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Where do we stand on cutting coal dependency? Evidence from the top coal-dependent economies

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ABSTRACT

Cutting the global economy's dependence on coal has always been seen as one of the most effective measures to reduce carbon emissions and ensure environmental sustainability. However, the demand for coal can vary greatly from country to country. Therefore, the primary objective of this study is to identify where the countries with the highest coal consumption stand in reducing coal dependence in energy supply from 1997 to 2021 by utilizing panel data methods and accounting for the possible occurrence of cross-sectional dependence. The empirical results denote that (i) the models used are cross-sectionally independent, (ii) there is a long-run relationship between the variables (iii) rising economic growth upsurges coal demand, while its square reduces coal consumption; therefore, the coal-Kuznets curve is valid; (iv) population density and industrialization boost coal consumption, while demand for natural gas and renewable energy reduces it. Based on the empirical outcomes, the study suggests that natural gas should be promoted alongside renewables to displace coal consumption globally, and that countries should consider the coal-Kuznets curve to channel the increased revenues into clean energy investments.

Nomenclature

List of Abbreviations			
ARDL	Autoregressive Distributed Lag	GDP	Gross Domestic Product
CD	Cross-Section Dependence	GHGs	Greenhouse Gas Emissions
CKC	Coal Kuznets Curve	IPS	Im-Pesaran-Shin
CO2	Carbon Emissions	NZE	Net Zero by 2050
DOLS	Dynamic Ordinary Least Squares	OECD	Organization for Economic Cooperation and Development
EKC	Environmental Kuznets Curve	SDGs	Sustainable Development Goals
FMOLS	Fully Modified Ordinary Least Squares	USA	United States of America
List of Symbols			
ln	Logarithm Operator	TRD	Trade Openness
COAL	Coal Consumption	NG	Natural Gas Consumption
GDP	Gross Domestic Product	REN	Renewable Energy Consumption
GDP^2	Gross Domestic Product Square	β_0	Constant Term
PD	Population Density	β_{1-4}	Long Run Coefficients
IND	Industrial Value Added	ε_{it1-5}	Error Term

1. Introduction

The energy of coal played a vital role in the Industrial Revolution, increasing the scale and speed of industrial iron smelting, a historic driver of Britain's economic power. In this regard, the invention of smelting iron ore in the early 18th century using coke instead of charcoal was a milestone for economic welfare, and coke was an efficient and reliable fuel for Britain's iron industry for decades. In the 1700s, annual iron production was almost 2500 tons [1], while in the second quarter of

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the 18th century it increased more than tenfold to over 29,000 tons, reaching 180,000 tons in the early 19th century [2]. Coal power therefore not only helped to enable the substitution of labor by machine power, but also boosted industrial production and economic performance by enabling the development of the British infrastructure system and industrial capacity. In this context, it can be argued that coal was the "king of the British industrial revolution".

Coal became the primary energy source for the British economy. Fig. 1 denotes the historical evolution of energy composition in England and Wales. Before the invention of the use of coke in British industry, the primary power sources were prevalently human power, draught animals, and firewood for economic activities, while coal became the primary source of energy in the 16th century. With the invention of coke in the iron industry, the share of coal boomed. Coal also provided the necessary energy for the famous steam engine, which helped to improve the capital-labor ratio in the British economy. Thus, coal's share of the overall energy mix gradually increased, and Britain powered its economy by generating almost 90 % of its energy from coal in the 19th century [3].

Coal has not only transformed Britain's energy mix and economic development path, but also the energy composition and economic performance of the global economy. Fig. 2 shows the historical movements of the global energy mix. Coal has a historical upward trend and began to dominate the global energy mix in the early 20th century, while oil has been the largest contributor to the global energy mix since the 1965s. Therefore, coal is the energy source that has recently accounted for the second largest share of global energy sources. Furthermore, coal is the largest single and reliable energy source in the world, generating almost 34 % of global electric power [4], and it has historically been "a port in the storm" for global economies by supplying energy for economic activities. Indeed, coal has been a reliable alternative energy source during solid economic performance (i.e., strong rebound of Asian economies following the COVID-19 lockdown) and times of turmoil (i.e., the Russian invasion of Ukraine). Global demand for coal, which is critical to energy security, has always been strong and reached a new record high in 2022 [5].

