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# Investigation of the Impact of Environmental Degradation on the Transition to Clean Energy: New Evidence from Sultanate of Oman

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**Abstract:** All nations are searching for ways to address their environmental gaps to assure long-term sustainability, given the alarming rate at which the environment is deteriorating. As one of the nations pursuing clean energy, Oman needs to embrace eco-friendly practices that can encourage sustainability and resource efficiency to establish green ecosystems. This study uses an autoregressive distributed lag (ARDL) model to examine the link between $CO_2$ emissions, GDP, energy consumption, financial development, foreign direct investment, urbanization, and population in the Sultanate of Oman between 1990 and 2023. The Middle Eastern nation of Oman was selected for the case study because it has traditionally depended on its domestic fossil fuel resources. Furthermore, the country has been a net exporter and surplus oil producer, underscoring Oman's long-standing reliance on fossil fuels. The findings indicate that urbanization and GDP lower $CO_2$ emissions, whereas population growth, energy use, FDI, and financial development raise emissions. As per the EKC model, the GDP2 coefficient was 0.488 and $\beta 1 < 0$. This suggests that there is a positive correlation between environmental degradation and economic growth in Oman, although the EKC only applies up to a particular income level. The findings suggest enacting additional environmental regulations to support sustainable business behavior, raising public understanding of environmental issues, using more clean energy technologies, lowering energy consumption, and reaching the goal of net-zero carbon emissions.

**Keywords:** $CO_2$ emission; climate change mitigation; ecosystem; EKC; environmental policies; ARDL model

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## 1. Introduction

Over the past few decades, environmental degradation has put sustainability under pressure. The rapid destruction of forests and deserts, the deterioration of the oceans, the huge damage to the ecosystem, the decrease of the maritime lifecycle, and the astonishingly excessive levels of dangerous emissions in the air are entirely fallouts of environmental deterioration because of economic actions [1]. This scenario will be exacerbated if the clean energy transition is not adopted. Consequently, to meet the Paris Agreement's net zero carbon targets, nations will inevitably transition from fossil fuel-based to renewable energy (RE) sources instantaneously [2].

Oman is a fossil fuel-dependent country with abundant oil resources and a net oil exporter [3]. The environmental quality of Oman, which is economically developing, is continuously deteriorating. Oman must determine the elements that will allow it to reduce its carbon footprint and its economy to address the environmental issues the nation has because of these divergent economic and environmental results [4]. Furthermore, Oman has committed to accomplishing net-zero emissions by 2050 to meet the 1.5 °C global warming target outlined in the Paris Agreement [5]. The goal of Oman is net zero, and it has launched some initiatives to highlight the significance of creating an energy infrastructure that is resistant to the consequences of climate change. Oman Vision 2040 and the National Energy Strategy both establish ambitious objectives for rising RE and boosting energy efficiency [6].

As part of the energy transition, Oman intends to raise the share of RE to 30% by 2030, 70% by 2040, and 100% by 2050. The strategy aims to increase energy efficiency to reach MJ/USD 6 of GDP by 2050. By 2050, all new automobile sales should be zero-emission vehicles, according to the strategy. In addition, Oman is establishing aggressive goals to produce green hydrogen, with plans to produce 1 million tons by 2030, 3.5 million tons by 2040, and 8 million tons by 2050 [7]. Oman has made significant strides in its energy transition and carbon reduction initiatives, especially with investments in renewable energy sources like wind and solar. For instance, the 7 GW Miraah Solar Power Plant contributes significantly to the production of green hydrogen, generating over 9.78 TWh annually [8].

Additionally, by enhancing the nation's ability to lower greenhouse gas emissions, the Dhofar Wind Power Project adds to this renewable energy landscape [8]. These are initiatives that are in line with the Oman 2040 Vision. Table A1 in the Appendix A details the main pillars of the 2040 vision.

In essence, there are a lot of renewable energy opportunities in Oman. Oman has 7340.19 Wh/m$^2$/day of sunshine, which places it on the greatest list. The southern region of Oman also offers a great deal of wind. Throughout the year, there is no variation in the wind pattern [9]. The energy shift will be accelerated in southern Oman with the installation of wind turbines. Additionally, pilot projects are being carried out to demonstrate the viability of alternative energy sources, and research is being conducted in Oman on hydrogen and carbon capture and storage (CCS) technology. To encourage electric vehicles to cut pollution, the transportation sector is also investing in public transportation infrastructure and charging stations [10].

In Oman, the majority of carbon dioxide ($CO_2$) emissions are caused by natural and human factors [11]. Table A2 in the Appendix lists the primary causes of Oman's greenhouse gas emissions. The $CO_2$ emissions by sector in Oman are shown in Figure 1.

As seen in Figure 1, the biggest cause of $CO_2$ emissions is electricity and heat. This situation is due to the geographical location of the country. It is inevitable to shift this expenditure to solar energy by making RE investments.

