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RESEARCH ARTICLE

The marginal effects of economic growth, financial development, and low-carbon energy use on carbon footprints in Oman: fresh evidence from autoregressive distributed lag model analysis

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Abstract

Oman is committed to turning carbon neutral by 2040 whereby identifying the environmental sustainability-stimulating factors has become a critically important agenda for the nation. Against this backdrop, this study attempts to evaluate the marginal effects of economic growth, financial development, and low-carbon energy use on Oman's carbon footprint levels using quarterly frequency data spanning from 1984Q1 to 2018Q4. Controlling for structural break concerns in the data, the results from the empirical analysis verify the carbon footprint-related environmental Kuznets curve hypothesis for Oman in the long-run. In this regard, the threshold level of per capita real GDP level of Oman is predicted at around US $23,500 which is below the average and maximum per capita real GDP level of Oman during the period considered in this study. Besides, the development of the financial sector and scaling up consumption of low-carbon energy resources are evidenced to boost and curb Oman's short- and long-run carbon footprint figures, respectively. More importantly, the joint carbon footprint-mitigating impact of financial development and low-carbon energy use is also unearthed from the findings. In line with these major findings, a couple of relevant policy interventions are suggested to help Oman accomplish its 2040 carbon-neutrality agenda.

Keywords Carbon footprint · Financial development · Economic growth · Low-carbon energy · Carbon neutrality · EKC hypothesis

Introduction

Achieving environmental sustainability has become an utmost important goal for Oman. The nation, a member of the Gulf Cooperation Council, is committed to mitigating its greenhouse gas emissions as a mechanism for limiting its vulnerability to adverse consequences of climate change. Besides, in solidarity with its decision to ratify the Paris Agreement, Oman has envisioned turning carbon neutral by 2040. But, attainment of this carbon-neutrality target is likely to be difficult for Oman given the fact that the nation's

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economic activities are predominantly fuelled by fossil fuels, especially natural gas. In 2015, Oman produced 97.4% of its domestic electricity output combusting natural gas while the rest was generated from burning oil (World Bank 2022). Furthermore, 68% and 32% of the total primary energy demand of Oman in 2019 were met by utilizing natural gas and liquid fuels, respectively (U.S. Energy Information Administration 2019). Hence, considering this acute fossil fuel dependency, it can be assumed that energy use plays a definitive role in dampening the quality of the environment in Oman. Nonetheless, for mitigating the adverse environmental consequences, it is not rational to reduce energy use since ensuring sufficient and reliable supply of energy is considered a prerequisite for sustaining the growth of any economy. As a result, unless Oman attempts to diversify its energy mix by replacing the traditionally consumed fossil fuels with alternative energy resources that are relatively cleaner, it is most likely to be impossible for the nation to phase out the trade-off between energy consumption-led economic growth and environmental degradation in Oman.

However, as per the environmental Kuznets curve (EKC) hypothesis, coined by Grossman and Krueger (1991, 1995), this economic growth-environmental degradation trade-off is likely to subside beyond a certain level of economic growth whereby economic activities are likely to be green and less damaging for the environment (Khan et al. 2022a, 2022b; Zhao et al. 2022; Murshed et al. 2022). Moreover, since this threshold economic growth level is likely to differ across countries, given the heterogeneity in their macroeconomic characteristics, it is pertinent for Oman to have an understanding of its growth threshold in order to harmonize its economic and environmental development policies. Apart from energy consumption, the financial sector is also acknowledged as a key influencer of economic and environmental well-being (Erdoğan et al. 2020; Aluko and Obalade 2020; Jahanger et al. 2022). Consequently, researchers have stressed exploring the impacts of financial development on the national income and carbon dioxide (CO_2) emissions levels to predict the economic and environmental impacts associated with the development of the financial sectors of the global economies. However, although in the majority of the cases financial development was claimed to foster economic growth, mixed findings regarding the financial development-environmental quality nexus have been documented in the literature (Khezri et al. 2021; Khan and Ozturk 2021). Thus, from the point of view of achieving environmentally-sustainable growth of the Oman economy, it is also necessary to check whether the development of its financial sector can harmonize the nation's objectives of securing economic and environmental well-being.

Against this background, this study aims to predict the environmental impacts of economic growth, energy use, and financial development in the context of Oman using quarterly data from 1984Q1 to 2018Q4. Besides, an additional objective of this study is to check whether or not the EKC hypothesis holds for Oman. It is pertinent to conduct the EKC hypothesis analysis for Oman because the rising trends in the nation's economic growth and greenhouse gas emission levels suggest that Oman probably has not yet reached the threshold growth level beyond which the aggravating trends in the nation's environmental quality can be reversed without sacrificing it economic growth performances. In this regard, the estimation of the economic growth threshold, via the EKC analysis, can be expected to help Oman in designing comprehensive and interactive economic and environmental development policies. The following research questions are addressed in this study:

- Does the EKC hypothesis hold for Oman?
- Is energy consumption responsible for environmental degradation in Oman?
- Can developing Oman's financial sector resolve its environmental problems?

The noteworthy contributions of this study to the related literature are three-fold. First, although several existing studies have examined the EKC hypothesis for the case of Oman, these have mostly utilized CO_2 emissions as the environmental quality indicator (Jiang et al. 2022; Hamid et al. 2022). However, interpreting changes in the quality of the environment in terms of shocks to the CO_2 emission level has recently been criticized for not providing a comprehensive account of environmental well-being. Hence, this study makes a novel attempt to scrutinize the EKC hypothesis for Oman using the nation's carbon footprints as an alternative proxy for its environmental quality. As opposed to CO_2 emissions, the carbon footprint can be considered a more holistic indicator of CO_2 emission-induced environmental degradation since it measures how fast energy is consumed to release CO_2 emissions compared to how fast the nature can absorb the emissions (GFN 2022). Second, while the existing studies have assessed the environmental impacts associated with energy use in Oman using the nation's total or disaggregated fossil fuel consumption data (Mahmood 2022), this study innovatively examines the impacts of low-carbon energy use on Oman's annual per capita carbon footprint levels. This is an extremely important important contribution since Oman meets its entire energy demand using hydrocarbons/fossil fuels (World Bank 2022); consequently, assessing the energy consumption-carbon footprint nexus using total or disaggregated energy use data is of minimal relevance as combustion of fossil fuels generates CO_2 emissions whereby the relationship between energy use and carbon footprint is likely to be positive in almost all cases. Lastly, instead of following the approaches adopted in the preceding studies, this study explores both the independent and joint effects of low-carbon energy consumption and financial development on environmental quality in Oman. Assessing the joint impacts helps to design interactive policies that, in comparison with isolated policies, can be assumed to be more effective in resolving the environmental concerns in Oman.

