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RESEARCH ARTICLE

Catalyzing green transformation: mitigating oil price impact on CO_2 emissions in Saudi Arabia via renewable energy transition

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Abstract
Exploring the relationship between international oil prices, income, and carbon dioxide (CO_2) emissions in Saudi Arabia, this study examines if renewable energy consumption plays a lowering tool in international oil prices' impact on CO_2 emissions, employing conventional econometric methods and the functional coefficient approach. The study reveals that the interaction between renewable energy consumption and international oil prices has a negative and statistically significant impact on CO_2 emissions. This emphasizes the potential for Saudi Arabia to reduce carbon emissions by prioritizing renewable energy projects. In addition, a positive and statistically significant relationship between income and CO_2 emissions is found, emphasizing the need to decouple economic growth from emissions growth. Furthermore, an interesting decoupling effect between oil price elasticity of CO_2 emissions and per capita GDP is noted from the early 2000s–2015. This indicates that economic growth driven by rising oil prices can be managed to mitigate environmental impact, showcasing Saudi Arabia's commitment to sustainable development. Policy recommendations involve intensifying efforts to promote renewable energy implementation, lowering fossil fuel dependence in power generation, and incentivizing emissions reduction for a more sustainable energy future.

Keywords Renewable energy · International oil prices · CO_2 emissions · Sustainable development · Economic growth · Saudi Arabia

1 Introduction

Human emissions of CO_2 and other greenhouse gas (GHG) are a primary driver of climate change and present one of the world's most pressing challenges. CO_2 is a major GHG that traps heat in the Earth's atmosphere. Excess CO_2 emissions from human activities, primarily burning fossil fuels and deforestation, have led to

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global warming and climate change (Shahzad et al. 2021; Mukhtarov and Mikayilov 2023; Ulussever et al. 2023). The escalating potential adverse outcomes of global warming due to the unchecked consumption of fossil fuels continue to be a pressing global concern. Additionally, the Intergovernmental Panel on Climate Change (IPCC 2018) projects that global warming is on track to reach 1.5 °C between 2030 and 2052 if the current trajectory persists. These predictions and heightened awareness have captured the attention of researchers, leading to a growing emphasis on studies aiming to propose solutions for mitigating human-induced global warming and its potentially adverse consequences. Therefore, climate change, driven by CO_2 emissions, disrupts ecosystems and threatens biodiversity. Many species struggle to adapt to rapidly changing temperatures and habitats. By reducing CO_2 emissions, we can help protect ecosystems and preserve the delicate balance of nature. Reducing CO_2 emissions is essential for slowing down the pace of climate change and mitigating its severe consequences, including more frequent and severe heatwaves, droughts, floods, and storms (Kartal et al. 2023).

Global carbon emissions from fossil fuels have significantly increased since the birth of the industrial revolution (Statista 2023a). Global CO_2 emissions have increased by about 64% in 2022 (37.49 $GtCO_2$) compared to the level of CO_2 emissions in 1990 (22.76 $GtCO_2$) (Statista 2023b). CO_2 emissions began to rise more steeply from the 1950s and by 2000 had reached 25.45 billion metric tons of CO_2. Emissions soared 31.1 percent between 2000 and 2010, and in 2021, totaled 37.12 billion metric tons (Statista 2023a). In 2019, it was observed that nearly 84% of the world's primary energy is generated from fossil fuels. Among them, oil has the largest share, with 33.1%, followed by coal at 27% and gas at 24.1% (Ritchie and Roser 2020). While countries focus on expanding renewable energy and using decarbonized fuels to reduce environmental degradation (Le et al. 2021), oil is still an essential source for several economic sectors, including transportation, industry, and electricity production. It propels vehicles, aircraft, ships, and other equipment, making it essential for modern industrial processes and everyday life. Besides, oil remains the main emitter of carbon emissions as the dominant energy source. The emissions from oil increased by 2.5% (268 Mt), reaching 11.2 gigatons in 2022 (IEA 2023). Nonetheless, it is important to recognize that even though oil has played a pivotal role in fostering economic growth over a long period, there is an increasing awareness of the imperative to move towards energy sources that are more environmentally friendly and sustainable. This shift is propelled by apprehensions about climate change, air quality degradation, and the limited availability of fossil fuels. Consequently, the world economy is progressively moving towards heightened energy efficiency and embracing renewable energy options.

The argument is that the volatility of oil prices has contributed to the increasing appeal of renewable energy to reduce reliance on oil, but this transition poses challenges. These challenges are not confined to oil-importing nations; oil-exporting countries are also grappling with them, particularly following sharp drops in oil prices in 2008 and 2014 (Deniz 2019). Omri et al. (2015) have discovered a positive and statistically significant impact of oil price changes on renewable energy consumption in the case of 64 countries (including developed and developing countries). In addition, Troster et al. (2018) found the presence of lower-tail dependence from fluctuations in oil prices to changes in the consumption of renewable energy. Similarly, Apergis and Payne (2014a) in the case of 25 OECD countries, Nguyen and Kakinaka (2019) for both low- and high-income countries, Deniz (2019) in the case of oil-importing countries, Padhan et al. (2020) in the case of OECD members, Bamati and Roofi (2020) in the case of developing and developed countries, have reached similar conclusions. However, oil-exporting nations face a different scenario. Higher oil prices may result in more government income for nations largely dependent on oil exports and economic growth. Increased energy use across several industries due to this economic expansion may result in greater CO_2 emissions.

Conversely, during periods of high oil prices, these oil-exporting countries may choose to invest their oil revenues in renewable energy projects to boost renewable consumption. Alternatively, they can export oil products while simultaneously promoting domestic renewable consumption to increase overall renewable energy usage. As a result, these lead to a decrease in CO_2 emissions. For instance, studies by Deniz (2019) for oil exporting countries, Mukhtarov et al. (2020) for Azerbaijan, Karacan et al. (2021) for Russia, Mukhtarov et al. (2021) for Kazakhstan, Mukhtarov et al. (2022) for Iran found a negative and statistically significant impact of oil prices on renewable energy consumption. It implies that when oil prices are high, resource-rich countries often have ample resources and may provide subsidies to domestic energy users. This results in increased consumption of conventional energy and reduced incentives for considering alternative sources, ultimately leading to increased CO_2 emissions.