The paper attempts to analyze the factors that affect $CO_2$ emissions during Oman's transition to clean energy, including GDP growth, energy consumption, financial development, FDI, urbanization, and population. In pursuit of this objective, it is envisaged that the present paper will contribute to the variety of the literature. First, as far as I know, no study of this kind has used variables and specific periods that have focused solely on Oman. So, in this sense, the paper is making a humble attempt at the contribution of the literature. Second, a significant amount of research is conducted for all together GCC countries. This article aimed to investigate the validity of the relationship between $CO_2$ emissions and economic development for only Oman from 1990 to 2023. Thus, this paper explores the status of Oman in the clean energy transition by exploring the long-term relationships among $CO_2$ emissions, economic variables, financial development, and foreign direct investment using an econometric approach using 33 years of data. Third, the EKC hypothesis presents some suggested policies to lessen environmental damage in this article, as well as highlighting the sorts of comprehensive environmental regulations that Oman ought to have. In other words, the findings highlight the crucial long-term relationships required to develop effective strategies, in addition to highlighting the notable variability and difficulties in $CO_2$ emissions. This study sheds light on Oman's continued dedication to technological advancement and energy diversification, highlighting the avenues that could result in a more resilient and sustainable future for the country.

Here is the structure of the current paper: The second section analyzes the literature review. The third section presents results, methods, and data. The concluding section includes a list of policy recommendations to assist the development of a clean/green energy sector in Oman and around the world and highlights the findings.

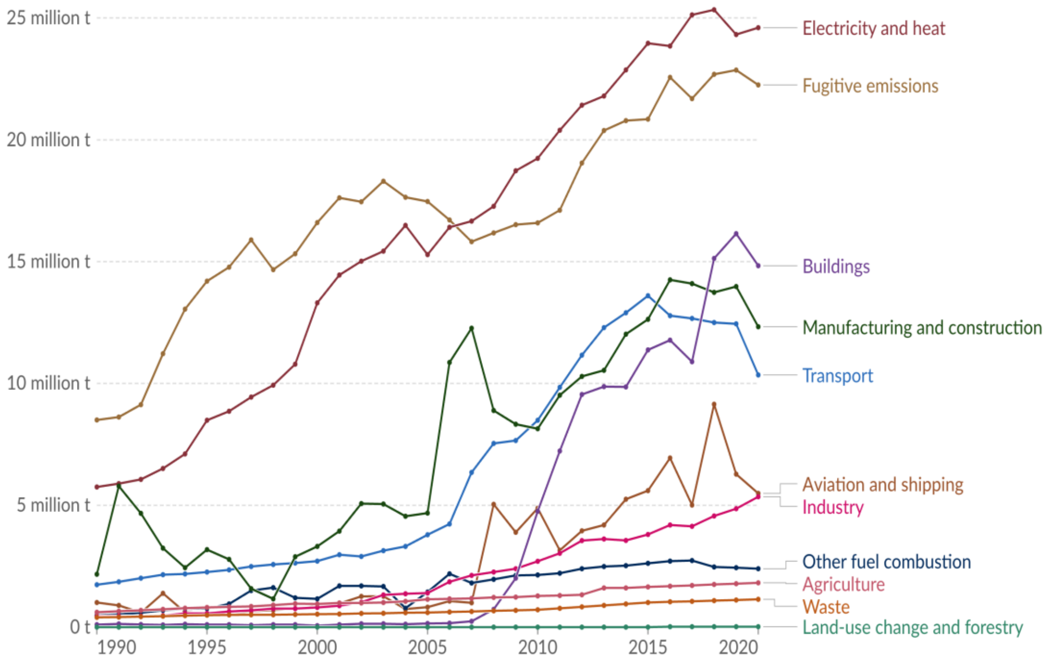


**Figure 1.** The $CO_2$ emissions by sector, Oman, 2020. Source: [12].

## 2. Literature Review

Oman is negotiating the energy transition and decarbonization processes to create a sustainable future. To lower diesel fuel consumption and greenhouse gas emissions in rural regions, hybrid power systems, such as PV–wind-diesel systems, are being investigated [13]. Additionally, the management of water and wastewater is being addressed, with an emphasis on the creation of green hydrogen from treated effluent and progressive reuse applications. To achieve its aim of having net-zero emissions by 2050, Oman is taking steps to improve its environment [8]. The nation's actions are in line with the shift to cleaner economies and global climate objectives.

Several empirical studies investigate Oman's decarbonization and transition to a sustainable future, while numerous studies have examined the $CO_2$ emissions and air pollution of the Gulf Cooperation Council (GCC) nations. Then, the research shows that energy use and economic development are the main causes of air pollution in GCC countries [14–16]. For instance, Aljawareen et al. [17] found that the relationship between GDP and $CO_2$ emissions is positive, while the relationship between environmental awareness and $CO_2$ emissions is negative. This means that the environmental policy in Oman was successful in reducing air pollution during the period 1998–2008, but economic growth increased $CO_2$. Hamid et al. [4] also claimed that the link between air pollution and economic growth in Oman depends on many different causes, such as foreign direct investment and capital investment. Furthermore, Zmami and Ben-Salha [15] found that the EKC hypothesis is valid at the USD 56,351 threshold income level based on data from GCC members.

The EKC hypothesis for Oman has rarely been examined in the literature. While some studies have shown that the EKC theory holds valid for Oman [4,18], others have found that it does not [19,20]. For instance, Mahmood [19] tests the asymmetric environmental impacts of energy sources for GCC countries with the environmental Kuznets curve (EKC) from 1975 to 2019. The findings do not support the validity of the EKC theory for Oman. Likewise, Alsamara et al. [20] scrutinizes the feasibility of the EKC hypothesis for contamination of the environment in the GCC utilizing panel data spanning the years 1980–2017. The EKC hypothesis for $CO_2$ emissions is valid for Qatar, Bahrain, Kuwait, Saudi Arabia, and the United Arab Emirates but not for Oman.