The remainder of the study is arranged as follows. The next section reviews and summarizes the findings from the previous studies that are related to this current one. In the subsequent sections, the empirical model and estimation strategy, the discussion of the findings, and the concluding remarks are presented.

Literature review

In this section, we summarize the findings of the empirical studies in the literature that have looked into the environmental impacts associated with greater economic growth, energy use, and financial development.

Literature on the economic growth-environmental quality nexus

Conventionally, the relationship between economic growth and environmental quality has been explored through the prism of the EKC hypothesis. In the context of Oman, Hamid et al. (2022) used annual data from 1980 to 2019 and found that economic growth initially deteriorates the environment by boosting emissions of CO2 while reducing the emission levels in the later phases of growth. In light of their findings, the authors asserted that the EKC hypothesis holds for Oman. In another related study on the EKC hypothesis for CO2 emissions in the context of Oman, Ardakani and Seyedaliakbar (2019) also found evidence of the EKC hypothesis being valid for this Gulf country. However, Mahmood (2022) utilized data spanning between 1975 and 2019 but could not verify the authenticity of the EKC hypothesis in the context of Oman. Moreover, Alsamara et al. (2018) used data from the members of the Gulf Cooperation Council and found that the EKC hypothesis for CO2 emissions holds for Qatar, Bahrain, Kuwait, Saudi Arabia, and the United Arab Emirates but not for Oman; however, the EKC hypothesis for sulfur dioxide emissions was verified for Oman, Saudi Arabia, Qatar, and the United Arab Emirates. Hence, these contrasting findings suggested that the authenticity of the EKC hypothesis for the case of Oman is conditional on the choice of the proxy used for quantifying environmental quality.

Although the country-specific literature on the EKC hypothesis for Oman is very limited, several researchers have explored the validity of this hypothesis using panel data sets comprising Oman and other global nations. Among these, once again using CO2 emissions to proxy environmental quality, Zmami and Ben-Salha (2020) used data from members of the Gulf Cooperation Council and remarked that the EKC hypothesis holds at the threshold income level of around US $56,351. Likewise, considering data from 12 Middle Eastern and North African (MENA) nations including Oman, Omri et al. (2015) also documented statistical evidence concerning the authenticity of the EKC hypothesis for CO2 emissions. On the other hand, among the preceding studies not focusing on Oman, Selcuk et al. (2021) used data from the Next Eleven (N11) countries and found that the EKC hypothesis holds for Bangladesh, Mexico, Nigeria, Turkey, and the full panel. Balsalobre-Lorente et al. (2021) also verified the CO2 emission-related EKC hypothesis for selected European Union member countries. Similarly, Sinha et al. (2019) opined that for the N11 nations the EKC hypothesis for CO2 emissions is valid only for the moderately and highly polluted countries but not for the less-polluted ones. The EKC hypothesis for the cases of Portugal, Ireland, Italy, Greece, and Spain was also affirmed in the study by Balsalobre-Lorente et al. (2022).

Although the majority of the EKC-related studies have examined the impacts of economic growth on CO2 emissions, some recent studies have shed light on the effects of economic growth on carbon footprints. However, none of these studies featured Oman which reveals a major gap in the literature. Elshimy and El-Aasar (2020) used data from selected countries in the Arab world and found that the EKC hypothesis concerning carbon footprints holds for these countries. Similarly, Bello et al. (2018) also verified the carbon footprint-related EKC hypothesis for the case of Malaysia. In contrast, in the context of selected MENA countries including Oman, Usman et al. (2021) stated that the EKC hypothesis is not valid since the findings revealed that higher economic growth initially reduces carbon footprints but later on increases them; thus, the findings portrayed a U-shaped association between economic growth and carbon footprint. Likewise, Sarkodie (2021) used data from Russia, the United States, China, Japan, and India and found that the EKC hypothesis does not hold because economic growth was evidenced to initially amplify the carbon footprint figures but later on these carbon footprint-boosting effects do not sustain.

Literature on the energy use-environmental quality nexus

Concerning the economy of Oman, Mahmood (2022) remarked that positive and negative shocks to oil consumption increase and decrease CO2 emissions, respectively. Similar impacts of natural gas consumption on the CO2 emission figures of Oman were also found in this study. In another related study on the members of the Gulf

Cooperation Council including Oman, Mahmood and Furqan (2021) found evidence that higher oil rents initially trigger higher emissions while beyond a certain oil rent threshold, a further increase in the oil rent figures result in lower CO2 emissions in these countries. Hence, in line with their findings, the authors opined that the oil rent-CO2 emission nexus for the Gulf Cooperation Council countries depicts an inverted U-shape. Apart from Oman, the energy consumption-CO2 emission nexus was also conducted for other global economies whereby equivocal environmental impacts associated with the consumption of different energy resources were documented in the previous studies. In general, these studies have highlighted that clean energy use, mostly in terms of renewable energy consumption and production, is associated with lower CO2 emissions while the use of unclean energy, mostly fossil fuels, triggered higher emissions of CO2 (Usman et al. 2022).

Among these, Mehmood (2022a) used data from selected South Asian countries and found evidence regarding higher renewable energy consumption curbing the CO2 emission levels of these countries. Similarly, Mehmood (2022b) also opined that renewable energy use not only directly helps to reduce CO2 emissions in South Asia but also exerts joint CO2 emission-inhibiting effects with higher quality of governance and greater inflows of foreign direct investment. On the other hand, exploring the fossil fuel consumption-CO2 emissions relationship for a global panel of 60 countries, Valadkhani et al. (2019) asserted that higher consumption of primary fossil fuels (oil, coal, and gas) positively affects CO2 emissions. However, the authors mentioned that for the cases of the highly developed countries switching from use of oil and coal to consumption of natural gas can help these nations cut their respective CO2 emission figures. Besides, Bandyopadhyay and Rej (2021) used data from India and found evidence that scaling up use of nuclear energy, a clean source of energy source, can help the South Asian nation to secure environmentally-sustainable economic growth by curbing its CO2 emissions.

