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RESEARCH ARTICLE

Income, coal consumption, and the environmental Kuznets curve in Vietnam

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Abstract

Concerns over adverse environmental effects have been raised due to Vietnam's reliance on fossil fuels like coal. At the same time, efforts are being made to boost the usage of renewable energy while simultaneously lowering greenhouse gas emissions. This study examines whether there is an environmental Kuznets curve (EKC) relationship between gross domestic product (GDP) and coal consumption in Vietnam by controlling for renewable energy consumption and oil prices from 1984 to 2021. We adopt the autoregressive distributed lag (ARDL) framework to explore a long-run level relationship between the study variables. We find that the GDP elasticity of coal demand has been greater than one since the 1990s and about 3.5 in recent years, indicating that the coal intensity of GDP has increased with economic growth. Thus, the GDP-coal consumption relationship resembles an upward-sloping curve instead of an inverted U-shaped EKC. This relationship is robust when we use other estimation methods and account for two additional independent variables. While a 1% rise in renewable energy consumption results in a 0.4% reduction in coal consumption, the impact of oil prices on coal consumption is negative but insignificant. The findings allow us to provide policy implications for the sustainable development of Vietnam: (1) more stringent policies, for example, enacting a carbon pricing scheme, are needed to reduce coal consumption; (2) policies should be implemented to make renewable energy sources more affordable; and (3) as facing high oil prices, the country should diversify its energy mix by expanding the usage of renewable energy.

Keywords Coal consumption · Economic growth · Renewable energy · Oil prices

Introduction

The EKC hypothesis has been a well-known empirical phenomenon by economists since the 1990s. One of the primary interests in this literature is whether environmental degradation increases or decreases when per capita income rises. An issue for the EKC analysis is choosing an appropriate proxy for environmental pollution. Apart from carbon dioxide emissions mainly used in the literature, several researchers look for one specific type of energy. When evaluating the EKC for China and Indonesia, some scholars advocate coal consumption as a proxy for environmental degradation (Hao et al. 2016; Hao et al. 2015; Kurniawan and Managi 2018; Qiao et al. 2019). Coal has been an essential part of these countries' energy mix due to its domestic availability and low cost, while most emissions are coal-related. These studies are critical for understanding the fundamental factors of coal consumption, which may give energy-specific policy recommendations to promote the sustainable development.

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In parallel to this literature, our paper tests whether the EKC hypothesis for coal consumption holds in Vietnam.

Over the last several decades, the rapid process of industrialization has brought about increased coal demand in Vietnam. Coal consumption has grown annually by about 8.15% over the 1984–2021 period. For the first time in 2019, Vietnam was one of the top ten coal-consuming countries, with more than half of electricity production coming from coal.[1] At COP26, Vietnam committed to achieving its net-zero climate target by 2050. While energy policies are carried out to replace coal with renewable energy through fiscal incentives (Nong et al. 2019; Do and Burke 2021), Vietnam's energy structure has still been dominated by coal (Shem et al. 2019; Clark et al. 2020; Dorband et al. 2020; Thong et al. 2021). The country depends on imported coal for energy needs and has been a net coal importer since 2015 (Thong et al. 2021). Besides, the Vietnamese economy has become susceptible to international energy price shocks (Apergis and Gangopadhyay 2020; Pham and Le 2020; Urom et al. 2023; Dagher and Hasanov 2023). Therefore, the main goal of this paper is to investigate the link between GDP and coal consumption in Vietnam while accounting for renewable energy consumption and oil price changes.

Recent attention among researchers and policymakers has been paid to the causes, effects, and solutions to the environmental pollution caused by energy consumption without harming the economic growth in emerging and developing countries (Chandio et al. 2020; Anwar et al. 2021; Bilgili et al. 2022; Shobande 2023). In this study, we attempt to provide the rationale behind the policy actions for the ecological sustainability of Vietnam. In particular, we argue that the GDP elasticity of coal demand is estimated based on the hypothesis of the EKC. While we acknowledge that future responses are less likely to repeat past ones, in this study, our GDP elasticity estimate of coal demand serves as a valuable benchmark for climate policy. If the GDP elasticity is above unity, coal intensity will increase with economic growth (coal consumption rises more rapidly than GDP). Therefore, policy interventions are needed to reduce coal consumption and related carbon emissions. By contrast, if the GDP elasticity is less than unity, coal intensity will reduce with economic growth (coal consumption grows more slowly than GDP). In this case, coal emission intensity reduction is achievable in the business-as-usual context, but policy interventions are still needed for carbon emission reduction. Furthermore, our study also examines how changes in renewable energy consumption and oil prices affect coal consumption. Behavioral responses to substitutes like renewables and oil have important implications for strategies to reduce coal usage and coal-related negative externalities.

[1] See the website: https://ourworldindata.org

We have used Vietnam's annual time series data over the 1984–2021 period. To take account of nonstationarity in time series data, we have applied a battery of unit root tests (augmented Dickey and Fuller test and Phillips and Perron test), cointegration tests (bounds testing procedure and residual-based cointegration test), and estimation methods (autoregressive distributed lag (ARDL), fully modified ordinary least squares (FMOLS), dynamic ordinary least squares (DOLS), and canonical cointegration regression (CCR)). We have also applied a recently developed technique to test and estimate structural breaks in the relationship between GDP and coal consumption. In the presence of the EKC hypothesis, there is at least one break in the link between these variables.