Some recent studies have clarified the implications of economic growth on carbon footprints despite many EKC-related studies focusing on the effects of growth on $CO_2$ emissions. Nevertheless, Oman was not included in any of these investigations, indicating a significant gap in the literature. Elshimy and El-Aasar [21] found a quadratic relationship between carbon footprint and real income for Arab countries (Oman is not included), supporting the EKC hypothesis. However, Usman et al. [22] found that the EKC hypothesis is not valid in the context of a few MENA countries, including Oman. The findings suggest that higher economic growth initially reduces carbon footprints but later increases them, resulting in a U-shaped relationship between economic growth and carbon footprint.

A recent literature review on EKC using $CO_2$ emissions for the Oman/GCC region is summarized in Table 1.

**Table 1.** A summary of current research on EKC utilizing $CO_2$ in Oman.

| Author/s | Periods | Country/ies | Variables | Method | Results |
|---|---|---|---|---|---|
| [4] | 1980–2019 | Oman | $CO_2$, GDP FDI, capital investment | ARDL | Inverted U-shaped |
| [6] | 1990–2022 | Oman | $CO_2$, GDP, EC, urban population, | Dynamic ordinary least squares | Inverted U-shaped |
| [11] | 1980–2018 | Oman | $CO_2$, GDP, OP, FD, Non-REC | ARDL | Inverted U-shaped |
| [18] | 1995–2014 | Algeria, Bahrain, Iran, Kuwait, **Oman,** Qatar, and Saudi Arabia | $CO_2$, GDP, EPC | Multivariate regression analysis | Inverted U-shaped for Oman |
| [19] | 1975–2019 | Kuwait, **Oman**, Saudi Arabia, and the UAE | $CO_2$, GDP, OC, NGC | | The EKC hypothesis is not valid. |
| [23] | 1980–2021 | Oman | $CO_2$, GDP, FDI, EC, globalization | NARDL | Inverted U-shaped |
| [24] | 2000–2019 | Bahrain, Oman, Qatar, Saudi Arabia and the UAE | $CO_2$, GDP, EC, FD, TEC | Durbin Hausmann cointegration | EKC is only valid in Oman. |
| [25] | 1997–2019 | SA, Qatar, UAE, Iran, Israel, Jordan, Bahrain, **Oman**, Lebanon, and Egypt | $CO_2$, GDP, TA, REN, FOS, EDU, TO | Cross-sectional dependence | The EKC hypothesis is not valid. |
| [26] | 1984–2018 | Oman | $CO_2$, GDP, FD, LCE | ARDL | Inverted U-shaped |
| [27] | 1984–2014 | Oman | $CO_2$, GDP, EC, DIV, EXM, IXM, | ARDL | Inverted U-shaped |
| [28] | 1991–2018 | Oman &UAE | $CO_2$, GDP, EC, FDI | Co Integration and Causality Tests | EKC hypothesis was found to be not applicable in Oman. |
| [29] | 1991–2017 | Bahrain, **Oman**, Qatar, Saudi Arabia and the UAE | $CO_2$, GDP, EC, globalization | DOLS, and FMOLS | EKC hypothesis is not supported for the GCC countries. |

***ARDL:*** autoregressive-distributed lag model ***$CO_2$:*** carbon dioxide, ***DIV:*** export diversification index, ***DOLS:*** dynamic ordinary least square ***EC:*** energy consumption, ***EDU:*** education, ***EPC:*** electric power consumption, **EXM:** extensive margin index, ***FD:*** financial development, ***FDI:*** foreign direct investment, **FMOLS:** the fully modified ordinary least square ***FOS:*** fossil fuel, ***GDP:*** gross domestic product, **IXM:** intensive margin index, ***LCE:*** low carbon energy consumption, ***NARDL:*** non-linear autoregressive-distributed lag model, **NGC:** natural gas consumption, ***OC:*** oil consumption, **OP:** oil price, ***REN:*** renewable energy, ***TA***: tourism, ***TEC:*** mobile cellular subscriptions, ***TO:*** trade openness.

Table 1 presents the results of the literature review, which varies by country in terms of the causal relationship between the factors impacting $CO_2$ emissions and the result of the EKC hypothesis. Up till now, research has investigated whether EKC is valid in Oman by combining two or three data sets. This study seeks to evaluate the validity of this hypothesis for Oman with the use of six explanatory factors. Explanatory variables are selected within the framework of literature, and their effects in Oman in clean energy transition are analyzed. Furthermore, the EKC hypothesis suggests that environmental degradation rises in the early phases of economic expansion but starts to decrease as income levels rise because more funds are allocated to environmental preservation and the implementation of greener technologies [30]. Similar trends have been noted in many developing economies, particularly those that are rapidly industrializing and urbanizing, like Oman.

To the best of my knowledge, no research has been conducted in this area to look at the link between $CO_2$ emissions and energy consumption, economic growth, financial development, foreign direct investment, and urbanization in Oman. The following empirical analysis helps to fill this gap in the existing energy literature using the example of Oman.