Oil-producing nations often boost their oil output in response to higher oil prices to capitalize on the heightened potential for revenue. This may result in increased exploitation activities, which may contribute to the formation of hydrocarbon reserves that are more detrimental to the environment and carbon intensive. Oil-exporting nations are significantly dependent on oil export revenue to sustain their economies. During periods of elevated oil prices, these nations often see a surge in economic expansion and heightened levels of industrial development. The acceleration of industrialization, particularly in the absence of rigorous environmental controls, may lead to elevated CO_2 emissions from industrial activities. Besides, oil-exporting nations may have less financial motivation to engage in energy-saving initiatives while oil prices are high. It's possible that the goal is to maximize oil revenue rather than put policies in place to reduce energy use and related emissions. In addition, several empirical studies have revealed that the increase in oil prices in oil-exporting countries leads to an increase in CO_2 emissions. Thus, Mrabet et al. (2017), Mensah et al. (2019), Mahmood et al. (2020), Ghazouani (2021), Aljadani et al. (2021), Mahmood et al. (2022), found that an increase in oil prices leads to environmental degradation. Therefore, renewable energy has the potential to serve as a protective shield, helping to mitigate the positive impact of oil prices on CO_2 emissions in the case of oil-rich countries. It is crucial to conduct specific studies for oil-rich countries. Although there are some papers Ebaid et al. (2022) for GCC countries, including Saudi Arabia, Okwanya et al. (2023), in the case of African countries (including oil-exporting ones as well), concluded that an oil price increase reduces CO_2 emissions in oil-exporting countries, the number of studies with the opposite findings dominate. For Saudi Arabian case Aljadani et al. (2021)

and Mahmood et al. (2020, 2022) concluded that, oil prices expansion increases CO_2 emissions. Having increasing impact of oil prices on CO_2 emissions for the oil-exporting nations seems more convincing, but the question is whether these nations are successful in transitioning these circumstances for better environmental conditions. In other words, considering the intriguing results between oil price and environmental quality in the literature, this paper seeks to explore if higher oil prices are good or bad for oil-rich countries' environmental quality and if there is a practice to be learnt from Saudi Arabian case.

Due to its high dependence on fossil fuels, especially oil, for both internal energy use and export, Saudi Arabia has traditionally been one of the world's greatest (8th place) CO_2 emitters (Kingdom of Saudi Arabia 2018; Statista 2023c). The economy has a strong interdependence on the oil industry. Oil exports accounted for about 76.1% of total exports in August 2023 (General Authority for Statistics 2023). The tremendous industrialization and urbanization of Saudi Arabia over the last several decades have significantly increased CO_2 emissions. Thus, in 2021, Saudi Arabia's CO_2 emissions amounted to 586.4 million tons. CO_2 emissions in Saudi Arabia witnessed a substantial rise, climbing from 75.9 million tons in 1972 to 586.4 million tons in 2021, with an average annual growth rate of 4.65% (Knoema 2023).

Saudi Arabia has taken measures to diversify its energy balance and increase energy efficiency in response to the pressing need to combat climate change and reduce carbon emissions. This involves making investments in clean energy sources like solar and wind energy. Saudi Arabia, as a participant in the Paris Agreement, has presented its nationally determined contribution (NDC) to align with the agreement's objective to restrict the increase in the worldwide average temperature to under 2 degrees Celsius and strive for a target as close as feasible to 1.5 degrees Celsius. In its initial nationally determined contribution (NDC), Saudi Arabia committed to an annual reduction of 130 million tons (Mt) of CO_2 equivalent (CO_2eq) in GHG emissions by the year 2030 (Kingdom of Saudi Arabia 2015). In accordance with the Paris Agreement, Saudi Arabia has also revised its nationally determined contribution and committed to more challenging goals for reducing GHG emissions. In its updated NDC, the country pledged to decrease GHG emissions by 278 MtCO_2eq annually by 2030 (Kingdom of Saudi Arabia 2021. Furthermore, Saudi Arabia has recently aspired to attain net-zero emissions by 2060 (Arab News 2021). Despite all this, Saudi Arabia would need to decrease its emissions levels by less than 389 million metric tons of CO_2 equivalent (MtCO_2e) by 2030 and below 263 MtCO_2e by 2050 to meet its emissions targets in line with a 'fair-share' approach compatible with the global 1.5 °C goal (Climate Transparency 2020). Therefore, Saudi Arabia, as a major global oil producer, is working to strike a balance between economic growth, energy consumption, and environmental sustainability (Belaïd and Mikayilov 2024).

Considering all these points, it is important to investigate how the positive effects of oil prices on CO_2 emissions can be absorbed by the expansion of renewable energy in the case of Saudi Arabia. Notably, there is a dearth of studies that specifically investigate how the positive impact of oil prices on CO_2 emissions can be mitigated through the expansion of renewable energy in the case of oil-rich countries. To address this gap, the present study aims to explore key research questions: (1)

does transition to renewable energy use lower the impact of international oil prices on CO_2 emissions in the Saudi Arabian case? (2) does oil price increase CO_2 emissions in Saudia Arabia?; and, (3) How does GDP influence the CO_2 emissions in Saudia Arabia?

The paper contributes to understanding energy dynamics in the Kingdom of Saudi Arabia. To the best of our knowledge, this study is the first to assess if the transition to renewable energy consumption lowers the impact of international oil prices on CO_2 emissions in Saudi Arabian. Secondly, from an empirical standpoint, we utilized conventional econometric methods and the Functional Coefficient (FC) approach. The FC approach models coefficients as a polynomial function of other variables and estimates these varying coefficients using various parametric and non-parametric methods (see Fan and Zhang 2008, among others). In addition, this study highlights that Saudi Arabia has managed to promote and utilize renewable energy in a way to dampen the impact of international oil prices on CO_2 emissions. This result shows the potential for Saudi Arabia to substantially mitigate its CO_2 emissions by investing in renewable energy sources. These renewable energy projects are targeted to serve to better environmental quality through the carbon credits as well (Arab News 2023). The study also finds that the growth trajectory brought by oil prices is well managed in a way that mitigates the impact on environmental quality. Finally, the findings of study have essential policy implications for the region's interest in sustainable energy strategies.