The contributions of this study are threefold. Firstly, this study adds to the literature by investigating whether the coal-induced EKC is valid in Vietnam. Though we are certainly not the first to conduct an EKC analysis in Vietnam, the mixed findings from previous studies call for further investigation. Unlike these studies, our research considers coal consumption a proxy for environmental pollution since coal is the leading energy source for electricity generation and the main contributor to carbon dioxide emissions in a rapidly growing economy like Vietnam (Finenko and Thomson 2014). Secondly, it is still unknown about the effect of economic growth and the substitution effects on coal consumption in a unified framework. Our study attempts to cover this gap by exploring the influences of renewable energy consumption, oil prices, and economic growth on coal consumption using recent time-series econometric techniques. Thirdly, we propose the three-step framework to test for a quadratic link between GDP and coal consumption. Few studies in Vietnam adopt such an appropriate procedure to investigate an EKC relation.

We have found that the significantly positive coefficient for per capita GDP squared is necessary but not enough to describe a U curve. The results in the two following steps show that the slope coefficients at both ends of the per capita GDP range are significantly positive and that the lower bound of the 95% confidence interval of the turning point is less than the minimum per capita GDP. Therefore, only the left half of the curve may be traced by the data. In such a case, the relationship may be monotonic but nonlinear, implying that the coal-induced EKC hypothesis does not hold in Vietnam. Moreover, renewable energy consumption is negatively associated with coal consumption, while oil price changes do not significantly affect coal consumption.

The remains of the paper are ordered as follows. While the "Literature review" section illustrates the related studies, the next two sections describe the model, data, methodology, results, and discussion. The "Robustness tests" section provides robustness tests. Conclusions and policy implications are given in the "Conclusion and policy implications" section.

Literature review

The early literature on the income-environment nexus builds on the inverted U-type EKC hypothesis, which states that environmental degradation grows at a diminishing rate and subsequently descends at an increasing rate with income. In their influential study, Grossman and Krueger (1995) explain this relation by combining the scale effect of economic activities with the composition and technique effects on polluting emissions. The latter two effects reflect the shift to less-polluting industries and technologies. The scale effect tends to dominate at low-income levels. Nevertheless, it is gradually overwhelmed by the composition and technique effects, so emissions begin to decrease as per capita income reaches certain levels (Dinda 2004; Stern 2004, 2017). Even though recent literature has thoroughly studied potential drivers of environmental pollution in addition to economic growth, there is no agreement on the existence of the EKC hypothesis. The findings from various studies might differ due to the choice of a proxy for environmental pollution and the inclusion of its determining variables (Inglesi-Lotz 2019; Sinha et al. 2019; Ajmi and Inglesi-Lotz 2021).

Selecting a suitable proxy for environmental degradation is one of the challenges facing the EKC investigation. Carbon dioxide is the most widely used in the literature (Dogan and Turkekul 2016; Rafindadi and Usman 2019; Shahbaz and Sinha 2019; Sharif et al. 2019; Sinha et al. 2020; Dogan and Inglesi-Lotz 2020; Ajmi and Inglesi-Lotz 2021; Anwar et al. 2021; Usman et al. 2021; Balsalobre-Lorente et al. 2022; Dogan et al. 2022; Cao et al. 2022; Zhang et al. 2022; Weimin et al. 2022) but not the only one. Because carbon dioxide is a global pollutant, it should be used when examining the EKC hypothesis for a large group of countries (Sinha et al. 2019). Several researchers suggest the use of energy consumption (Suri and Chapman 1998; Judson et al. 1999; Nguyen-Van 2010; Zhang et al. 2018; Lawson and Nguyen-Van 2021), carbon dioxide damage (Bilgili et al. 2022), ecological footprint (Ajmi and Inglesi-Lotz 2021; Murshed et al. 2021; Alvarado et al. 2021), and environmental quality indicator (Ahmad et al. 2022).

A small but rising body of literature contends that coal consumption should be used as a proxy for environmental deterioration. For instance, Hao et al. (2015) and Qiao et al. (2019) show that there is evidence of the presence of the EKC in China, while Kurniawan and Managi (2018) find that the coal-induced EKC holds in Indonesia. Hao et al. (2015) and Qiao et al. (2019) explain that coal is the primary driver of carbon dioxide emissions in China and accounts for around 70% of total energy consumption. Kurniawan and Managi (2018) illustrate that the dominance of coal in the energy mix of Indonesia may be attributed to its domestic reserves and low price. The authors add that coal-fired power plants require more coal to produce the same heat since coal has a poorer thermal efficiency than other fossil fuels like oil and gas. As a result, coal combustion causes higher emissions of carbon dioxide. Moreover, Sinha et al. (2019) state that the choice should consider the single-country context since it may ensure better insights for specific policy recommendations.

Another econometric problem is the inclusion of other independent variables that might affect the environmental sustainability as well as the EKC relationship. Several studies have plenty of evidence on the role of renewable energy consumption in reducing environmental degradation (Danish et al. 2017; Sharif et al. 2021, 2019, 2020,; Erdogan et al. 2020; Anwar et al. 2021; Alola et al. 2021; Usman et al. 2021; Bilgili et al. 2022; Dagar et al. 2022; Murshed et al. 2022; Ahmad et al. 2022), whereas others show that emission mitigation effect is not found for renewable energy consumption (Antonakakis et al. 2017; Pata and Caglar 2020; Vo and Ho 2021). Furthermore, the impact of oil prices on environmental pollution has been examined extensively in the literature (Balaguer and Cantavella 2016; Boufateh 2019; Erdogan et al. 2020; Malik et al. 2020).