## 3. Data and Method

### *3.1. Data*

This study tested the validity of the EKC hypothesis for the years 1990 to 2023 in Oman using the time series analysis approach. The assumptions and theories linked to the explanatory variables enhance the research, and the explanatory factors are those that are commonly discovered in the literature. The variables used in the paper are given in Table 2, alongside their descriptions, sources of information, and units of measurement. Natural logs are used to express each variable to reduce a measurement variable's skewness [31].

**Table 2.** Depiction of the analysis's variables.

| Variables | Definition | Unit of Measurement | Sources |
|---|---|---|---|
| $CO_2$ | Carbon emission per capita | Metric tons per capita | [32] |
| GDP | Gross domestic product per capita | Current USD | [32] |
| EC | Primary energy consumption per capita | Measured in kilowatt-hours per person | [33] |
| FD | Financial development index | Percentage (index) | [34] |
| FDI | Foreign direct investment | BoP, current USD | [32] |
| URB | Urbanization | Percentage of total population | [32] |
| POP | Population | Person | [33] |

The dependent variable, $CO_2$ emissions, is measured in tons of $CO_2$ per person and is a result of using fossil fuels like coal, natural gas, and oil. Economic growth per capita is measured by GDP. GDP2 is the logarithm of GDP squared in current dollars, comparable to GDP.

FD is a financial development metric that looks at the factors that contribute to the expansion of the financial sector. Financial development can affect $CO_2$ emissions in plenty of ways [35]. Financial development facilitates firms' access to additional capital for investment [36,37]. In this vein, Oman is focused on properly allocating financial, service, and industrial activities across all its economic sectors to maximize their benefits and successfully integrate the environment and sustainable growth [38].

FDI affects emissions of $CO_2$. The pollution haven theory is supported by the fact that FDI significantly raises the $CO_2$ emissions of the host nation [39]. Numerous studies have also demonstrated that FDI increases $CO_2$ emissions [40,41]. By the end of 2022, Oman had received 27,135 billion Omani riyals (OMR) in FDI. Oil and gas (71.1%), converting industries (9.1%), financial brokerage (8.9%), real estate, leasing, and commercial operations (4.9%) were the most favored sectors for FDI. A total of 6% were drawn to other activities [42].

URB is calculated as the proportion of the total population that lives in urban areas. Empirical studies on the relationship between $CO_2$ emissions and urbanization yielded a variety of findings for various locations and eras, including no statistically significant association, two-way correlation, non-linear connection, and positive or negative correlation. For instance, Wang et al. [43] shows that urbanization has a modest effect on $CO_2$ emissions in OECD nations, while [44] indicates that URB significantly affects $CO_2$ in seven nations: Brazil, India, China, Malaysia, Mexico, the Philippines, and Thailand.

EC is the logarithm of the total energy use expressed in kWh per person. The EC variable includes nuclear power, coal, gas, oil, and RE. It is not unexpected that much research chooses to use energy consumption statistics to support the EKC model because fossil fuels contribute significantly to overall energy consumption when reviewing the literature [45,46]. This is because fossil fuels have clear negative environmental effects [47–49].

POP is measured in millions and is a statistical log. Findings on population and EKC show that growing populations have a detrimental effect on the ecosystem and cause the EKC curve to shift upward, which results in degradation [50].

### 3.2. Method

This study, which examines the association between Oman's economic growth and environmental degradation from 1990 to 2023, puts forth the central EKC hypothesis that the environmental degradation indicator is a quadratic function of per capita income. This implies that although pollution rises in the early stages of economic expansion, improvements happen when growth reaches a particular threshold [51]. Income elasticity is constant across nations at all income levels, notwithstanding the possibility of regional variations in the level of an environmental deterioration indicator [52]. To scrutinize the validity of the EKC theory, this paper used the quadratic model provided in Equation (1):

$$CO_2 = f\left(GDP,\ GDP^2,\ X\right), \tag{1}$$

where $CO_2$, GDP, $GDP^2$, and X denote the environmental degradation, gross domestic product (income), income square, and various causes that can positively or negatively impact $CO_2$ emissions. Six additional variables that are anticipated to affect $CO_2$ emissions are added to the model given in Equation (1) in the current study in the following ways:

$$CO_2 = f\left(GDP,\ GDP^2,\ EC,\ FD,\ FDI,\ URB,\ POP\right) \tag{2}$$

This study aimed to investigate the main variables that may affect the carbon footprint with six new explanatory variables. Equation (3) illustrates the use of the logarithm form to demonstrate the modified EKC model with the help of the ARDL approach to find out how $CO_2$, economic growth, and other factors in Oman are related. Mainly, refs. [53,54] established the ARDL technique. A few advantages of the ARDL approach over other cointegrations include its applicability regardless of whether the series is purely cointegrated at the I(0), I(1), or mutually and approximated small sample qualities [52]. The ARDL model's short-run elasticities quantify how sensitive the dependent variable is to shifts in the independent variables. The dependent variable's steady-state sensitivity to long-term changes in the independent variables is measured by the long-run elasticities. Thus, the ARDL approach depicts the equilibrium connection among the variables after short-term dynamics are taken into consideration [55]. Furthermore, the ARDL economic technique allows critical values to be endogenous in all directions [56].

$$\begin{aligned} LnCO2_{it} = \beta_{oi} + \beta_{1i}LnGDP_{it} + \beta_{2i}LnGDP_{it}^2 + \beta_{3i}LnEC_{it} + \beta_{4i}LnFD_{it} + \beta_{5i}LnFDI_{it} + \beta_{6i}LnURB_{it} \\ + \beta_{7i}LnPOP_{it}e_{it} \end{aligned} \tag{3}$$

where t represents time, and i stands for nation. $\beta_{oi}$ shows the nation-specific fixed effect, while $e_{it}$ stands for estimated residuals, which show how long-run equilibrium has deviated.