Regarding the limited literature on the impacts of energy use on carbon footprints, it can be said that the energy use-carbon footprint nexus is a relatively less researched topic within the related narrative. Among the very few studies focusing on this issue, Bello et al. (2018) opined that as the consumption of hydroelectricity goes up in Malaysia, the country's carbon footprint levels tend to decline. Similarly, for the cases of 13 emerging Asian countries, Saqib (2022a) recently found that higher renewable energy consumption reduces the carbon footprint levels in India, Malaysia, Nepal, Pakistan, Sri Lanka, Thailand, and Vietnam while higher non-renewable energy consumption was evidenced to boost carbon footprints in Malaysia, Vietnam, and China. Besides, several studies have explored the effects of energy use on ecological footprints which are derived by summing carbon and non-carbon footprints. In a related study on Ecuador, Paraguay, Pakistan, Croatia, Indonesia, Georgia, El Salvador, Honduras, Morocco, Jordan, and Sri Lanka, Mehmood (2022c) found statistical evidence that higher use of energy imposes adverse environmental conditions by boosting ecological footprints both in the short- and long-run. Similarly, employing data from selected countries that are members of the Organization for Economic Cooperation and Development (OECD), Destek and Sinha et al. (2020) concluded that renewable energy consumption is related to lowering the ecological footprint levels of these countries. Identical conclusions were reported in the studies by Sharma et al. (2021) for developing countries from Asia, Danish and Khan (2020) for Brazil, Russia, India, China, and South Africa (BRICS), and Destek et al. (2018) for selected members of the European Union.

Literature on the financial development-environmental quality nexus

In the existing literature, financial development has mostly been quantified in terms of the share of domestic credit provided to the private sector in the gross domestic product (GDP) of the economy of concern. Accordingly, exploring the environmental effects accompanying financial development in Oman, Omri et al. (2015) used data from 12 MENA countries and found that financial development does not influence CO2 emissions in Oman while reducing CO2 emissions in Jordan and increasing CO2 emissions in Qatar. Similarly, using data from selected countries from the Middle East including Oman, Abdouli and Hammami (2020) stated that financial development amplifies CO2 emission levels in Oman, Jordan, Kuwait, Qatar, and the full panel Middle Eastern nation while it reduces CO2 emissions only in the context of the United Arab Emirates. In another study on Oman and the other members of the Gulf Cooperation Council, Salahuddin et al. (2015) remarked that developing the financial sector is helpful in curbing the CO2 emission figures of these countries. Regarding the financial development-CO2 emissions nexus in the context of studies focusing on countries other than Oman, Anwar et al. (2022) used data from 15 Asian countries and found evidence of financial development imposing CO2 emission-boosting effects. In the context of Chile, Kirikkaleli et al. (2022) recently showed that financial development helps to mitigate emissions of consumption-based CO2 in this Latin American country.

Against the vast literature on the impacts of financial development on CO2 emissions, the literature on the financial development-carbon footprint nexus is very slim. Besides, none of the preceding studies has explored this relationship in the context of Oman which reveals another key gap in the literature. However, using data from 63 emerging and developed countries, Saqib (2022b) opined that reducing

Table 1 The Zivot-Andrews unit root test results

Variable	*t*-stat.	Break	Variable	*t*-stat.	Break	Decision
lnCFP	−4.171	1999Q2	ΔlnCFP	−6.599***	2001Q2	Stationary at I(1)
lnG	−6.514***	2002Q2	ΔlnG	−7.725***	2007Q4	Stationary at I(0)
lnFD	−3.592	2009Q2	ΔlnFD	−7.272***	1999Q3	Stationary at I(1)
lnLCE	−4.832*	2005Q2	ΔlnLCE	−6.575***	1991Q2	Stationary at I(0)

Δ represent first difference operator; The test statistics are estimated considering a structural break in constant and trend; The Akaike Information Criterion (AIC) determines optimal lag length; ***statistical significance at 1%; *statistical significance at 10%

carbon footprints require the development of the financial sectors in these countries. Conversely, Wang (2021) found evidence of financial development boosting the carbon footprint figures of Brazil, Russia, India, and China in the long run but not in the short run. In another related study on 13 emerging countries in Asia, Saqib (2022a) stated that financial development exerts equivocal environmental impacts. The results revealed that developing the financial sector increases carbon footprints in Bangladesh, Sri Lanka, and Vietnam while reducing carbon footprints in Iran and Nepal. However, in the context of the panel of these 13 Asian countries, no impact of financial development on carbon footprints could be established.

Model, data, and methodology

Empirical model and data

In line with the objectives of this study and the theoretical underpinnings of the EKC hypothesis, the following nonlinear baseline model is considered:

$$\textbf{Model 1}: \mathrm{lnCFP_t = \alpha + \delta_a lnG_t + \delta_b lnG2_t + \delta_c lnFD_t + \delta_d lnLCE_t + \varepsilon_t} \quad (1)$$

where t indicates the time dimension and ε stands for the error term. The parameter α indicates the intercept while the parameters $\delta_i(i = a, b, \ldots, d)$ represent the elasticities of the dependent variable to be predicted. The dependent variable lnCFP represents the natural logarithm of the annual per capita carbon footprint level of Oman which is used as a proxy for the level of environmental well-being in Oman. The carbon footprint figures are provided in terms of the quantity of biologically productive lands required for absorbing the volume of CO2 emitted in Oman. Hence, the unit of measurement is in terms of global hectares of land per capita. Since higher CO2 emissions indicate environmental deterioration and would require a greater volume of land for the emissions to be absorbed, a larger carbon footprint figure would portray environmental deterioration and vice versa. The data concerning the carbon footprints are sourced from the Global Footprint Network database (GFN 2022).