In the present study for Vietnam, we will shed light on the effects of renewable energy consumption and oil prices on driving coal consumption. Firstly, prior studies show that rising competition from renewable energy reduces coal usage in the USA (Fell and Kaffine 2018; Hauenstein and Holz 2021) and Australia (Guidolin and Alpcan 2019). Despite the recent rise of renewable energy, coal dominates the energy structure in China (Qiao et al. 2019), India (Roy and Schaffartzik 2021), and Vietnam (Shem et al. 2019; Clark et al. 2020; Dorband et al. 2020; Thong et al. 2021). Renewables add to the existing energy system rather than replace coal (York and Bell 2019). Secondly, it is found that oil prices have different effects on the amount of coal consumed. Bloch et al. (2015) show that coal consumption increases in China when oil prices rise due to the substitution of coal for oil. By contrast, Zou and Chau (2020) suggest that increasing oil prices diminish coal use in China by replacing it with cheaper renewable energy. Mushtaq et al. (2022) show improvements in coal efficiency in China's industrial sector as a result of rising fuel prices. Matisoff et al. (2014) discover that US utilities rely on coal for power generation regardless of oil price changes. Dagher et al. (2020) argue that as oil prices drop, oil-exporting countries in the Middle East and North Africa (MENA) region have changed their energy structure by using more natural gas and renewables.

The results of earlier EKC research in Vietnam are inconclusive. Tang and Tan (2015) find evidence of the EKC since the income-emission relationship reveals an inverted U shape. Shahbaz et al. (2019) show that the income-emission nexus resembles an N-type curve, demonstrating an inverted U curve at low-income levels. However, income growth causes emissions to rise again after a second turning point. Nevertheless, other studies point out that the EKC does not exist in Vietnam because carbon dioxide emissions exhibit a U-shaped relation with income (Vo and Ho 2021) and industrial growth (Ali et al. 2020), and the income-pollution relationship is linear (Linh and Lin 2014; Al-Mulali et al. 2015).

Moreover, these studies do not apply an appropriate procedure to test for the existence of a quadratic relation between income and environment. Because the expected sign and significance of per capita income squared is a necessary but insufficient condition to prove if the relationship is inverted U-shaped (U-shaped), one should consider the three-step strategy. First, the per capita income squared coefficient needs to be significantly negative (positive). Second, the slope must change from positive (negative) at the start of the per capita income range to negative (positive) at its end. Third, the income range needs to hold the turning point of environmental degradation. One exception is the study of Ali et al. (2020), which finds a U-shaped linkage between industrial growth and emissions, even though the slope coefficients at both endpoints of the sample range are not statistically different from zero.

In short, previous studies in Vietnam have yielded conflicting findings. No study has investigated the EKC hypothesis for energy consumption in general and coal consumption in particular. Motivated by the growing role of coal in the energy mix, in this study, we employ various econometric techniques and the aforementioned three-step procedure to determine whether the coal-induced EKC hypothesis holds in Vietnam. The second hypothesis to be examined is whether or not renewable energy consumption and oil prices significantly affect coal consumption. Vietnam's environmental quality is under pressure because of its rapid economic growth and rising dependence on coal for electricity generation. Therefore, our findings may provide energy-specific policy insights and suggestions to reduce the use of coal and protect the environment.

Methodology

Model specification and data

We follow the earlier studies (Hao et al. 2015; Kurniawan and Managi 2018), which consider coal consumption a proxy for environmental degradation, to test the EKC relationship of coal consumption with GDP. Besides, we incorporate two variables, renewable energy consumption and oil prices, into the coal consumption function to assess the possible substitution of renewable energy and oil for coal. We specify the following empirical models:

$$COAL_t = \alpha_0 + \alpha_1 GDP_t + \varepsilon_t \quad (1)$$

$$COAL_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 GDP_t^2 + \varepsilon_t \quad (2)$$

$$COAL_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 GDP_t^2 + \alpha_3 REN_t + \varepsilon_t \quad (3)$$

$$COAL_t = \alpha_0 + \alpha_1 GDP_t + \alpha_2 GDP_t^2 + \alpha_3 REN_t + \alpha_4 OP_t + \varepsilon_t \quad (4)$$

where t, $COAL$, GDP, REN, OP, and u_t stand for time-series dimension, per capita coal consumption, per capita GDP, per capita renewable energy consumption, crude oil prices per cubic meter, and an error term, respectively. $\alpha_{j(j \geq 1)}$ represents the long-run parameters. The coefficient α_1 is supposed to be positive to reflect the scale effect of income. The coefficient α_2 is supposed to be negative to capture the effects of composition and technique, which tend to lower the use of polluting energy (Suri and Chapman 1998). All the series are transformed into natural logarithms to handle heteroscedasticity and provide the elasticities of coal consumption.

We apply a procedure to test a (invested) U-shaped relationship between two variables, as suggested by Haans et al. (2016), Hasanov et al. (2021), and Lind and Mehlum (2010).[2] Accordingly, the necessary and sufficient conditions for the existence of a quadratic relationship between GDP and coal consumption are as follows: (i) the coefficient α_2 is statistically significant, with the negative sign suggesting an inverted U-shape of the EKC or the positive sign implying a U-shaped relationship; (ii) the curve is not flattened at both ends of the per capita GDP range; and (iii) the turning point is entirely placed within this GDP range. We propose using this three-step procedure to make a robust conclusion on the shape of the relationship.