$\beta_{1i}\ldots\beta_{7i}$ refers to the long-run elasticities of independent variables. Within the context of EKC, according to Equation (3), the model may produce the following results [57,58].

$\beta_1 = \beta_2 = 0$, with no association between $CO_2$ and income.

$\beta_1 > 0$ *and* $\beta_2 = 0$, the association between $CO_2$ and GDP is linear.

$\beta_1 < 0$ *and* $\beta_2 = 0$, the association between $CO_2$ and GDP is negative.

$\beta_1 > 0$ *and* $\beta_2 < 0$, the association between $CO_2$ and GDP is "inverted U", and the EKC is acceptable.

The validity of the EKC varies on the "inverted U" link between $CO_2$ and economic growth. The findings that indicate the turning point is the GDP per capita level ($GDP^* = -\beta_1/2\beta_2$) pursuit of the approval of the EKC model as the pattern shifts toward declining ecological pollution.

The long-run equilibrium value is forthrightly attained if the ECM coefficient is between 0 and −1. If the ECM coefficient is between −1 and −2, the error correction procedure is stated to progress as reducing fluctuations around the long-run balance. The equilibrium has been moved away if the coefficient is more than −2 or positive. Lastly, Brown et al. [59] proposed that the CUSUM and CUSUMSQ tests be used to evaluate the stability of the model. When a structural break occurs, time series data can be subjected to the CUSUM and CUSUMSQ tests.

### *3.3. Empirical Findings and Discussion*

First, the data's stationarity was checked using an augmented Dickey–Fuller (ADF) and Philips–Perron (PP) tests. These tests can be used to recognize whether the time series is stationary. If it is not, the number of differences can be used to make it stationary [59,60]. Each variable's level and initial difference values have been tested to unit root analyses correspondingly. The results are shown in Table 3.

**Table 3.** ADF and PP unit root test findings.

| Variables | ADF | | PP | |
|---|---|---|---|---|
| | I(0) | I(1) | I(0) | I(1) |
| **GDP** | 0.798 | 0.000 *** | 0.835 | 0.000 *** |
| **$GDP^2$** | 0.832 | 0.000 *** | 0.821 | 0.000 *** |
| **FD** | 0.225 | 0.000 *** | 0.205 | 0.000 *** |
| **FDI** | 0.566 | 0.000 *** | 0.637 | 0.000 *** |
| **URB** | 0.985 | 0.000 *** | 0.960 | 0.000 *** |
| **EC** | 0.610 | 0.000 *** | 0.612 | 0.000 *** |
| **POP** | 0.911 | 0.000 *** | 0.890 | 0.000 *** |
| **$CO_2$** | 0.798 | 0.000 *** | 0.785 | 0.000 *** |

Notes: (***) Significant at the 1%, Lag Length based on SIC.

Table 3's ADF and PP unit root test findings show that the variables are stationary at the first difference by both unit root tests. The ARDL boundaries test should be used to identify long-term associations because the variables are stationary at various levels.

The lag interval was studied utilizing a vector auto-regressive (VAR) model, and the lag delay interval was estimated using a combination of a randomly chosen lag interval with the variables. Table 4 displays the results of the lag interval test.

**Table 4.** Selection standards for lag orders in VAR.

| Lag | LogL | LR | p | AIC | HQC | SC |
|---|---|---|---|---|---|---|
| 0 | 64.73 | - | 0.000 * | −3.981 * | −3.878 * | −3.651 * |
| 1 | 65.09 | 0.734 | 0.001 | −3.937 | −3.819 | −3.560 |
| 2 | 65.09 | 0.000 | 0.001 | −3.868 | −3.735 | −3.444 |

* indicates the lag order that the criterion chose. LR: sequential modified LR test statistic (each test at 5% level). AIC: Akaike information criterion. HQC: Hannan–Quinn information criterion. SC: Schwarz information criterion.

As can be seen in Table 4, VAR = 0 was selected as the optimum lag length to be utilized to test the cointegration because three distinct criteria were all pointed in that way. Additionally, the AIC, SC, and HQC criteria were used to find the optimal lag lengths for the ARDL bound test used to scrutinize the cointegration link between the six pieces of data in the present paper. Moreover, AIC assists in selecting the longest possible delay length. Table 5 displays the long-term links bound test findings.