The remaining part of the paper is structured as follows: Sect. 2 provides the background of renewable energy in Saudi Arabia. Section 3 presents the reviewed literature. Section 4 give the applied methodology and used data. Section 5 presents the results of empirical analyses, and Sect. 6 discusses the results. The last section concludes and provides policy suggestions.

2 Renewable energy in Saudi Arabia

Saudi Arabia aims, by 2030, a target of a 50% contribution from renewable energy to its overall electricity generation (Gulf Research Center 2022). The 'Saudi Vision 2030,' revealed in 2016, outlines goals such as increasing the portion of non-oil exports from 16 to 50% of export value by 2030 (Mordor Intelligence 2023). Furthermore, the vision emphasizes the growth of renewable energy within the country's energy framework and the domestic localization of both the renewable energy and industrial equipment sectors (Mordor Intelligence 2023). In 2016, the government announced its objective to attract investments ranging from US$30 to $50 billion in renewable energy by 2023, including contributions from the private sector (Gulf Research Center 2022).

The government of Saudi Arabia aims to reduce its heavy reliance on oil for power generation and intends to generate one-third of the country's electricity from solar sources. This shift increased the demand for solar energy and, consequently, for the renewable energy sector in the nation, making it the dominant player in 2020 among other renewable energy types. The Saudi Arabian Government's 2030 goal involves the establishment of 40 GW of solar photovoltaic (PV) capacity and 2.7

GW of concentrated solar power (CSP) capacity (Mordor Intelligence 2023). In November 2021, the Haradh solar farm, with a capacity of 30 MW, became operational, supplying electricity to the National Agricultural Development Co. under a 25-year power purchase agreement at a rate of SAR 0.094 per kWh. Additionally, in August 2021, ACWA Power successfully concluded financial arrangements for the 1.5 GW Sudair solar photovoltaic power plant in Sudai Industrial City, marking the initial project under the Public Investment Fund's renewable energy program (Mordor Intelligence 2023). In early 2020, Saudi Arabia initiated the third round of its renewable energy program, aiming to add 1.2 gigawatts of solar photovoltaic power capacity to the grid, with six solar energy projects of a combined capacity of 1.2 GW open for bidding (Growth Market Reports 2022). ACWA Power and NEOM are gearing up to establish a green hydrogen facility fueled by solar and wind energy. This facility is poised to generate 660 tons of green hydrogen daily, a quantity comparable to the current annual global production. The produced green hydrogen will undergo conversion into liquid ammonium and subsequently be transported to Asia, with a focus on South Korea and Japan (International Trade Administration 2021). Consequently, considering these factors, the solar energy segment is anticipated to dominate the renewable energy market in Saudi Arabia in the near future (Mordor Intelligence 2023). Figure 1 presents the installed capacity of the solar energy.

As a result of implemented policies by Saudi Arabia, renewable energy consumption has increased. As can be seen in Fig. 2, the share of renewable energy consumption in total consumption increased from 0.01% to 0.06% during 2016–2020 (World Bank 2023).

In addition, the increase in renewable energy consumption is clearly observed in Fig. 3. Thus, energy consumption increased rapidly in the last period, reaching 9148.42 kilotons of oil equivalent (ktoe) in 2020.

In its pursuit of achieving net-zero emissions by 2060 (Arab News 2021), Saudi Arabia is intensifying its tender processes to augment renewable power capacity integrated into its power grid. The nation is currently advancing 13 renewable energy projects with a combined capacity of 11.3 GW. Notably, the

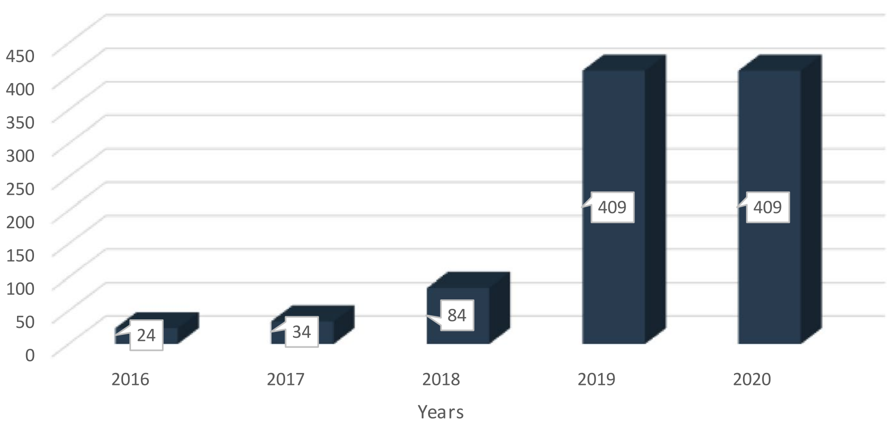

Fig. 1 Solar energy installed capacity (unit is MW). Source: Mordor Intelligence (2023)

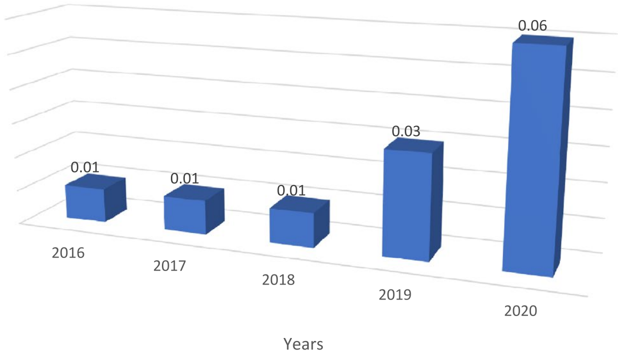

Fig. 2 Renewable energy consumption (% of total final energy consumption). Source: World Bank (2023)