Data for GDP and population (to calculate per capita GDP, per capita renewable energy consumption, and per capita coal consumption) are extracted from the World Development Indicators. Data for renewable energy consumption (including hydropower, solar, wind, and modern biofuels), crude oil prices, and coal consumption are from the Our World In Data website. The annual data of Vietnam span the period 1984–2021 for the extent to which declared data for GDP are obtainable. Table 1 provides descriptive statistics of the dataset used for this study. Figure 1 plots an increasing trend in per capita coal consumption (GJ), per capita GDP (constant 2015 US dollars), and per capita

[2] The procedure is much used in management science. The command *utest* in Stata implemented by Lind and Mehlum (2010) tests the existence of a U-shaped (or inverse U-shaped) relationship on an interval. The command is used after estimation commands.

Table 1 Summary of descriptive statistics of data to test for a coal-induced EKC hypothesis

Variable	Mean	Std. dev.	Min.	Max.
Per capita coal consumption (GJ)	5.934	6.024	1.207	21.859
Per capita GDP (constant 2015 US dollars)	1576.033	885.566	577.470	3373.083
Per capita renewable energy consumption (GJ)	3.221	2.796	0.231	9.985
Oil prices per cubic meter (US dollars)	283.055	194.937	79.969	702.291

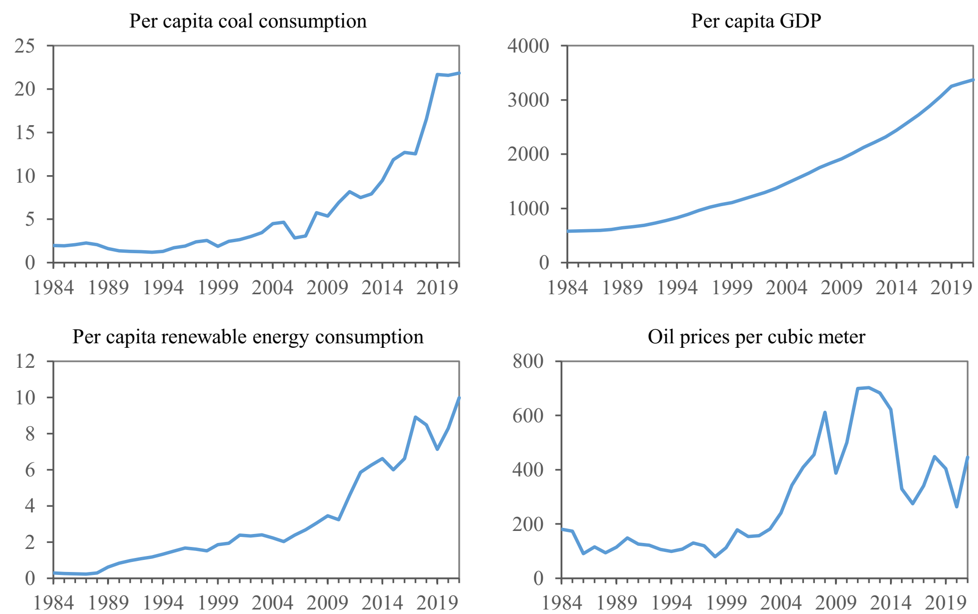

Fig. 1 Trends of the relevant variables for 1984–2021

Table 2 Unit root test results

Variable	Augmented Dickey and Fuller test				Phillips and Perron test			
	At level		At first difference		At level		At first difference	
	t-Stat.	Lag	*t*-Stat.	Lag	*t*-Stat.	Bw	*t*-Stat.	Bw
COAL	−2.254	0	−5.169[a]	1	−2.078	6	−5.538[a]	1
GDP	−2.218	2	−3.326[b]	1	−3.362[b]	3	−2.331	3
GDP^2	−4.030[b]	1	−2.441	0	−4.851[a]	2	−2.352	4
REN	−1.815	0	−4.530[a]	1	−1.874	4	−4.222[a]	8
OP	−2.513	0	−5.549[a]	1	−2.513	0	−5.919[a]	5

[a] and [b] indicate significance at the 1% and 5% levels, correspondingly. Intercept and trend are included in the level equation, while only intercept is included in the first difference. *Bw* bandwidth

renewable energy consumption (GJ) but a fluctuation in oil prices per cubic meter (US dollars).

Test of stationarity

Two unit root tests (Dickey and Fuller 1979; Phillips and Perron 1988) have been applied to determine the stationarity properties of time series. Moreover, we use the Schwarz information criterion (SIC) to specify the optimal number of lags of the augmented Dickey and Fuller (1979) test. In contrast, the Phillips and Perron (1988) test uses the Bartlett kernel for spectral estimation with Newey-West bandwidth selection. Table 2 shows the results of those tests. We find that the variables are first-difference stationary, which are *I*(1), except for *GDP* and GDP^2, which are trend stationary. Generally, we can conclude that all the examined variables seem to be integrated of order not exceeding two. Therefore, it is possible to apply the ARDL model.