Among the dependent variables, lnG and lnG2 represent the natural logarithms of the annual per capita level of real GDP of Oman and its squared term, respectively. Linking with the theoretical framework of the EKC hypothesis, we proxy economic growth using the real GDP figures of Oman. The EKC hypothesis would be validated if the elasticity parameter attached to lnG is positive (i.e., $\delta_a > 0$) and that attached to lnG2 is negative (i.e.,$\delta_b < 0$); consequently, the economic growth-carbon footprint nexus would depict an inverted U-shape. Contrarily, if the predicted signs of these elasticity parameters do not follow this order, the EKC hypothesis would not be verified. The data regarding the per capita real GDP level of Oman is retrieved from the World Development Indicators database of the World Bank (2022). The variable lnFD indicates the natural logarithm of the share of domestic credit provided to the private sector by banks in the GDP of Oman which is used as a proxy for financial development in Oman. It is well acknowledged in the literature that the higher the value of this share the more developed the financial sector of an economy and vice versa (Omri et al. 2015). If financial development in Oman exerts adverse environmental consequences by boosting the nation's carbon footprint figures, the predicted sign of the elasticity parameter attached to the variable lnFD is likely to be positive (i.e., $\delta_c > 0$). On the other hand, in the context of financial development causing environmental improvement in Oman by reducing the nation's carbon footprints, the predicted sign of the corresponding elasticity parameter is likely to be negative (i.e., $\delta_c < 0$). The financial development-related data is measured in terms of constant 2015 US dollar prices and is also compiled from the World Development Indicators database of the World Bank (2022).

Lastly, the variable lnLCE stands for the low-carbon energy use variable. Since no specific variable is available to quantify the level of low-carbon energy consumption, we innovatively proxy it by the ratio of the volume of energy consumed per unit of CO2 emitted. This is a novel technique that is backed up by the understanding that since greater use of low-carbon energy resources (i.e., relatively cleaner energy) can be expected to limit the volume of CO2 emitted, a rise in the ratio of energy use to CO2 emissions can be interpreted as a rise in the level of low-carbon energy consumption and vice-versa. Under such circumstances, higher consumption of low-carbon energy can be hypothesized to exert favorable environmental outcomes in Oman by reducing the nation's carbon footprints; consequently, the predicted sign of the corresponding elasticity parameter is likely to be negative (i.e., $\delta_d < 0$). Although ideally renewable energy consumption is a more appropriate indicator of clean energy use, the fact that Oman does not consume renewable energy resources to meet its energy demand justifies the decision to use the low-carbon energy use figures to proxy clean energy use in the context of Oman. The low-carbon energy use-related variable is measured in terms of kilograms of oil equivalent worth of energy consumed per ton of CO2 emitted; this variable is estimated by the authors using data from the World Bank's World Development Indicators database (World Bank 2022) and the Global Carbon Atlas database (GCA 2022).

Moreover, to explore the possible joint impacts of financial development and low-carbon energy consumption on carbon footprints in Oman, we augment our baseline model with an interaction term as follows:

$$\textbf{Model 2}: \mathrm{lnCFP_t} = \alpha + \delta_a \mathrm{lnG_t} + \delta_b \mathrm{lnG2_t} + \delta_c \mathrm{lnFD_t} + \delta_d \mathrm{lnLCE_t} + \delta_e \left(\mathrm{lnFD_t} \times \mathrm{lnLCE_t}\right) + \varepsilon_t \quad (2)$$

where the variable lnFD × lnLCE stands for the interaction term that captures the interaction between financial development and low-carbon energy consumption. Accordingly, the predicted sign of the corresponding elasticity parameter attached to this interaction term (i.e., δ_e) would indicate the joint impacts of these variables on the carbon productivity figures of Oman. For all the variables, the annual frequency data is converted to quarterly frequencies, spanning from 1984Q1 to 2018Q4, using the match-sum quadratic technique. Several preceding studies have advocated in favor of utilizing this technique for converting low frequency data into high frequencies as a means of addressing issues concerning short time dimension of data (Shahzad et al. 2017; Shahbaz et al. 2021).

Estimation techniques

The estimation strategy involves three major stages. In the first stage, the order of integration among the variables is checked by conducting the unit root analysis. It is pertinent to assess the integration order because it determines the choice of the regression estimators that are to be utilized for predicting the econometric models. Besides, the unit root analysis also helps to check whether or not the variables included in the models are non-stationary. This is important because regression analysis involving non-stationary (i.e., non-mean-reverting) data generates spurious regression outcomes (Awan et al. 2022). Hence, we follow Minlah and Zhang (2021) and utilize the Zivot-Andrews unit root estimation technique proposed by Zivot and Andrews (2002). This unit root estimator is built on the shortcoming of the traditional methods which did not consider the issue of structural breaks in the data. However, ignoring the possible structural break concerns generate biased integration properties of the variables of concern (Lee and Strazicich 2004). Under the Zivot-Andrews technique, a *t*-statistic is predicted assuming the null hypothesis of non-stationarity of the series of concern considering one structural break in the data (in the constant, or trend, or both constant and trend). Thus, for the variable to be stationary (i.e., mean-reverting), the null hypothesis needs to be rejected.

In the second stage, the long-run associations between the variables in both the models considered in this study are checked by conducting the cointegration analysis. It is important to examine whether or not the variables have cointegrating/long-run relationships among themselves (i.e., whether or not they move together in the long run) because without the presence of cointegrating relationships, the long-run regression outcomes cannot be predicted. Accordingly, following Dogan and Ozturk (2017), the Gregory-Hansen cointegration estimator proposed by Gregory and Hansen (1996) is used in this study. Unlike the previously developed methods which assume no structural break in the data, the Gregory-Hansen technique predicts the possible cointegrating associations assuming one structural break in four possible locations: (a) in the constant, (b) in the constant and trend, (c) in the constant and slope, and (d) in the constant, slope, and trend. Under this approach, for each of the four structural break location-related assumptions mentioned above, three test statistics are predicted which include the ADF, Z_α, and Z_t statistics. These test statistics are estimated considering the null hypothesis of no cointegrating relationship in the respective model against the alternative hypothesis of the presence of at least one cointegrating equation in the model. Thus, for affirming cointegration among the variables and fulfilling the prerequisite to predicting the long-run regression outcomes, the null hypothesis of no cointegration has to be rejected. Besides, the identified location of the structural break is used for constructing a structural break dummy variable which is then augmented into the respective model to account for the structural break concerns within the regression analysis. Precisely, the decision to include this dummy variable in the respective model is influenced by the motive of eliminating the bias of the regression estimates that would have been generated if the structural break concerns are left unaccounted for within the regression analysis.