**Table 5.** Bound test and long-term coefficients of the ARDL model.

| k = 7 | Case II | | Case III | |
|---|---|---|---|---|
| **F Statistic** | **23.914** | | **23.570** | |
| **Narayan level (2005)** | **I(0)** | **I(1)** | **I(0)** | **I(1)** |
| **%10** | 1.92 | 2.89 *** | 2.03 | 3.13 *** |
| **%5** | 2.17 | 3.21 *** | 2.32 | 3.5 *** |
| **2.5%** | 2.43 | 3.51 *** | 2.6 | 3.84 *** |
| **%1** | 2.73 | 3.9 *** | 2.96 | 4.26 *** |
| **Pesaran et al. level (2001)** | **I(0)** | **I(1)** | **I(0)** | **I(1)** |
| **%10** | 2.19 | 3.37 *** | 2.3 | 3.60 *** |
| **%5** | 2.59 | 3.90 *** | 2.75 | 4.20 *** |
| **%1** | 2.73 | 3.9 *** | 3.84 | 5.68 *** |

Case II: Restricted constant and no trend. Case III: Unrestricted constant and no trend. ***, denotes a 1% significance level.

Table 5 shows that, for scenarios II and III, the anticipated F statistics for the chosen model are significant at the 1% significance level. The F statistic exceeds the low critical values, proving cointegration and rejecting the null hypothesis. Table 6 presents the estimated long-term coefficients.

**Table 6.** Coefficients throughout the long run for the ARDL model.

| Variables | Coefficient | t-Statistic | Diagnostic Test | F Statistic | *p* Value |
|---|---|---|---|---|---|
| ***InGDP*** | −8.167 *** | −7.695 | ***t-statistic*** | 0.781 | 0.491 |
| ***InGDP$^2$*** | 0.401 *** | 7.718 | ***F statistics*** | 0.610 | 0.000 *** |
| ***InFD*** | 0.763 *** | 4.164 | ***LR*** | 5.187 | 0.02 ** |
| ***InFDI*** | 0.036 ** | 5.923 | ***Probability*** | 0.871 | |
| ***InURB*** | 6.264 *** | −5.126 | ***Jarque-Bera*** | 0.275 | |
| ***InEC*** | 0.905 *** | 12.434 | ***Durbin Watson value*** | 2.73 | |
| ***InPOP*** | 0.280 | 16.840 | ***$R^2$*** | 0.99 | |
| ***C (constant)*** | 103.750 ** | 4.787 | ***Adjusted $R^2$*** | 0.99 | |

The symbols *** and ** denote significance levels of 1% and 5%, respectively.

Table 6 estimates the long-term ARDL model. The results show that while financial development, FDI, energy consumption, and population growth increase $CO_2$ emissions, GDP and urbanization reduce emissions. Moreover, the model revealed that $\beta_1 > 0$ and the GDP coefficient was $-9.678$. According to the EKC model, $\beta_1 < 0$, and the GDP$^2$ coefficient was 0.488. This implies that the EKC only applies in Oman up to a certain income level, after which there will be a positive link between environmental deterioration and economic growth. This can be used to determine the turning point level of the EKC, which was calculated utilizing the ($GDP = -\frac{a1}{2a2}$ and exp(GDP*) formulation. A turning moment can be identified by the paper at GDP* = 0.285.

It has been found that financial development, FDI, energy consumption, and environment are positively correlated, as shown in Table 6. Environmental pollution increases by 0.76%, 0.03%, and 0.90%, respectively, for every 1% increase in financial development, FDI, and energy consumption. This outcome aligns with research conducted by [61–63]. However, the population is not significant with $CO_2$ emission. This result is in line with [64].

The study's findings clearly show the link between Oman's economic growth and $CO_2$ emissions. While they differ from other studies, they align with some of the earlier research. Similarly, Guo et al. [65] found that economic expansion is negatively related to environmental excellence. This result means that as a country experiences higher economic expansion, its ecological footprint increases. On the contrary, this analysis shows that GDP squared positively correlates with $CO_2$ emissions, but GDP per capita has a negative correlation. This outcome differs from the research conducted by [66]. The correlation between GDP and $CO_2$ emissions emphasizes how urgently Oman must implement cleaner energy technology and boost energy efficiency to lessen the negative environmental effects of its economic expansion.

Furthermore, this study reveals the complexity of the relationship between financial development, FDI, and $CO_2$ emissions. The results show that financial development and FDI have an impact on $CO_2$ emissions in Oman. The environmental impacts of financial development and FDI are often influenced by other factors such as the type of investment, regulatory framework, and overall economic structure [67,68]. For example, FDI can increase or decrease $CO_2$ emissions depending on whether the investments are directed towards environmentally friendly projects or energy-intensive industries [69]. Therefore, financial development and FDI emissions have the potential to contribute significantly to a low-carbon economy if they are compatible with sustainable development goals. Financial development also refers to ensuring a range of financial products and services to consumers and businesses to satisfy their requirements and make them economically viable in the long term, which is another definition of financial development.

The predicted ARDL model uses zero lag lengths. The Jarque–Bera test indicates that the error terms are normally distributed. The short-term study of the established model is another stage associated with the ARDL cointegration test, and Table 7 reports the values associated with the developed model.