Autoregressive distributed lag (ARDL) model

The static model regressions of Eqs. (1) to (4) do not handle the endogeneity and error serial correlation concerns. The

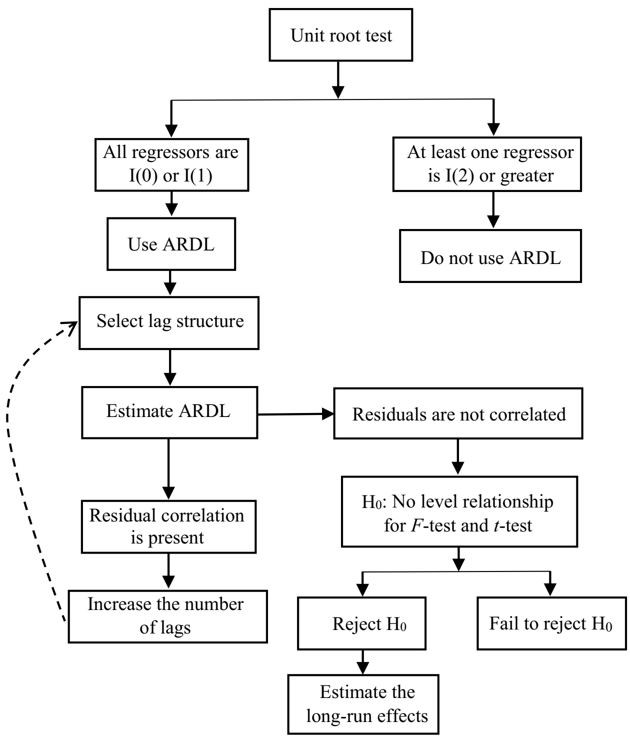

Fig. 2 ARDL approach to a level relationship

estimated parameters using the OLS method are super-consistent but not asymptotically normal. A cointegration test, hence, is no longer applicable. Therefore, we have used the ARDL model developed by Pesaran et al. (2001) because of its advantages over others (Fig. 2). First, the ARDL model can be applied regardless of whether the regressors are integrated of order zero, order one, or fractionally integrated. Second, the ARDL model mitigates the endogeneity bias and the residual serial correlation if an adequate number of lags are comprised. Third, it allows a correction for small-sample bias by using the finite-sample critical values (Kripfganz and Schneider 2020), which are computed with a Stata program implemented by Kripfganz and Schneider (2018). For these reasons, we employ the ARDL model to investigate the factors influencing coal consumption in Vietnam. For simplicity, only the ARDL specification of Eq. (4) is considered as follows:

$$\begin{aligned}\Delta COAL_t =& \delta_0 + \sum_{i=1}^{p-1}\beta_{0i}\Delta COAL_{t-i} + \sum_{i=0}^{p-1}\beta_{1i}\Delta GDP_{t-i} \\ &+ \sum_{i=0}^{p-1}\beta_{2i}\Delta GDP^2_{t-i} + \sum_{i=0}^{p-1}\beta_{3i}\Delta REN_{t-i} \\ &+ \sum_{i=0}^{p-1}\beta_{4i}\Delta OP_{t-i} + \lambda_0 COAL_{t-1} \\ &+ \lambda_1 GDP_{t-1} + \lambda_2 GDP^2_{t-1} + \lambda_3 REN_{t-1} + \lambda_4 OP_{t-1} + \varepsilon_t\end{aligned} \tag{5}$$

After estimating Eq. (5) with the OLS method, we apply the bounds testing procedure for a level relationship proposed by Pesaran et al. (2001): (i) the F-test for the coefficients of the lagged variables in levels: H_0: $\lambda_{j(j=0,1,2,3,4)}=0$ versus H_1: any $\lambda_j \neq 0$, and (ii) the t-test for the coefficient of the lagged dependent variable in level: H_0: $\lambda_0=0$ versus H_1: $\lambda_0<0$.[3]

Kripfganz and Schneider (2020) estimate response surface models to calculate small sample critical values of the F-test and the t-test. The lower-bounds and upper-bounds critical values are calculated assuming that all the regressors are either purely $I(0)$ or purely $I(1)$, correspondingly. We cannot make an inference about the null hypothesis if the computed statistics fall inside the critical bounds. On the contrary, we can make a conclusive inference if the computed statistics fall outside the critical bounds. If the two null hypotheses are rejected, we can conclude that a level relationship exists between the variables. We can thus estimate the long-run effects in Eq. (4) as $\alpha_j = -\lambda_j/\lambda_0$, respectively.

Findings and discussion

We begin with testing the existence of a level relationship among the variables. Because annual data are used in this study, the maximum lag is set to two, while the lag length selection is based on the SIC. The diagnostic tests show that the regression models obtained from Eqs. (1) to (4) do not suffer from residual serial correlation and heteroscedasticity at the 5% level. The lines of the cumulative sum of recursive residuals (CUSUM) and its square (CUSUMSQ) imply the stability of the estimated parameters over the sample period. Table 3 illustrates the test results.

As presented in Table 3, the null hypothesis of no level relationship is rejected since the computed F- and t-statistics exceed the 10% upper bounds critical values in Model (2) and the 1% upper bounds critical values in Models (3) and (4). However, we cannot reject the null hypothesis in Model (1), which considers a linear relationship between GDP and coal consumption. Thus, we find statistical evidence for a long-run level relationship between the investigated variables in the EKC models. We can estimate the long-run effects under these ARDL specifications. Table 4 gives the results of the estimation. The results of Model (1) are also presented for comparison purposes.

Though we find that the coefficient of per capita GDP squared is significantly positive, it is not sufficient to conclude that the GDP-coal consumption relation exhibits a

[3] Wagner (2008) doubts the results of previous studies that have used nonlinear transformations of integrated regressors to investigate the EKC hypothesis. The author claims that this invalidates cointegration and unit root approaches. However, since the bounds procedure for evaluating a level relationship does not require all regressors to be $I(1)$, the ARDL model can be applied in this study. The results in the previous section show that both GDP and $GDP^2$are trend-stationary.