In the third stage, following Khan et al. (2022a, 2022b), the short- and long-run elasticity parameters are estimated using the Autoregressive Distributed Lag (ARDL) model proposed by Pesaran et al. (2001). However, the application of the ARDL technique for regression purposes is conditional on the integration properties of the variables included in the respective model. While the conventional regression estimators mostly require the variables to be integrated at the first difference, the ARDL method pre-requisites the dependent variable to be integrated at the first difference while the explanatory variables are allowed to have a combination of integration at the level, I(0), and the first difference, I(1); but not at the second difference, I(2) (Manzoor et al. 2021). Among the several advantages of using this regression technique, the ARDL approach corrects for the small sample size issues in the data and also accounts for endogeneity issues (Pesaran et al. 2001). It involves two steps within the estimation process. In the first step, the bounds test is performed to further check for cointegration among the variables. However, unlike the Gregory-Hansen technique, the ARDL bound test does not consider the structural break issue. In this step, an F-statistic is predicted under the similar null hypothesis of non-cointegration and if the value of this test statistic is above the lower and upper bound critical values then cointegrating associations among the variables of concern can be affirmed.

In the second step, the short- and long-run elasticity parameters are estimated using an error-correction model. The baseline model considered in this study can be expressed in terms of the ARDL model specification as follows:

$$\begin{aligned}\Delta \ln CFP_t = \beta_0 + \sum_{i=1}^{a} \beta_1 \Delta \ln G_{t-1} + \sum_{i=1}^{b} \beta_2 \Delta \ln G2_{t-1} \\ + \sum_{i=1}^{c} \beta_3 \Delta \ln FD_{t-1} + \sum_{i=1}^{d} \beta_4 \Delta \ln LCE_{t-1a} + \rho \ln CFP_{t-1} \\ + \vartheta_1 \ln G_{t-1} + \vartheta_2 \ln G2_{t-1} + \vartheta_3 \ln FD_{t-1} + \vartheta_4 \ln LCE_{t-1} + \varepsilon_t\end{aligned} \quad (3)$$

where Δ stands for the first difference operator; t stands for the time; the superscripts a, b, c, d, and e are the optimal lag lengths which can be different for each variable; β_0 is the intercept/constant parameter; β_i $(i = 1, 2, \ldots, 4)$ is the short-run elasticity parameters while ϑ_j $(j = 1, 2, \ldots, 4)$ is the long-run elasticity parameters; ρ is the parameter denoting the one-period lagged error-correction term. The error-correction terms present the rates at which disequilibrium for the long-run level at the current period is adjusted in the next period. Furthermore, for robustness check, the long-run elasticity parameters are predicted using the dynamic ordinary least squares (DOLS) regression estimator.

Results and discussion

The outcomes from the empirical analysis are reported and interpreted in this section. Firstly, Table 1 reports the results from the Zivot-Andrews unit root analysis. It can be seen that the dependent variable lnCFP is stationary at the first difference, I(1). Among the independent variables, the results show that lnFD is stationary at the first difference, I(1), while lnG and lnLCE are stationary at the level, I(0). Hence, these findings confirm a mixed order of integration among the variables with a combination of integration at the level, I(0), and the first difference, I(1). Moreover, these findings also certify that the pre-requisites to performing the ARDL analysis are also fulfilled. The Zivot-Andrews outputs also present the locations of the structural breaks for the respective variables which are also graphically illustrated in Fig. 1. Following the unit root analysis, the cointegration analysis is conducted to check for long-run relationships between the variables of concern.

Table 2 presents the findings from the Gregory-Hansen cointegration analysis. It can be observed that there are cointegrating relationships among the variables in the cases of both models since the predicted test statistics are statistically significant. Hence, in light of these findings, it can be said that there are long-run relationships between Oman's carbon footprint, per capita national income, the share of private sector credit in GDP, and low-carbon energy consumption figures. Besides, for both models, it can be seen that the identified break dates are between 1985 and 1986. This is an expected finding since before 1982 almost the whole energy demand in Oman was met using exported crude oil. However, from 1983 onwards, Oman started consuming domestic crude oil. Hence, this transition from the use of exported to indigenous energy resources could have influenced the location of the identified structural breaks. Moreover, the locations of the structural breaks (presented within the parentheses) corresponding to the ADF statistic are used to construct the structural break dummy variables for inclusion in the respective model for regression purposes. Considering the results from the Zivot-Andrews unit root and Gregory-Hansen cointegration analyses, the ARDL analysis is conducted for predicting the short- and long-run elasticities of carbon footprints in response to positive shocks to the levels of the explanatory variables.

In the first step of the ARDL analysis, cointegration among the variables is re-checked using the bounds test. The results from the bounds test, as shown in Table 3, reveal that for both models the value of the predicted F-statistic is above the lower and upper bounds critical values at the 1% significance level. Hence, the statistical significance of the predicted F-statistics corroborates the earlier cointegration findings from the Gregory-Hansen analysis to re-confirm long-run relationships between Oman's macroeconomic variables of concern. The next step within the ARDL analysis involves the estimation of the short- and long-run elasticity parameters for both models.

Table 4 presents the elasticity estimates from the ARDL analysis. Overall, the predicted signs of the elasticity parameters are found to be identical for both models which indicates that the estimated marginal environmental impacts

Fig. 1 The Zivot-Andrews analysis plot. Source: authors' computation

associated with positive shocks to Oman's economic growth, financial development, and low-carbon energy consumption figures are robust across alternative empirical model specifications. Specifically, the results from both models 1 and 2 indicate that only in the long-run economic growth initially degrades the quality of the environment in Oman by triggering the nation's carbon footprint levels while improving environmental quality later on by reducing the carbon footprint levels. This statement is justified by the positive and negative signs of the predicted elasticity parameters concerning the variables lnG and lnG2 (i.e., proxies for economic growth and its squared term, respectively). Therefore, these findings are in line with the theoretical underpinnings concerning the EKC hypothesis whereby it can be said that the economic growth-carbon footprint nexus depicts an inverted U-shaped relationship in the context of Oman. Thus, the EKC hypothesis for carbon footprints is verified. This finding is parallel to the findings in the preceding studies by Elshimy and El-Aasar (2020) for Arab countries and Bello et al. (2018) for Malaysia but opposes the results documented by Usman et al. (2021) for MENA countries and Sarkodie (2021) for Russia, the USA, China, Japan, and India.