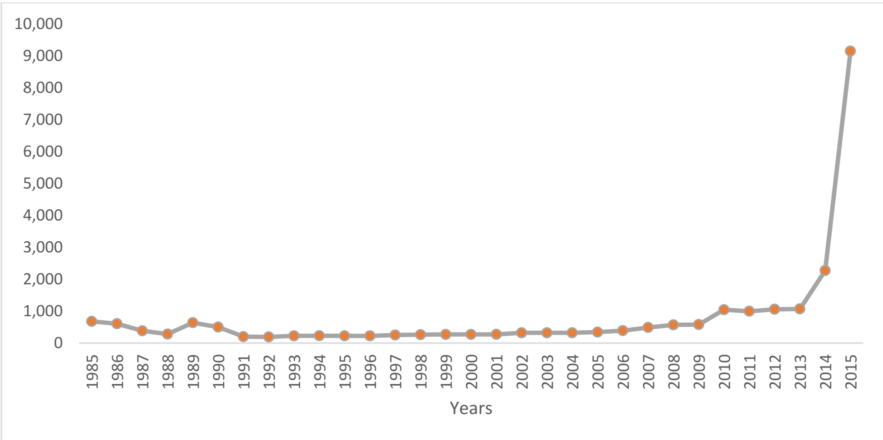

Fig. 3 Renewable energy consumption. Source: Authors' calculation based on IEA (2022). (Unit is ktoe.)

largest among these initiatives, the 2.6 GW Al Shuaibah solar plant, has progressed further, having secured financing led by the National Development Fund on August 20, 2023 (Gnana 2023). In May 2023, Saudi Arabia's Water and Electricity Holding Co. (Badeel) and ACWA Power inked deals with the Saudi Power Procurement Co. for three extensive solar initiatives, boasting a total capacity of 4.55 GW. The projects, namely Ar Rass 2, Saad 2, and Al Kahfah, are anticipated to yield capacities of 2.0 GW, 1.1 GW, and 1.4 GW, with a cumulative worth of Riyals 12.2 billion (Gnana 2023). The King Salman Renewable Energy Initiative, a part of Saudi Arabia's Vision 2030, aims to reach 58.7 GW (40 GW solar PV, 16 GW wind, and 2.7 GW CSP) by 2030 (Gnana 2023).

Hence, the anticipated shift by Saudi Arabia in reconfiguring its economy to reduce dependence on oil is projected to propel the market soon (Mordor Intelligence 2023).

3 Literature review

Numerous research studies examine how oil prices (OP) affect CO_2 emissions across various countries (e.g., Adebayo and Kartal 2023; Kartal et al. 2024). A few studies examine this relationship in the case of Saudia Arabia. Mahmood et al. (2020) examined the effects of oil prices and urbanization on carbon emissions in Saudia Arabia from 1980 to 2014, applying the ARDL technique. The findings indicated that oil prices and urbanization exerted statistically significant positive effects on CO_2 emissions. Another study conducted by Mahmood et al. (2022) explored the influence of OP on CO_2 emissions and revealed its positive impact on oil prices in Saudia Arabia. On the other hand, Ebaid et al. (2022) found that the negative impact of oil prices on CO_2 emissions was revealed for GCC countries (including Saudi Arabia). In this section, we extend our examination to encompass studies that investigate the influence of oil prices on CO_2 emissions across various countries. We summarize the reviewed studies in Table 1 to enhance readability without sacrificing brevity.

As seen in Table 1, most of the studies found a positive effect of oil prices on carbon emissions in oil-exporting countries. On the other hand, in many studies conducted in the case of oil-importing countries, this relationship has been revealed to be negative. As shown in Table 1, the literature review reveals a lack of time-series studies to investigate how the positive effects of oil prices on CO_2 emissions can be absorbed by the expansion of renewable energy in the case of oil-rich countries. This research aims to bridge this gap by investigating whether renewable energy consumption can mitigate the impact of international oil prices on CO_2 emissions in Saudi Arabia, utilizing both conventional econometric approaches and the functional coefficient approach.

4 Methods

4.1 Methodology

Numerous studies have examined CO_2 emissions, frequently utilizing frameworks like the Environmental Kuznets Curve (EKC) and STIRPAT, which predominantly emphasize the roles of income and population. However, these frameworks have notable limitations, as highlighted by scholars such as Tisdell (2001), Ezzati et al. (2001), Dinda (2004), Brock and Taylor (2010), Hasanov et al. (2021), and Berk et al. (2022). In response, researchers including Criado et al. (2011), Berk et al. (2022) and Brock and Taylor (2010) advocate for more comprehensive and theoretically robust models. Recent investigations by Mrabet et al. (2017), Mensah et al. (2019), Mahmood et al. (2022), Abumunshar et al. (2020), Aljadani

Table 1 A summary of reviewed empirical studies

Author(s)	Time Period	Scope	Methodology	Impact of OP on CO_2 emissions
Sadorsky (2009)	1980–2005	G7 countries	Panel cointegration	Strong evidence of cointegration
Apergis and Payne (2014b)	1980–2010	7 Central American countries	Panel cointegration	Strong evidence of cointegration
Balaguer and Cantavella (2016)	1874–2011	Spain	ARDL	N&S
Mrabet et al. (2017)	1980–2011	Qatar	ARDL	P&S on ecological footprint,
Nwani (2017)	1971–2013	Ecuador	ARDL	P&S
Zhou (2018)	1983–2013	US	Granger causality test	bi-directional causality between OP and CO_2
Agbanike et al. (2019)	1971–2013	Venezuela	ARDL	N&IS
Boufateh (2019)	1976–2013	China and USA	ARDL	P&S for China; N&S for USA
Mensah et al. (2019)	1990–2015	22 African countries	PMG	P&S for both oil-exporting and non-oil-exporting African countries
Abumunshar et al. (2020)	1985–2015	Turkey	ARDL, DOLS, CCR, and FMOLS	N&S
Chaudhry et al. (2020)	1975–2018	Pakistan	Nonlinear ARDL	N&S
Mahmood et al. (2020)	1980–2014	Saudi Arabia	ARDL	P&S in Long-run
Malik et al. (2020)	1971–2014	Pakistan	ARDL	N&S
Aljadani et al. (2021)	1970–2020	Saudi Arabia	ARDL, N ARDL	P&S
Alkathery and Chaudhuri (2021)	January 02, 2013–March 20, 2019	Kuwait, Saudi Arabia, and the United Arab Emirates	multivariate GARCH	presence of volatility spillover impacts and co-movement among variables
Ghazouani (2021)	1972–2016	Tunisia	ARDL	P&S
Husaini et al. (2021)	2010–2018	20 Asian oil-producing countries	Threshold effect test	N&IS
Mujtaba and Jena (2021)	1986–2014	India	Nonlinear ARDL	P&S
Ali et al. (2022)	1990–2019	South Africa	ARDL	N&S
Ebaid et al. (2022)	1996–2016	Six (GCC) countries	Panel DOLS and FMOLS	N&S
Habeşoğlu et al. (2022)	1981–2015	Turkey	FMOLS, CCR, DOLS, and ARDL	N&S