**Table 7.** ARDL error correction model.

| Variables | Coefficient | t-Statistic | Variables | Coefficient | t-Statistic |
|---|---|---|---|---|---|
| $\Delta InGDP$ | −8.167 *** | −16.859 | $\Delta InURB$ | 6.264 *** | 9.279 |
| $\Delta InGDP_{t-1}$ | 8.021 *** | 13.855 | $\Delta InURB_{t-1}$ | −12.828 *** | −19.245 |
| $\Delta InGDP^2$ | 0.401 *** | 16.578 | $\Delta InEC$ | 0.905 *** | 19.194 |
| $\Delta InGDP^2{}_{t-1}$ | −0.420 *** | −14.098 | $\Delta InECI_{t-1}$ | −0.584 *** | −12.973 |
| $\Delta InFD$ | 0.763 *** | 20.757 | $\Delta InPOP$ | 0.280 ** | 2.293 |
| $\Delta InFD_{t-1}$ | 0.269 *** | 9.946 | $\Delta InPOP_{t-1}$ | −1.528 *** | −8.836 |
| $\Delta InFDI$ | 0.036 *** | 14.724 | $R^2$ | 0.99 | |
| $\Delta InFDI_{t-1}$ | −0.045 *** | 14.724 | $ECT_{t-1}$ | 0.000 | |

The symbols *** and ** denote significance levels of 1% and 5%, respectively.

Table 7 shows that the model's test statistics are suitable. The error correction term is a crucial concern in short-run studies. The error correction term's statistical value generally should fall between "0" and "−1". It was determined that the established model's error correction term is statistically significant. This means that the following period corrects %99 of short-term deviations.

Finally, the stability of the model and the general frequency of structural breaches in the data set were evaluated using the CUSUM and CUSUMQ tests and the long-run coefficients of the ARDL model. A structural break's existence is ascertained by the CUSUM test, and its duration is ascertained by the CUSUMQ test [70]. The linked tests are understood as follows: the estimated parameters are stable if the curves taken from the test statistics of the error terms fall below the critical limits. Figure 2 displays the test diagrams for CUSUM and CUSUMQ.

The CUSUM and CUSUMQ diagrams display that the started long-term link does not have any structural fractures. The diagrams fall within the critical value band at the 5% significance level, representing that the factors are significant. Additionally, the ARDL models' coefficients are shown to be stable by the results of the CUSUMSQ and CUSUM analyses. In other words, red lines in the plots indicate the confidence intervals and blue lines outline the residuals. The model's stability is demonstrated by the variables' residuals continuously staying inside the confidence intervals at the 5% significance level.

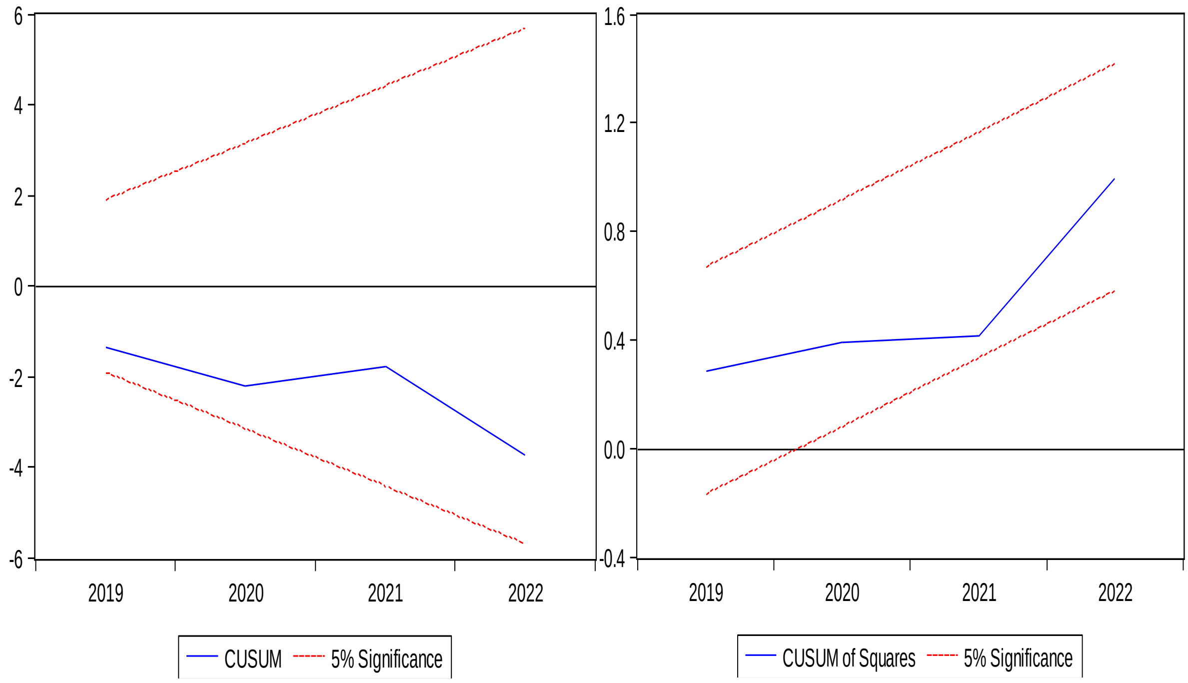


**Figure 2.** Results of CUSUM and $CUSUM^2$ test.

## 4. Conclusions

The present research used the ARDL cointegration test to examine the applicability of the EKC or the Oman economy utilizing data spanning from the 1990s to 2023. In this framework, a quadric model was used to apply the ARDL cointegration test. The GDP and GDP2 variables were deemed to be statistically significant in testing the EKC hypothesis.