Table 3 Results from ARDL bounds tests and diagnostic tests

	Model (1)	Model (2)	Model (3)	Model (4)
Lag	1, 0	1, 0, 0	2, 0, 0, 0	2, 0, 0, 0, 0
Bounds tests				
F-statistic	4.635	4.914[c]	8.266[a]	6.395[a]
t-statistic	−2.543	−3.295[c]	−5.223[a]	−5.126[a]
Diagnostic tests				
Serial corr.	0.062	0.438	2.440	2.295
ARCH	0.164	0.003	0.609	0.638
CUSUM	Stable	Stable	Stable	Stable
CUSUMSQ	Stable	Stable	Stable	Stable

[a] and [c] denote significance at the 1% and 10% levels, respectively. The critical value bounds are based on case III with unrestricted intercept and no trend. Serial corr. and ARCH show the test statistics for serial correlation and heteroscedasticity

U-shape pattern. The following two steps must be performed to ensure the necessary and sufficient conditions. Using the Delta method, we find that the slope coefficient at the log of minimum per capita GDP is insignificantly positive in Model (2) but is significantly positive in Models (3) and (4). Furthermore, the lower bound of the 95% confidence interval of the turning point is smaller than the log of minimum per capita GDP in Models (2) to (4). Thus, we can conclude that the GDP-coal consumption relationship resembles a monotonic but nonlinear curve instead of a U-shaped curve or conventional EKC.

This finding concurs with previous studies (Suri and Chapman 1998; Nguyen-Van 2010; Zhang et al. 2018; Lawson and Nguyen-Van 2021), which show the upward-sloping linkage between income and energy consumption. However, our finding differs from that of studies by Hao et al. (2015), Kurniawan and Managi (2018), and Qiao et al. (2019), which highlight that the coal-induced EKC hypothesis holds in China and Indonesia. It may be explained that the peak of coal consumption was recorded in China and Indonesia, whereas coal consumption continues to rise at an increasing rate in Vietnam. Specifically, the GDP elasticity of the demand for coal tends to increase when per capita GDP grows over time. For the preferred specification in Model (4), we find that since the 1990s, the estimated GDP elasticity of coal demand has been more than unity, and in recent years, it has been around 3.5.

It suggests that the coal intensity of GDP has risen with economic expansion. A possible explanation is that since economic growth triggers electricity demand, coal-fired power plants have been built and used to meet this increased demand. Consequently, coal consumption grows faster than GDP during the study period. The other explanations include local coal availability, artificially low coal prices, coal infrastructure subsidies, and inadequate environmental regulations (Dorband et al. 2020; Do and Burke 2021). In other words, coal is the largest contributor to the energy structure because of its cost-related advantages relative to other energy sources.

It can be seen from Table 4 that the usage of renewable energy is negatively correlated with the usage of coal. In particular, a 1% increase in renewable energy consumption decreases coal consumption by about 0.37% in Models (3) and (4), holding others constant. This finding is in line with previous research (Fell and Kaffine 2018; Guidolin and Alpcan 2019; Hauenstein and Holz 2021), which shows that an increase in renewable energy leads to a reduction in coal usage. This inverse relationship reflects that coal may be replaced by renewable energy in terms of consumption. The finding supports the view from several recent studies that long-term environmental sustainability is enhanced by renewable energy (Danish et al. 2017; Sharif et al. 2019, 2020, 2021; Anwar et al. 2021; Alola et al. 2021; Usman

Table 4 Estimates of long-run effects and testing for a quadratic relationship

	Model (1)		Model (2)		Model (3)		Model (4)	
	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
Long-run estimates								
GDP	1.807[a]	0.275	−9.891[a]	3.363	−8.788[a]	1.838	−8.726[a]	2.020
GDP^2			0.794[a]	0.231	0.753[a]	0.121	0.749[a]	0.130
REN					−0.374[a]	0.104	−0.377[a]	0.111
OP							−0.007	0.085
Testing for a quadratic relationship								
GDP_L			0.208	0.438	0.792[b]	0.391	0.811[b]	0.413
GDP_H			3.011[a]	0.411	3.452[a]	0.215	3.458[a]	0.241
τ			6.227[a]	0.313	5.833[a]	0.300	5.818[a]	0.359
CI			[5.614; 6.841]		[5.245; 6.420]		[5.115; 6.521]	

[a] and [b] denote significance at the 1% and 5% levels, respectively. GDP_L is the slope at the log of minimum per capita GDP (6.358), and GDP_H is the slope at the log of maximum per capita GDP (8.124). $\tau = -0.5\alpha_1/\alpha_2$ is the turning point. CI is the 95% confidence interval of the turning point

et al. 2021; Bilgili et al. 2022; Ahmad et al. 2022). However, although renewable energy is on the rise, it is vital to remove existing barriers, such as institutional, financial, and technical barriers, that prevent Vietnam from moving towards a low-carbon development path (Shem et al. 2019; Do and Burke 2021; Thong et al. 2021).