Table 1 (continued)

Author(s)	Time Period	Scope	Methodology	Impact of OP on CO_2 emissions
Mahmood et al. (2022)	1980–2019	GCC	Nonlinear ARDL	P&S for Oman, Qatar, and Saudi Arabia;
Rasheed et al. (2022)	1997–2017	30 European countries	Panel FMOLS	N&S
Sreenu (2022)	1990–2020	India	ARDL	P&S

CCR canonical cointegrating regression, *DOLS* dynamic ordinary least squares, *FMOLS* fully modified ordinary least squares, *OP* oil price, *N&S* negative and statistically significant, *N&IS* negative and statistically insignificant, *P&S* positive and statistically significant, *GCC* Gulf Cooperation Council, *ARDL* autoregressive distributed lags bounds testing, *PMG* pooled mean group et al. (2021), Ghazouani (2021), Mahmood et al. (2022) and Ali et al. (2022), have integrated oil price variables to enhance the analysis of CO_2 emissions. Additionally, Jin and Kim (2023) suggested a novel approach to understanding the role of renewable energy in hedging against fluctuations in international oil prices. They revealed that rising oil prices constitute an economic risk that can reduce gross output, whereas the consumption of renewable energy serves as a mitigating factor against the adverse effects associated with oil price volatility. Considering the above-mentioned studies, the research question is to discover if the transition to renewable energy use lowers the impact of international oil prices on CO_2 emissions in the Saudi Arabian case. This is investigated via econometric estimation techniques. Precisely, we are estimating the below relationship:

$$\begin{aligned} Ln(CO2PC_t) = \alpha_0 + \alpha_1 Ln(GDPPC_t) + \alpha_2 Ln(OilPrice_t) \\ + \alpha_3 Ln(REPC_t) * Ln(OilPrice_t) + \varepsilon_t. \end{aligned} \tag{1}$$

CO_2PC = per capita CO_2 emissions, GDPPC = per capita GDP, Oil Price = international oil price, and REPC = per capita renewable energy consumption ε_t is an error term of the econometric model. Ln stands for the natural logarithm. As an oil exporting country, the sign of α_2 is expected to be positive for Saudi Arabia. The aim is to explore if the transition toward renewable energy sources mitigates the impact of international oil prices on CO_2 emissions. In other words, we will test if the sign of α_3 is negative and statistically significant. Mathematically, we treat oil price elasticity as a linear function of renewable energy consumption. The relationship in Eq. (1) is used for econometric estimations. Explicitly, if we denote the elasticity by η_t, then,

$$\eta_t = \frac{\partial(CO2PC_t)}{\partial(OilPrice_t)} * \frac{OilPrice_t}{CO2PC_t} = \alpha_2 + \alpha_3 Ln(REPC_t) \tag{2}$$

The relationship (1) can be estimated by conventional econometric approaches (e.g., Burnside and Dollar 2000; Jin 2022; Jin and Kim 2023), as well as utilizing the functional coefficient approach. Namely, we have applied the dynamic ordinary least squares (DOLS, Saikkonen 1992; Stock and Watson 1993), fully modified ordinary squares (FMOLS, Hansen 1992a, b; Phillips & Hansen 1990), canonical cointegration regression (CCR), and bounds testing approach to autoregressive model with distributed lags (ARDLBT, Pesaran et al. 2001; Pesaran and Shin 1999) to estimate Eq. (1). As a robustness check, we also utilized the Functional Coefficient (FC) approach (Cai et al. 2000; Fan and Zhang 2008, inter alia). The FC approach treats coefficients as a polynomial function of other variables and estimates the varying coefficients via different parametric and non-parametric techniques (see Fan and Zhang 2008, inter alia). In our case, the oil price elasticity of CO_2 emissions is treated as a function of renewable energy consumption under the FC approach. Due to its better statistical properties, we utilized the DOLS approach as a main approach in our estimations (DOLS, Saikkonen 1992; Stock & Watson 1993).

The stationary properties of the used variables have been checked with augmented Dickey and Fuller (ADF) tests (Dickey & Fuller 1981). The existence of a cointegration relationship is examined via Engle-Granger (Engle & Granger 1987) and Bounds (Pesaran et al. 2001; Pesaran & Shin 1999) tests for cointegration.

4.2 Data

The study uses data spanning from 1984 to 2020. CO_2 emissions data is taken from EnerData (2022), Gross Domestic Product data (GDP) and oil price for Arabian light from SAMA (2022), renewable energy consumption share is from International Energy Agency (2022) and applied to the total energy consumption data (IEA 2022) to calculate renewable energy consumption (RE) data. CO_2 emissions data expresses CO_2 emissions without LULUCF (in million tonnes). GDP is the real GDP in millions of 2010 SAR. Oil price is in US Dollars per barrel, in real terms. Oil price was in 2005 values. It was rebased by the authors using OPEC basket deflator. Total energy consumption data is final energy consumption, excluding non-energy use, in ktoe. CO_2, GDP, and renewable energy consumption are expressed per capita using population data from the UN (2022). Figure 4 demonstrates CO_2 emissions and GDP data in per capita terms.

5 Empirical results

Using time series data, first, the stationarity properties of the variables are examined. The results of unit-root tests are presented in Table 2. The ADF test takes the maximum lag number four and selects the optimal lag number via the Schwarz information criteria.