The study's investigation and conclusions showed that, in the Sultanate of Oman, the EKC hypothesis is true up to a certain income level. It is expected that environmental deterioration and economic expansion would positively correlate if the income threshold were exceeded. Though this is an optimistic sign for the initial stages of economic development, it is a disappointing consequence for the latter phases of economic growth, according to the EKC theory. In the short-term linking of the model developed for the research, the error-correcting mechanism works well, and its coefficient is statistically significant.

Some policy recommendations for Oman and the rest of the world can be made considering the findings. This study's policy implications are especially significant for Oman's attempts to balance its transition to sustainable energy. First, to reduce $CO_2$ emissions, Oman can transform from fossil fuels to clean energy, or RE. Utilizing cutting-edge technology to expand energy use efficiency and raising the proportion of carbon-free energy sources in total energy consumption can further accelerate Oman's transition to clean energy. Second, policymakers ought to give top priority to establishing a regulatory framework that incentivizes green investments and inspires the finance industry to back sustainable development projects. For investments in energy-efficient technologies, sustainable urban development, and renewable energy, this can entail providing tax breaks or subsidies. Furthermore, the financial industry in Oman ought to be supported in developing green financing options that ease the shift to a low-carbon economy. Economic growth and environmental preservation can be achieved in Oman by utilizing foreign direct investment and financial development to support sustainable practices.

The findings also have wider ramifications for international sustainability initiatives and how they relate to the Sustainable Development Goals (SDGs) of the UN. Since this study sheds light on energy consumption, it can especially help efforts towards SDG 7 (Affordable and Clean Energy). Additionally, it is evident how relevant the findings are to SDG 13 (Climate Action) since they highlight the significance of decarbonization strategies for Oman and other economies. By determining the primary causes of CO2 emissions, this study offers practical information that can be used to inform national and international policies that will jointly fight climate change and advance sustainable development.

The study has some limitations. First, not all the causes affecting the clean energy transition could be included in the analysis due to data access issues. For instance, RE use is one of the most important factors supporting the clean energy transition, but RE use in Oman is too new and at too low a rate to be included in the data. Second, to determine the effects of the chosen policy and the geographic changes, it is important to look at the problem from a diversity of viewpoints with extra causes or to compare the present situation to that of other nations.

Additionally, it is essential to compare the present condition to that of other Middle Eastern nations to exhibit the influence of the policies that have been implemented and the modifications for geographical reasons. Furthermore, future research could provide deeper insights by including a wider range of sectors, using more recent data (e.g., technological adoption, energy policy stringency). Additionally, future studies need to assess the intricate problems from a variety of angles. "What must be done for Oman to accept the EKC hypothesis?" is another question that can be the focus of future research.

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## Appendix A

**Table A1.** The Vision 2040 pillars for Oman.

| | |
|---|---|
| **People and Society** | Attempts to create a prosperous and healthy society with social safety, top-notch healthcare, education, and cultural identity. |
| Economy and Development | Provides industry diversification based on innovation, technology, and knowledge as top priority. Another important goal is setting high standards for environmental and socioeconomic goals. |
| Governance and Institutional Performance | Concentrates on creating adaptable, creative, and forward-thinking administrative organizations that practice good governance. To prevent corruption, an efficient and impartial supervision mechanism will encourage accountability and openness. |
| Sustainable Environment | Aims to create resilient, balanced, and efficient ecosystems in order to safeguard the environment and guarantee the sustainability of natural resources for the benefit of the country's economy. To attain energy security this entails the growth of renewable energy, energy source diversity, and consumption reduction. Promoting a green and circular economy satisfies domestic demands while keeping up with international trends. |

Source: [71].

Oman Vision 2040 is a thorough plan for the Sultanate's social and economic change that will take place between 2021 and 2040. A common dedication to directing Oman's future via equitable and sustainable development is reflected in the Vision. It seeks to promote a competitive and innovative ecosystem while diversifying the economy, improving social well-being, and ensuring environmental sustainability. This framework plays a key role in propelling Oman's economic development into a contemporary, globally connected economy.

**Table A2.** Main reasons for Oman's $CO_2$ emissions.

| No | Reasons | Explanation |
|---|---|---|
| **1** | Energy production | Oil and gas production causes a significant amount of Oman's $CO_2$ emissions. Since the nation's economy and electricity generation rely heavily on natural gas and oil, fossil fuels are used in power plants and other industrial operations. This helps to the substantial amounts of $CO_2$ released into the air. |
| **2** | Transportation | The $CO_2$ emissions are from gasoline and diesel-powered automobiles, which are more prevalent due to Oman's increasing population and economy. Private vehicles are even more essential due to the absence of an advanced public transportation system. |
| **3** | Industrial processes | Industrial processes that make petrochemicals, furnace metal, and cement emit greenhouse gases. |
| **4** | Waste management | Waste management is essential to lower methane emissions. Methane may be released during the anaerobic breakdown of organic waste that is improperly disposed of in landfills as solid waste. However, these emissions can be increased by putting in place appropriate recycling and waste management processes. |
| **5** | Agriculture | Urbanization and deforestation are two examples of land use changes that can fall carbon sinks and release carbon contained in plants and soils. This fall in biodiversity could have a major effect on the climate and biosphere. The ecology and climate may be significantly affected by this fall in carbon sinks. |
| **6** | Wastewater systems | Poor wastewater treatment system management can lead to an increase in greenhouse gas emissions. Methane emissions can be decreased and environmental health can be enhanced with improved wastewater treatment systems. |

Source: [6].

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