Additionally, the impact of oil prices on coal consumption is negative but insignificant (Table 4). This result contradicts previous papers, which show that the effect of oil prices is positive. Apergis and Gangopadhyay (2020) demonstrate that rising oil prices increase energy consumption (including coal), whereas falling oil prices diminish energy consumption in Vietnam due to the substitution between oil and coal. Similarly, Bloch et al. (2015) find that increased oil prices boost coal consumption in China. Dagher et al. (2020) indicate that the MENA countries attempt to replace fossil fuels with renewables in the energy mix when oil prices decrease. However, our finding is somewhat consistent with several previous studies, which document that the influence of oil prices is negative or insignificant. For example, Zou and Chau (2020) find that as oil prices rise, customers in China use less coal and more renewable energy, which is relatively cheaper. In a recent study, Mushtaq et al. (2022) show that rising fuel prices play a critical role in improving coal consumption efficiency in China's industrial sector. Matisoff et al. (2014) show that US coal-fired power plants are resilient to changes in oil prices.

Robustness tests

The first check is related to confirming cointegration between the variables. We have employed the residual-based cointegration test of Shin (1994) for Eqs. (1) to (4). Table 5 presents the results of this test. The residual-based test shows that we cannot reject the null hypothesis of cointegration. An exception is that the null hypothesis of cointegration is rejected at the 1% level when using OLS estimation for Eq. (1). Therefore, these results have supported the cointegrating relationship among the study variables. Furthermore, we check the robustness of our estimation results of Eq. (4) using the FMOLS estimator of Phillips and Hansen (1990), the DOLS estimator of Saikkonen (1992) and Stock and Watson (1993), and the CCR estimator of Park (1992).[4] The estimation results in Table 6 back up those obtained in Table 4.

In particular, consistent with the ARDL results, the GDP elasticity of coal demand has increased over the 1984–2021 period, rising from around 1 in 1984 to roughly 3.5 in recent years. Thus, there is similar evidence of the

[4] We use the command *cointreg* in Stata implemented by Wang and Wu (2012).

Table 5 Results of testing the residual-based cointegration

Estimation	Test stat.	1% CV	5% CV	10% CV	Eq.
OLS	0.648	0.533	0.314	0.231	(1)
DOLS	0.065	0.533	0.314	0.231	
OLS	0.129	0.380	0.221	0.163	(2)
DOLS	0.018	0.380	0.221	0.163	
OLS	0.060	0.271	0.159	0.121	(3)
DOLS	0.015	0.271	0.159	0.121	
OLS	0.054	0.280	0.121	0.094	(4)
DOLS	0.006	0.280	0.121	0.094	

CV denotes critical values for the model with a constant. Long-run consistent variance estimation method is Bartlett

upward-sloping relationship between GDP and coal consumption. It confirms that the EKC for coal consumption is not present in Vietnam. We also discover that renewable energy consumption is adversely associated with coal consumption. When renewable energy consumption rises by 1%, coal use falls by 0.43%. Furthermore, oil prices negatively but insignificantly affect coal consumption.

In the final check, we test and estimate structural breaks in the relationship between GDP and coal consumption using a new technique developed by Ditzen et al. (2021). If the EKC relationship exists, then the long-run GDP elasticity of coal consumption should vary from positive to negative with increasing income levels. In other words, there is the presence of one or two or more breaks in the GDP-coal consumption link as a consequence of interventions, such as policy changes in the energy market. Table 7 shows that there is a break, and the break year is estimated to be 1994. It can be explained that Vietnam's demand for coal has been rising since 1994 when its integration into the global economy was followed by impressive economic growth. The estimated results in Model (5) show that the GDP elasticity is 3.06. However, the coefficient of the interaction variable between GDP and the dummy variable (to account for a break in 1994) is not statistically significant. Despite this, the result indicates that the coal-induced EKC hypothesis does not hold in Vietnam. Furthermore, the coefficients of renewable energy consumption and oil prices are similar to those obtained from other estimators.

In Fig. 3, we illustrate the GDP elasticity estimates of coal demand over different estimation methods. In particular, Fig. 3 shows that the GDP elasticity of coal demand is about 1.8 in Model (1), in which GDP^2, *REN*, and *OP* are not included. This estimate is smaller than a 3.06 value in Model (5) when we control a break in the GDP-coal consumption relationship. However, the results of Models (2) to (4), FMOLS, DOLS, and CCR show that the long-run GDP elasticity has increased over time and has been greater than unity since the 1990s. We have also calculated

Table 6 Results of robustness checks

	FMOLS		DOLS		CCR	
	Coef.	Std. err.	Coef.	Std. err.	Coef.	Std. err.
Long-run estimates						
GDP	−7.537[a]	1.855	−8.153[a]	1.647	−7.457[a]	1.923
GDP^2	0.681[a]	0.121	0.721[a]	0.107	0.676[a]	0.126
REN	−0.434[a]	0.105	−0.426[a]	0.095	−0.435[a]	0.103
OP	−0.086	0.078	−0.057	0.068	−0.087	0.078
Testing for a quadratic relationship						
GDP_L	1.124[a]	0.368	1.014[a]	0.330	1.134[a]	0.368
GDP_H	3.529[a]	0.233	3.560[a]	0.210	3.519[a]	0.253
τ	5.533[a]	0.401	5.655[a]	0.321	5.519[a]	0.412
CI	[4.747; 6.319]		[5.026; 6.284]		[4.712; 6.327]	

[a]denotes significance at the 1% level. GDP_L is the slope at the log of minimum per capita GDP (6.358), and GDP_H is the slope at the log of maximum per capita GDP (8.124). $\tau = -0.5\alpha_1/\alpha_2$ is the turning point. CI is the 95% confidence interval of the turning point

the coal intensity of GDP ($COAL_t/GDP_t$) for comparison purposes (base 2005 = 100). Overall, we can conclude that the findings are robust when using different cointegration tests and estimation techniques and that they could be applied to formulating and implementing policies.[5]

Conclusion and policy implications

This paper explores the relationship between coal consumption and its determinants in Vietnam from 1984 to 2021. Doing so allows us to determine whether the coal-induced EKC hypothesis is valid. Moreover, to mitigate the omitted variable bias, we add two variables, renewable energy consumption and oil prices, to the standard EKC model. These variables capture the substitution effects on coal consumption. This study uses the ARDL model to deal with small sample bias, endogeneity, and serial correlation problems. The bounds test results show that the *F*- and *t*-statistics lie above the upper bounds of the critical values for the EKC models. Hence, we reject the null hypothesis that no level relationship exists. In other words, a long-run level relationship is established between the investigated variables.