Moreover, considering the predicted values of the elasticity parameters, the threshold levels of per capita real GDP are estimated to be US $23,011 and US $23,503 for models 1 and 2, respectively. Intuitively, the validation of the EKC hypothesis and the estimated thresholds imply that Oman can be expected to get over its economic growth-environmental degradation trade-off once its per capita real national income level exceeds the threshold levels; whereby with a further rise in the income level the nation's carbon footprint figures are likely to decline. This is a key finding for the case of Oman because during the period considered in this study Oman's annual level of per capita real GDP level was on average around US $18,550 and reached a maximum of US$ 21,458 in 2009 (World Bank 2022). Hence, it can be said that Oman is yet to reach the threshold economic growth level beyond which it can adopt relevant policies to facilitate economic growth and environmental welfare (via reducing carbon footprints) in tandem. Besides, the finding of the economic growth level in Oman being below the predicted threshold level of growth is likely to be influenced by the fact that Oman still meets its entire energy demand using fossil fuels. Consequently, economic activities performed by combusting these unclean fuels are bound to amplify the nation's CO2 emission figures whereby the carbon footprint levels are likely to rise as well. Moreover, extraction of natural resources for meeting energy demand can be assumed to further pile up Oman's carbon footprint figures. However, currently, Oman is thinking of diversifying its energy mix with cleaner energy resources; however, this objective of undergoing a clean energy transition can possibly be facilitated provided the economy of Oman rapidly grows to surpass the identified threshold levels of annual real per capita GDP.

The ARDL estimates also reveal that financial development in Oman is not helping the nation to improve its environmental quality. The predicted elasticity parameters indicate that as the financial sector of Oman is developed it increases the nation's carbon footprint levels both in the short- and long-run. Collectively for both models 1 and 2, it can be seen that a 1% rise in the share of private sector credit provided by banks in Oman's GDP tends to increase the short-run and long-run per capita carbon footprint levels by 0.09–0.11% and 1.72–1.86%, respectively, *ceteris paribus*. An additional thing to note here is that the carbon productivity-boosting impacts of financial development tend to increase with time as the values of the predicted short-run elasticity parameters are relatively smaller than the long-run counterparts. Similar findings were also reported by Saqib (2022a) for Bangladesh, Sri Lanka, and Vietnam and by Wang (2021) for Brazil, Russia, India, and China only in the context of the long-run. For the case of Oman, the finding of the positive correlation between financial development and carbon footprint indicates that private sector borrowings in Oman, invested for consumption and production purposes, are probably triggering higher energy demand which is being met with carbon-intensive fossil fuels (especially natural gas). Accordingly, financial development can justifyably be held responsible for boosting the carbon footprint figures of Oman.

Besides, the ARDL estimates also portray that enhancing the consumption level of low-carbon energy resources can reduce carbon footprints in Oman both in the short- and long-run. Precisely, a 1% rise in the ratio of energy consumed to CO2 emissions (indicating a rise in consumption of low-carbon energy resources) is predicted to reduce per capita carbon footprint levels by 0.90–1.13% and 1.72–1.86% in the short- and long-run, respectively, *ceteris paribus*. These estimated elasticity parameters also reveal that the marginal carbon footprint-reducing effects associated with low-carbon energy consumption increases with time since

Table 2 The Gregory-Hansen cointegration test results

Model	ADF stat.	Zt stat.	Za stat.	Decision
Model 1	−6.69** (1985Q4)	−7.11*** (1986Q1)	−53.41 (1986Q1)	Cointegration exists
Model 2	−6.30* (1985Q2)	−6.87** (1986Q1)	−47.89 (1986Q2)	Cointegration exists

The test statistics are estimated considering a structural break in constant and trend; The structural break locations are reported within the (); The AIC determines optimal lag length; ***statistical significance at 1%; ** statistical significance at 5%; *statistical significance at 10%

Table 3 The bounds test results

Model	***F***-statistic	Decision	Critical values at 1%	
			Lower bound	Upper bound
Model 1	20.39***	Cointegration exists	5.22	6.69
Model 2	21.05***	Cointegration exists		

The AIC determines optimal lag length; ***statistical significance at 1%

the long-run impacts (indicated by the relatively larger size of the long-run elasticity parameter) are evidenced to be relatively larger compared to the short-run impacts (indicated by the relatively smaller size of the short-run elasticity parameter). This finding can be linked with similar findings shown in the previous studies that have advocated that enhancing the consumption of renewable energy (i.e., clean/low-carbon energy resources) can curb CO2 emissions and carbon footprints (Bello et al. 2018; Saqib 2022a; Destek and Sinha 2020; Mehmood 2022a). From the point of view of Oman's future clean energy transition and environmental well-being enhancement objectives, this particular finding from this study highlights the importance of using relatively low-carbon-intensive energy resources in order to tackle the nation's environmental concerns. It is important to note that although Oman meets more than 95% of its energy demand using natural gas which is a relatively clean fossil fuel compared to other oil-based petroleum fuels, it further needs to gradually look for cleaner alternative fossil and non-fossil fuels to diversify its energy mix in an environmentally-sustainable manner.

Moreover, specifically focusing on the ARDL estimates for model 2, it can be seen that the predicted elasticity parameter concerning the interaction term (i.e., lnFE × lnLCE) is negative and statistically significant for both the short- and long-run scenarios. Therefore, these findings imply that financial development and low-carbon energy consumption jointly help to curb the carbon footprint figures

