco, Turkey, and Iran based on data availability) over the period from 1970 to 2020. In juxtaposing, the paper used modern ARDL procedure to deal with any kind of possible effects. First, we used the augmented ARDL (AARDL) model presented by McNown et al. (2018) to avoid the dependent variable integer in order 0 issues. Second, we applied the NARDL model presented by Shin et al. (2014) to deal with the effect of positive and negative changes of WUI on carbon emissions. Third, we used the MTNARDL model proposed by Pal and Mitra (2015) in order to examine the effect of extremely small and large changes in WUI on CO₂ emissions. The outcomes revealed that uncertainty affects carbon emissions only in Morocco, Turkey, and Iran with an asymmetric effect from both small and large changes in the long-run term. Conversely, the results showed no evidence of any effect of WUI on environmental pollution in Algeria, Saudi Arabia, and Egypt. Besides, the results showed that population and energy consumption are the key determinant factors of CO₂ emissions in these countries. Furthermore, the inverted *U* shape of EKC is achieved in Algeria, Saudi Arabia, Morocco, and Turkey while the *U* shape is achieved in Iran and Egypt.

Based on these findings, we can therefore offer some policy recommendations for these governments. It is first necessary to invest in R&D to advance new technologies that use environmentally friendly production methods and products in Algeria and Saudi Arabia in order to decouple economic growth from carbon emissions, as well as to reduce production methods that depend on oil and hydrocarbon sources.

Since the third and fourth thresholds have the greatest effects in Morocco and Turkey, it is crucial to deal with changes in uncertainty. This is because these two countries' institutions have adopted conventional, unsustainable technologies that heavily rely on hydrocarbons in an effort to cut production costs and prevent shocks brought on by uncertainty. In order to prevent unexpected developments, the governments of these two countries must handle the high levels of uncertainty with caution by providing aid and subsidies to institutions. They must also adopt preventative measures to deal with significant shifts in uncertainty, including clear and transparent laws and policies, special tax exemptions to lower production costs, facilitation of international trade, the provision of raw materials at reasonable prices, partnerships with foreign firms to supply modern technologies, and increased investment in renewable energy innovation.

The MTNARDL results in Iran showed that medium modifications are far more significant in raising CO₂

emissions than are high increases. Due to the low levels of uncertainty, the Iranian government should take precautions to prevent its institutions and businesses from using production techniques that worsen the environment. To do this, it should impose additional taxes and fees on the production process, especially for the very affordable oil products that are Iran's trademark. This calls for a review of the prices of the petroleum materials used in the production process. These findings may encourage such countries to adopt renewable energy to lessen the effects of population increase and climate change, both of which are highly prevalent in the MENA countries. In order to reduce the number of ineffective activities that contribute to environmental degradation, such as deforestation and conventional agricultural and industrial practices, these countries must impose lower taxes and provide assistance for the use of these energies by making them available at affordable prices for individual consumption, and increase national awareness of the economic and social costs of pollution.

Although the importance and sensitivity of uncertainty subject, it has not yet received enough attention to enable the identification of opportunities that can be used to improve environmental conditions and lower greenhouse gas emissions. Therefore, it is crucial to do research on how many categories of uncertainty (commercial, financial, monetary, health care, geopolitical risks, and taxation) affect carbon emissions and identify the primary causes of environmental deterioration in order to regulate carbon emissions in the future. In order to have reliable findings on the specific impacts of each sector of the economy and identify which sectors should be prioritized for the reduction of carbon emissions and other greenhouse gases, it is also necessary to study the impact of uncertainty of all kinds on various sectors of the economy (residential, transportation, commercial, industrial, and power generation).

Author contribution Hicham Ayad: conceptualization, introduction, literature writing, data curation, software, data analysis, results and discussion, manuscript writing and editing. Salah Eddin Sari-Hassoun: data collection, results improvement, review, manuscript writing and editing. Muhammad Usman: abstract, implications, visualization, project administrative, supervision, revised draft, manuscript writing and editing. Paiman Ahmad: results improvement, validation, manuscript reviewing and editing.

Data availability Available upon request.

Declarations

Ethics approval and consent to participate We confirmed that this manuscript has not been published elsewhere and is not under consideration by another journal. Ethical approval and informed consent are not applicable for this study.

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