Besides, this study follows the three-step framework to test for a quadratic link between GDP and coal consumption. Although the estimated coefficient of per capita GDP squared is significantly positive, there is insufficient evidence to support a U-shaped curve. Using the Delta method, we find that slope coefficients at both ends of the per capita GDP range are positive and statistically significant at a normal level; the lower bound of the 95% confidence interval of the turning point is smaller than the lowest value of per capita GDP. Hence, just the right half of the U-shaped curve is fitted by the data, suggesting the upward-sloping relationship between GDP and coal consumption. We can conclude that the hypothesis of the EKC for coal consumption does not hold in Vietnam. This conclusion is robust when considering different cointegration and estimation methods and controlling for other regressors.

Table 7 Results of testing breaks and estimating coefficients

Sequential test for multiple breaks at unknown break points		
	$F(1\|0)$	$F(2\|1)$
	15.05[a]	0.64
Break year	1994	
CI	[1993; 1995]	
Long-run estimates	Model (5)	
ARDL(1, 0, 0, 0, 0)	Coef.	Std. err.
GDP	3.067[a]	0.437
$GDP * break_{1994}$	−0.039	0.040
REN	−0.629[a]	0.220
OP	−0.202	0.164

[a]denotes significance at the 1% level. CI is the 95% confidence interval of the break year

The results show that the GDP elasticity of coal demand has been more than one since the 1990s and has been around 3.5 in recent years. It means that the coal intensity of GDP has grown as per capita income increases (coal consumption rises at a higher rate than GDP). The large GDP elasticity does not mean that we perceive coal as a luxury good in Vietnam. An increase in the demand for coal may be driven by economic growth and a rapid expansion of coal-fired power plants to fulfill the increased demand for electricity.

[5] The other robustness check is that the EKC analysis is based on the level form of the variables instead of their per capita form in Eqs. (1) to (4). The bounds test and estimation results support those obtained using the per capita form in Tables 3, 4 and 6. The results are not reported in detail here but are available from the corresponding author upon request.

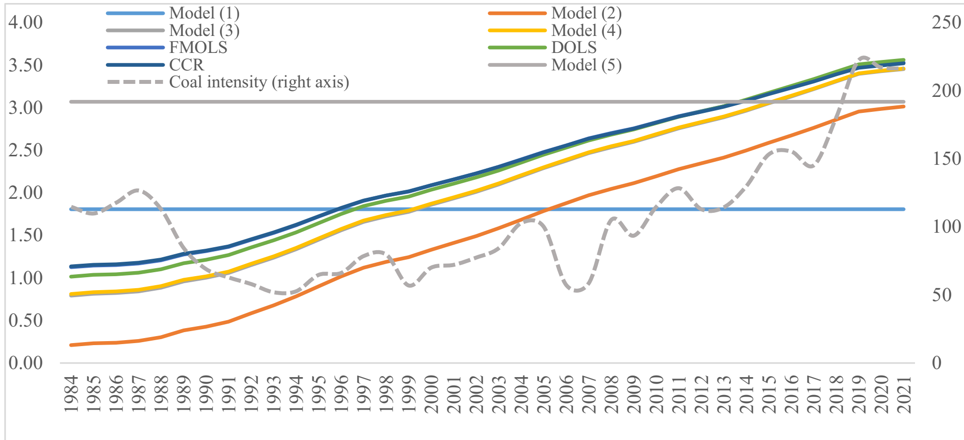

Fig. 3 The GDP elasticity estimates of coal demand over the estimation methods

Furthermore, we find that renewable energy consumption, including hydropower, solar, wind, and modern biofuels, is adversely correlated with coal consumption. Generally, a 1% rise in the use of renewable energy coincides with a drop of 0.4% in the use of coal. Moreover, changes in oil prices have no significant long-term effect on coal consumption.

These findings have significant policy implications. First, the high GDP elasticity suggests that environmental risks associated with coal will continue to grow in Vietnam without policy improvements. To fulfill the emission goals, it is an urgent need for more stringent policy interventions, for example, imposing a carbon pricing scheme. Such a policy could boost investments in the renewable energy sector and help meet emission reduction targets without compromising long-term economic growth (Do and Burke 2021). Second, it should be a policy priority to promote the sustainable growth of renewable energy through measures such as upgrading power transmission networks, encouraging green finance, and developing a direct purchase mechanism between developers and customers. Third, when oil prices rise, Vietnam should diversify its energy mix by increasing the use of renewable energy rather than other fossil fuels. The current high oil price is an opportunity to eliminate distortions, such as subsidies to energy-intensive industries.

Since the present study is limited to investigating the substitution of renewables and oil for coal, future research should be undertaken on inter-factor and inter-fuel substitution in Vietnam. The emission mitigation effect of high energy prices is another critical issue for further work.

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Data availability Data will be made available upon request.

Declarations

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