Table 4 The short- and long-run results from the ARDL analysis

Dependent variable: lnCFP				
	Model 1		Model 2	
	Coefficient	Std. error	Coefficient	Std. error
Short-run results				
ΔlnG	−25.485	40.702	−30.006	31.245
ΔlyG2	1.166	2.084	1.340	1.460
ΔlnFD	0.107***	0.033	0.089***	0.028
ΔlnLCE	−0.901***	0.153	−1.130***	0.307
ΔlnFD*lnLCE	-	-	−0.451***	0.156
SBY	−1.129**	0.549	−1.400***	0.560
Long-run results				
lnG	482.300***	167.201	501.231***	199.870
lyG2	−24.010***	8.479	−24.903***	10.213
lnFD	0.130**	0.065	0.162**	0.072
lnLCE	−1.722***	0.176	−1.858***	0.205
lnFD*lnLCE	-	-	−0.670***	0.204
SBY	−2.439***	1.002	−2.616***	1.120
Constant	−264.845***	67.330	−215.530***	55.175
ECT(-1)	−0.611**	0.301	−0.650***	0.285
Threshold per capita real GDP level	$23,011		$23,503	
Observations	139		139	
Adj. R-squared	0.645		0.664	
Diagnostic test	Test stat.	Prob.	Test stat.	Prob.
Breusch-Godfrey LM	1.250	0.515	1.514	0.351
Breusch-Pagan- Godfrey	21.220	0.156	21.220	0.156
Jarque-Bera	1.048	0.522	1.115	0.488
Ramsey RESET	0.280	0.440	0.240	0.360

Δ represent first difference operator for the short-run model; SBY refers to the structural break year dummy variable for the respective model; ECT(-1) denotes the error-correction term; ***statistical significance at 1%; **statistical significance at 5%

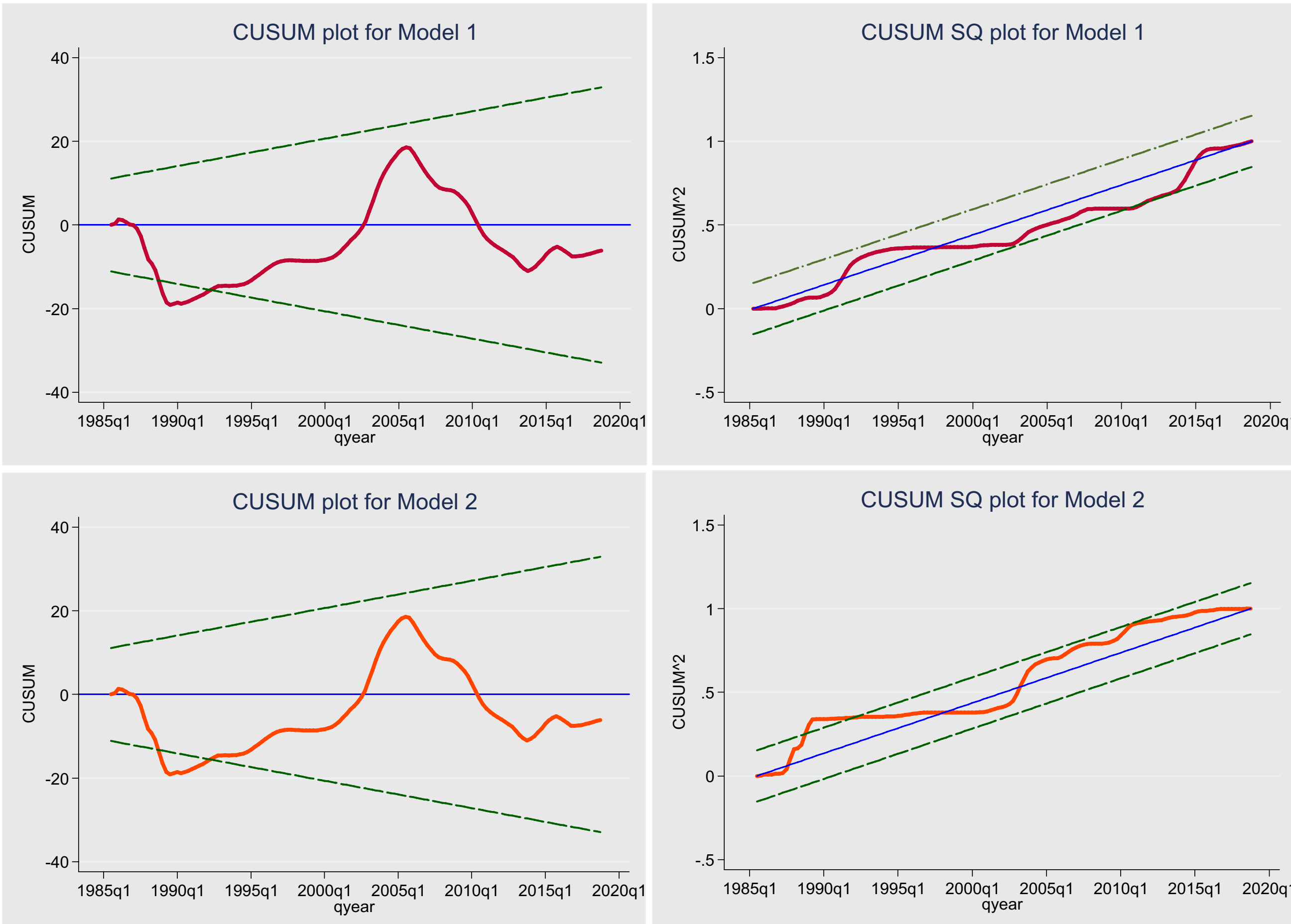

Fig. 2 The CUSUM and CUSUMSQ plots. Note: the null hypothesis of stability of all the coefficients in the respective model cannot be rejected since the plots of the CUSUM and CUSUMSQ tests (denoted by the red and orange lines), for both models 1 and 2, are within the critical bounds of a 95% confidence interval (denoted by the dashed green lines). Source: authors' computation

Table 5 The results from robustness analysis using the DOLS estimator

Dependent variable: lnCFP

Regressors	Model 1		Model 2	
	Coefficient	Std. error	Coefficient	Std. error
lnG	284.56***	95.619	296.156***	92.332
lyG2	−14.301***	4.867	−14.801***	4.165
lnFD	0.035***	0.011	0.036**	0.018
lnLCE	1.220**	0.600	1.050***	0.222
lnFD*lnLCE	-		−0.239***	0.082
SBY	−1.950***	0.340	−2.120***	0.411
Constant	−195.521***	69.129	−201.115	74.129
Threshold per capita real GDP level	$20,930		$22,142	
Observations	139		139	
Adj. R-squared	0.835		0.811	

SBY refers to the structural break year dummy variable for the respective model; ***statistical significance at 1%; **statistical significance at 5%

in Oman. More importantly, this noteworthy finding suggests that low-carbon energy use can help to neutralize the adverse environmental consequences associated with the development of Oman's financial sector. This situation can be explained by the understanding that if relatively cleaner energy resources can be utilized to meet the financial development-induced surge in Oman's energy demand, then the energy consumption-based CO2 emissions can be contained to a large extent which, in turn, can help to reduce the nation's carbon footprint figures as well. On the other hand, the joint favorable environmental outcome of financial development and low-carbon energy consumption can also be justified from the point of view that as the financial sector of Oman gets developed, it would enhance both the capital stock and purchasing power of the private sector entities whereby the borrowed funds can possibly be utilized for developing technologies necessary for generating electricity using low-carbon primary energy sources or be utilized for consuming the relatively more expensive low-carbon energy resources. In both cases, the adverse environmental impacts of financial development can be tackled via the channel of low-carbon energy use.