The unit-root test results from Table 2 conclude that all variables under investigation become stationary after taking the first difference. Therefore, the long-run co-movement of the variables can be tested in the next step. To test for

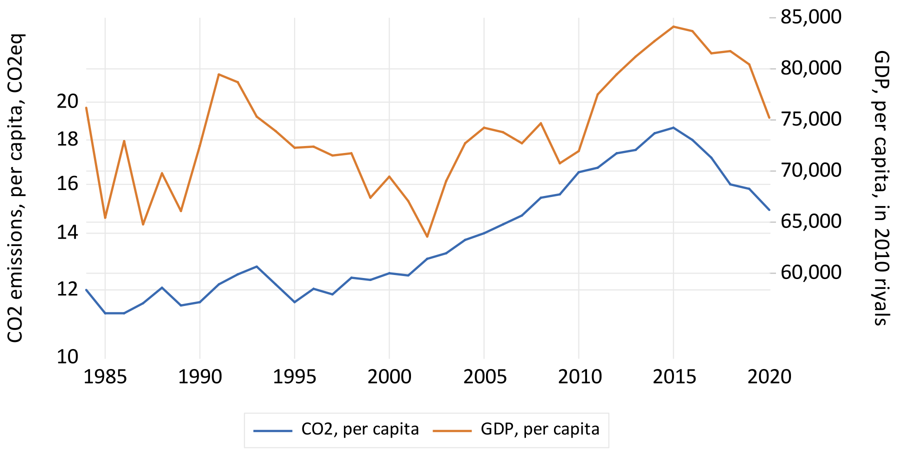

Fig. 4 CO_2 emissions and GDP visualization (Unit is per capita terms). Source: authors based on EnerData (2022) and SAMA (2022). GDP data on the right axis

Table 2 Unit root test results

	CO_2PC	GDPPC	OIL PRICE	REPC
Level	– 0.863	– 2.366	– 1.818	0.650
1st difference	– 4.544***	– 9.049***	– 5.669***	– 3.619**

Differenced = first difference; *** and ** stand for the rejection of the null hypothesis at 1% and 5% significance level

Source: estimation results

Table 3 Results of the cointegration tests

Test type	Engle-Granger test	Bounds test
Test statistics	– 40.290***	5.818**

The null hypothesis for both tests are" Series are not cointegrated." *** and ** = rejection of the null hypothesis at a 1%, and 5% significance level, respectively

Source: estimation results

Table 4 Results of the econometric estimations

	DOLS	FMOLS	CCR	ARDL
GDPPC	0.676***	0.698***	0.786***	0.769***
OILPRICE	0.188***	0.119***	0.125***	0.157***
REPC*OILPRICE	– 0.018***	– 0.009**	– 0.013**	– 0.02**
Trend	0.006***	0.008***	0.008***	0.009***

*** and ** for rejecting the null hypothesis at a 1% and 5% significance level, respectively

cointegration relationships, the Bounds Testing Approach, and the Engle-Granger tests were utilized, and the results are shown in Table 3. The test statistics from the Engle-Granger tests reject the null hypothesis that the series are not cointegrated. Additionally, if the calculated F-statistic exceeds the critical values for the upper bound, the null hypothesis of "Series are not cointegrated." is rejected. Therefore, the findings from the both cointegration test confirm the existence of a long-run cointegration relationship between the variables.

The results from different estimation techniques are presented in Table 4.

The maximum lag is taken as two for the dynamic approaches, DOLS and ARDL BT, and the optimal lag is selected using the Schwartz information criteria (Schwarz 1978). The estimated models meet the diagnostic tests for model adequacy. We do not report the diagnostic tests' results to save space, but they are available upon request. As can be seen from Table 4, all applied estimation methods have produced quite similar results. The magnitudes of the estimated parameters are close to each other across the employed estimation approaches. It is found that the impact of interactive terms (product of renewable energy consumption and international oil price) is negative and statistically significant for all methods. For the income elasticity, a positive, statistically significant relationship is found. The magnitude of the estimated income elasticity of CO_2 emissions does not substantially differ across utilized techniques. It is also worthy to note that, to avoid potential endogeneity problem we have estimated the relationship (1) utilizing Two-Stage Least Squares estimation technique. The estimations produce similar outcomes.

6 Discussion

The estimation techniques concluded that the oil price elasticity of CO_2 emissions is a decreasing/non-increasing function of renewable energy. This finding lets us conclude that deploying renewable energy reduces the impact of international oil prices on CO_2 emissions in the Saudi Arabian case. To investigate further, Fig. 5 presents values of oil price elasticity versus logarithmic values of per capita renewable energy consumption.

As seen in Fig. 5, the elasticity indeed decreases over time when more renewable energy is used. To explore the behavior of the oil price elasticity over time, Fig. 6 presents the elasticity values versus time.

As from Fig. 6, the elasticity is decreasing over time except for a few observations. The declining oil price elasticity of CO_2 emissions over time is mainly in line with what we have seen in Fig. 3 since renewable energy consumption is increasing over time. As the largest nation in the Middle East, Saudi Arabia holds a crucial position in achieving global climate objectives (Belaïd and Massié, 2023). The Saudi government has taken significant steps to cut carbon emissions, including launching the Vision 2030 Plan in 2016, which seeks to foster sustainable economic growth and balance the budget by boosting both oil and non-oil revenue (Vision 2030, 2022; Belaïd and Massié, 2023). Saudi Arabia has set a goal for renewable energy to make