Furthermore, the ARDL estimates also show that the coefficient parameters attached to the structural break year dummy variables are statistically significant. Thus, the relevance of controlling for the structural break concerns within the regression analysis is portrayed by these findings. Besides, regarding the predicted error-correction terms (i.e., ECT(-1)), it can be said that the rate of adjustment from disequilibrium in the current period to long-run equilibrium in the next period is around 61% and 65% for models 1 and 2, respectively. Moreover, the high adjusted R-squared values imply a good fit of both the models. Precisely, considering the adjusted R-squared values, it can be said that around 64.5–66.4% of total variations in Oman's carbon productivity levels can be explained by variations in the nation's economic growth, financial development, and low-carbon energy consumption levels. As far as the results from the diagnostic tests are concerned, the statistical insignificance of the predicted test statistics from the Breusch-Godfrey LM, Breusch-Pagan-Godfrey, Jarque-Bera, and Ramsey-Reset tests indicate that both our models do not suffer from autocorrelation, heteroskedasticity, non-normal distribution of residuals, and model misspecification problems, respectively. Furthermore, the cumulative sum of squares (CUSUM) and squared cumulative sum of squares (CUSUMSQ) plots presented in Fig. 2 confirm the stability of the predicted short- and long-run elasticity parameters.

The long-run elasticity estimates from the robustness analysis using the DOLS estimator are presented in Table 5. Since the predicted signs of the long-run DOLS elasticity parameters are identical to the predicted signs of the corresponding long-run ARDL elasticity parameters (reported in Table 4), the robustness of the long-run findings across alternative regression techniques is affirmed. However, the sizes of most of the elasticity estimates and the threshold levels of per capita real GDP derived from the ARDL are comparatively larger than those generated from the DOLS analysis. Hence, considering the advantageous feature of the ARDL technique in terms of handling data of mixed integration order (as in the case of our data set), it can be said that the ARDL technique corrects the underestimate bias of the DOLS outcomes.

Conclusion and policies

Achieving environmental sustainability has become a core agenda of the global economies to which Oman is no exception. Accordingly, the nation has pledged to turn carbon-neutral by 2040, especially by diversifying the national energy mix with relatively cleaner low-carbon fuels. However, attaining this target is likely to be difficult for Oman since the nation is yet to undergo this clean energy transition as the entire energy demand of the nation is met by conventional fossil fuels (particularly natural gas). Consequently, although the economy of Oman has flourished over the last couple of decades, such favorable economic growth performances led to a persistent aggravation in the quality of the environment in Oman. Against this background, this study aimed to assess the marginal effects of positive shocks to economic growth, financial development, and low-carbon energy consumption levels on carbon footprints in Oman considering quarterly frequency data from 1984Q1 to 2018Q4. Besides, this study also scrutinized the joint environmental impacts of financial development and low-carbon energy consumption. Overall, controlling for structural break concerns in the data, the findings validated the carbon footprint-related EKC hypothesis for Oman at threshold per capita real GDP levels of around US $23,500 in the long-run. Moreover, the predicted economic growth threshold are observed to be higher than the average economic growth level of Oman during the study period considered in this study. Besides, financial development and low-carbon energy consumption were found to boost and reduce Oman's carbon footprint figures, respectively, in both the short- and long-run. Lastly, the joint carbon footprint-inhibiting impact of financial development and low-carbon energy consumption was also affirmed from the outcomes derived from the regression analysis. In line with these critically important findings, the following macroeconomic policy interventions can be suggested.

Firstly, since the per capita real GDP level in Oman is below the predicted threshold levels, it is important for Oman to speed up its economic growth rate in order to surpass the threshold levels. If Oman can manage to do so, it can be assumed that the nation would be sufficiently empowered economically whereby it can adopt and implement relevant environmental welfare-enhancing policies that are difficult to be implemented at present. Secondly, Oman should try and restructure its financial development policies by integrating environmental welfare policies into them. In this regard, greening Oman's financial sector is of paramount importance which can possibly be achieved by liberalizing interest rates charged on funds borrowed for investment in green innovation-based projects, in particular. Thirdly, it is time Oman considers undertaking policy interventions that would diversify the nation's national energy portfolio and reduce its fossil fuel dependency. Thus, it is essential for the nation to look for alternative sources of low-carbon energy which can replace the conventionally consumed high-carbon intensive energy resources (natural gas and petroleums). Lastly, considering the finding of joint carbon footprint-inhibiting impact, it is critically important for Oman to design interactive policies through which the financial sector can be developed in an environmentally sustainable manner by simultaneously enhancing supplies of clean energy resources in Oman. In this regard, facilitating the use of the borrowed funds for investment in clean energy development in Oman is major energy sector reform that can be considered by the energy-related policymakers.

Highlighting the future research directions, this study may be expanded to research the impacts of green investment and technological innovation on different environment-related indicators in the context of Oman. Besides, similar studies can also be performed for the other members of the Gulf Cooperation Council in order to check for external validation of the findings presented in this current study.

Data availability The data sources are mentioned in the "Model, data, and methodology."

Author contribution **NA** conceptualized, conducted the econometric analysis, and wrote the introduction. **NIH** analyzed the findings and conducted the literature review. **SAJ** conducted the literature review and reviewed the draft. **MM** conceptualized, wrote the original draft, conducted the econometric analysis, highlighted the policy implications, supervised the work, and revised the manuscript. **HM** wrote the introduction and concluding remarks. MSA wrote the original draft and compiled the overall manuscript.

Declarations

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Consent to participate Not applicable.

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