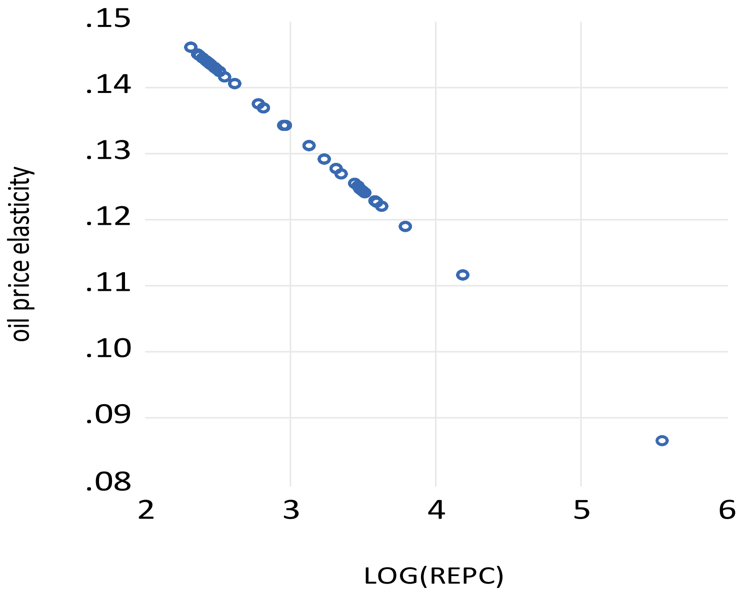

Fig. 5 Oil price elasticity of CO_2 emissions vs renewable energy consumption. Source: estimation results

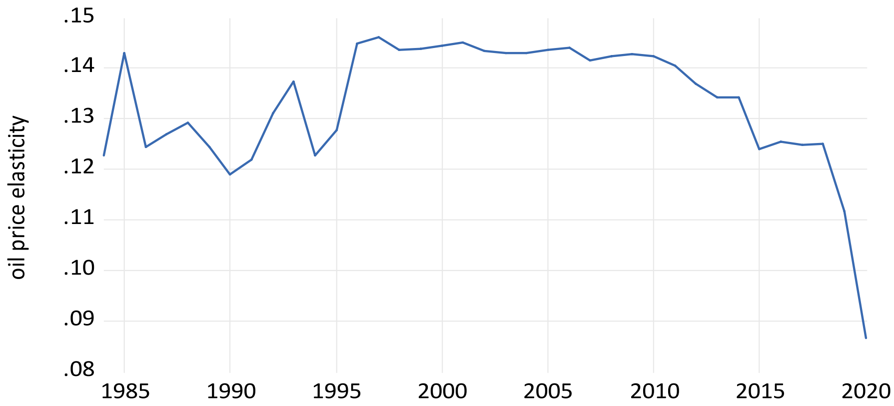

Fig. 6 Oil price elasticity of CO_2 emissions over time. Source: estimation results

up 50% of its total electricity generation by 2030 (Gulf Research Center 2022). In 2016, the government set a goal to attract between US$30 and $50 billion in renewable energy investments by 2023, with support from the private sector (Gulf Research Center 2022). Additionally, In 2021, Saudi Arabia pledged to reach carbon neutrality by 2060, signaling its intention to lead the global shift toward a low-carbon economy (Belaïd and Al-Sarihi 2022; Belaïd and Massié, 2023). Saudi Arabia is ramping up its tender processes to expand the renewable energy capacity in its power grid as part of its goal to reach net-zero emissions by 2060 (Arab News 2021). The country is currently progressing with 13 renewable energy projects, totaling 11.3 GW in capacity (Gnana 2023).

Another result concluded from Fig. 6 is that the decline became more evident over the last years. This is a natural result of the substantial increase in renewable energy deployment in recent years. Renewable energy and oil can be considered as substitute goods for generation of energy. Increasing the proportion of renewable energy in the overall energy consumption results in a reduced percentage of energy derived from fossil fuels, leading to a decrease in CO_2 emissions. The assumption here is that the rise in energy demand is fulfilled by renewable sources, while the quantity of fossil fuel energy decreases. Consequently, there is a growth in both renewable energy usage and its contribution to the total energy mix. Ceteris paribus, the volume of fossil fuel energy and, consequently, CO_2 emissions decrease.[1] As the use of renewable energy sources increases over time, the substitution effect is reinforced, resulting in a reduced sensitivity of oil demand to fluctuations in its price, consequently, decreases an oil price elasticity of CO_2 emissions.

As mentioned in the Methodology section, we have employed the Functional Coefficient approach as a robustness check. Like the other approaches, the oil price elasticity of CO_2 emissions is treated as a linear function of renewable

[1] In this context, we assume that CO_2 emissions stem from fossil fuels. This assumption is reasonable, considering that approximately 87% of the total CO_2 emissions originate from fossil fuel sources (DeepMarket 2023).

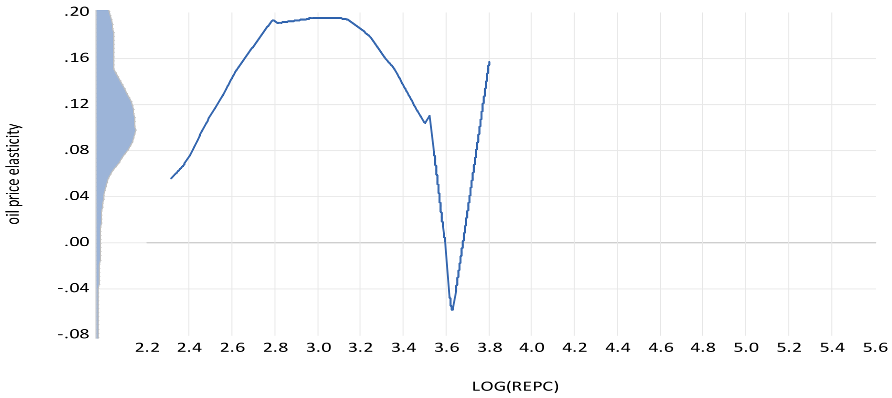

Fig. 7 Oil price elasticity of CO_2 emissions vs. renewable energy consumption, functional-coefficient approach. Source: estimation results

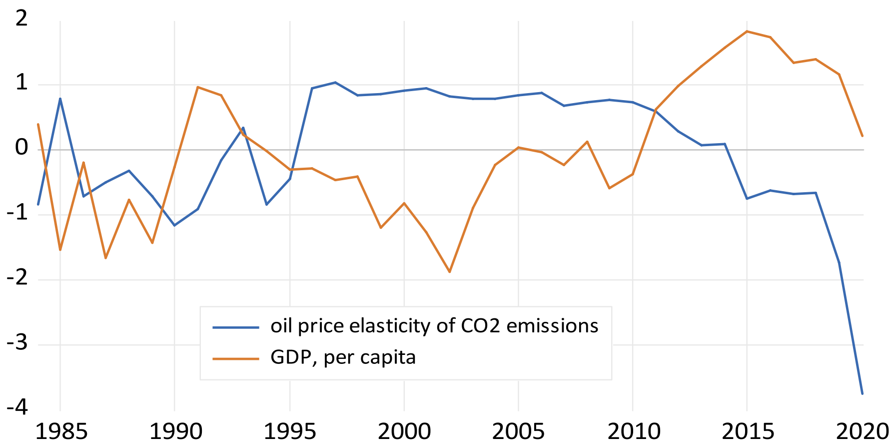

Fig. 8 Oil price elasticity of emissions and GDP per capita, normalized scale. Source: estimation results

energy consumption. We have also treated elasticity as a quadratic and cubic function of renewables, but these estimations did not produce reasonable outcomes. Hence, we only discuss the linear case. The estimated oil price elasticity of CO_2 emissions from the FC approach is presented in Fig. 7.

Figure 7 shows that elasticity is mainly a decreasing function of renewable energy consumption. The last observation that increases is the value corresponding to 1990 and does not demonstrate the recent elasticity behavior. Summarizing the findings, we conclude that deploying renewable energy lowers the impact of international oil prices on CO_2 emissions in the Saudi Arabian case. To assess the finding from a different perspective, Fig. 8 compares the trajectory of oil price elasticity of emissions and GDP per capita. To avoid the scale problem, both variables are expressed in a normalized scale.[2]

Figure 8 helps us to elaborate on the coupling/decoupling of the response of Saudi CO_2 emissions to international oil prices and per capita GDP. In other words, does the economic reinvigoration driven by international oil prices bring an economic development path followed by higher emissions? If the trajectory of oil price elasticity of CO_2 emissions and per capita GDP follow each other, it means increased revenues are "encouraging" the emissions-intensive development path. As can be seen from Fig. 8, from the early 2000s until 2015, the two are mowing in totally different directions. This could be interpreted as the economic growth path toward a less-emission-intensive environment. In other words, the modernization brought by oil prices is well managed in a way to mitigate the impact on environmental quality.

In addition, several empirical studies suggested that implicit carbon pricing strategies, such as raising energy prices or eliminating fossil fuel subsidies, are more appropriate and easier to implement in developing economies than explicit measures like carbon taxation or emissions trading systems (Aldy and Stavins 2012; Klenert et al. 2018; Hasanov et al. 2020; Mukhtarov 2022). Saudi Arabia's recently implemented implicit carbon pricing policies have significantly contributed to reducing carbon emissions. Hence, Saudi Arabia has implemented "Fiscal Sustainability Program". This program includes a series of energy price reforms aimed at aligning domestic energy prices with international market rates. These reforms were rolled out in two phases. The first phase, which targeted fuel, electricity, and water prices, was implemented on January 1, 2016. The second phase, focusing on gasoline and residential electricity, was introduced on January 1, 2018. As a result, gasoline prices tripled, and electricity prices doubled. These two programs also prevented approximately 164 million tonnes of CO_2 emissions between 2016 and 2018.

7 Conclusions and policy suggestions

7.1 Conclusion

Our research findings provide valuable insights into the complex relationship between renewable energy consumption, international oil prices, income, and CO_2 emissions in Saudi Arabia. These findings have worthy implications for policy development and the search for sustainable energy strategies in the region:

Our research consistently reveals that the interaction between renewable energy consumption and international oil prices has a negative and statistically significant impact on CO_2 emissions. This key finding indicates that Saudi Arabia can effectively lower its carbon emissions by investing in and implementing renewable energy sources. Renewable energy projects should be prioritized in policymaking as a tool to mitigate the environmental impact of fluctuations in oil prices.

[2] The conventional z-score normalization is used.

The research finds income's positive and statistically significant impact on CO_2 emissions. This finding implies the necessity of measures to be taken to decouple economic growth from emissions growth.

Moreover, the study reveals that from the early 2000s through 2015, the trajectories of oil price elasticity of CO_2 emissions and per capita GDP move in opposite directions. This disparity reflects a decoupling effect, in which economic expansion driven by rising oil prices does not imply increased emissions. This occurrence of decoupling suggests that the economic growth route, pushed by oil prices, has been well controlled to prevent negative consequences on environmental quality. It represents a concerted attempt to modernize the economy while reducing emissions intensity. This is a positive indication of Saudi Arabia's commitment to long-term development.

7.2 Policy suggestions

The efforts to invest in and promote the use of renewable energy sources should be intensified. This could be achieved through expanding solar and wind energy projects since they offer abundant regional resources. This transition process could be sped up by encouraging private sector involvement and offering incentives for renewable energy adoption.

Reducing the country's reliance on fossil fuels for electricity generation should remain a top priority. To realize this objective, Saudi Arabia targets deploying 50% renewable and 50% natural gas in the power generation energy mix by 2030.

To conclude, our research highlights the potential for Saudi Arabia to employ renewable energy as a powerful tool for lowering the impact of international oil price fluctuations on CO_2 emissions. While economic growth remains essential, navigating this growth in a sustainable direction is vital. To facilitate this transition by establishing a favorable environment for renewable energy development, promoting energy efficiency, and incentivizing emissions reduction, policymakers could play a pivotal role. These policies can benefit the environment and provide long-term economic stability and energy security in Saudi Arabia.

Lastly, it's important to acknowledge the limitations of this study, which could pave the way for future research opportunities: (1) we tested this research question specifically in the context of Saudi Arabia, an oil-rich country. However, to further support this idea, it is essential to conduct analyses using a sample of additional oil-rich countries to gather more evidence. (2) The data used in this study extends only up to 2020, so the effects of geopolitical risks resulting from the Russia-Ukraine war and recent conflicts in the Middle East are not considered in the analysis. It would be beneficial for future studies to take these factors into account.

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Declarations

Conflict of interest The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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