Boosting global economic activities and economic development through the use of energy has not been costless [6]. In particular, the use of coal has led to significant environmental degradation [7], as coal is the most carbon-intensive energy source, which is one of the main causes of the concentration of global GHGs and climate change [8]. Coal-based energy production causes 40 % of total energy-related carbon emissions (CO_2) [9]. Therefore, cutting CO_2 emissions to secure global energy supply has always been an important goal for policymakers in international initiatives such as the Kyoto Treaty, the Sustainable Development Goals (SDGs) and the Paris Agreement [10]. Reducing coal dependency is one of the most vital aims of the Net Zero by 2050 (NZE) projection. In this regard, the aim is to replace 14 % of coal-powered energy production with clean and renewable energies every year. In addition, the OECD countries are expected to phase out coal-fired power generation worldwide by 2040 [4,11].

Although cutting coal dependence is crucial for reducing GHGs and paving a sustainable development road for the global economy, it is not an easy task for policymakers. The coal industry is expected to create nearly 11 million jobs and generate nearly US$2 trillion in revenue on a global scale between 2024 and 2029 [12]. Coal alone meets almost 25 % of total global energy demand in all dimensions, while this share is nearly 10 % higher for in electricity production. Moreover, cutting coal dependency becomes an even more severe task when country-specific energy structures are taken into account. Panel A in Fig. 3 shows the percentage of electricity generated in coal-fired power plants in the top 25 coal consumer countries. The share of coal in total electricity production is generally relatively high, and in some countries, such as China, India, Indonesia, Kazakhstan, Poland, Serbia, and South Africa, coal dominates the energy mix.

Panel B in Fig. 3 shows that the four largest coal-power countries, namely China, India, Japan, and the United States, generate more than 75 % of the world's coal-fired electricity [13]. Therefore, it can be argued that cutting coal dependency is an arduous task to pave a sustainable development path for both the leading coal power countries and the global economy. Where do we stand on cutting coal dependence? Has the demand for coal peaked in the major coal-consuming countries? The existing literature is far from providing answers to these questions.

The motivation for the study is that the reduction of coal is a necessity as it has negative effects on human health and causes CO_2 emissions. As high coal consumption exerts enormous pressure on the environment, many policymakers are drawing attention to this issue [14]. Coal accounts for 1/3 of global production and is a carbon-intensive energy source [15]. Coal is responsible for 0.3C of the 1C rise in global temperature [16]. The activities associated with coal mining, coal dust, coal residues and mine water can have a negative impact on human health [17]. Coal-fired power plants release large amounts of CO_2, and therefore the reduction of coal is a necessity to achieve low-carbon levels by reducing CO_2 [18]. However, the direct substitution of coal with renewable energy sources is currently limited. Although China and India have adopted carbon neutrality targets, they are reluctant to commit to a complete coal phase-out [19]. China and India are the two countries that consume the most coal-fired electricity in this study. Their reluctance to phase out coal and their high dependence on fossil fuels are a major problem for global CO_2 reduction.

In many of the top 25 coal-consuming countries analyzed, more than half of their energy consumption comes from coal. It has been empirically proven in many studies that coal increases CO_2 emissions (see e.g. Ref. [20]). In the hypothesis analysis of the environmental Kuznets

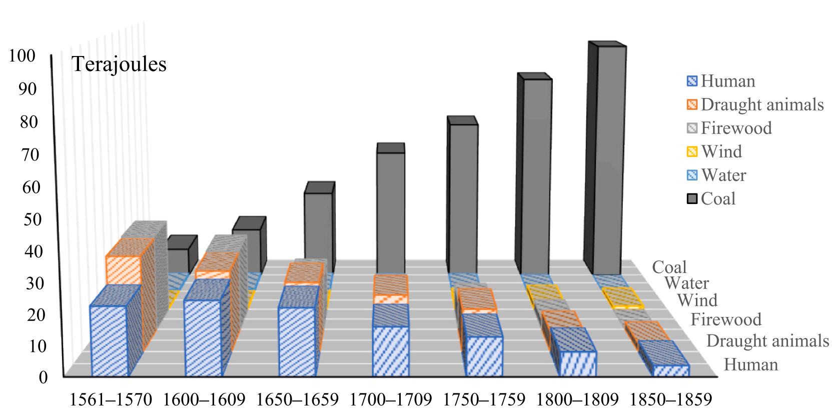

Fig. 1. Historical energy composition of england and wales.
Source: This figure has been created by authors by retrieving data from Wrigley [3].

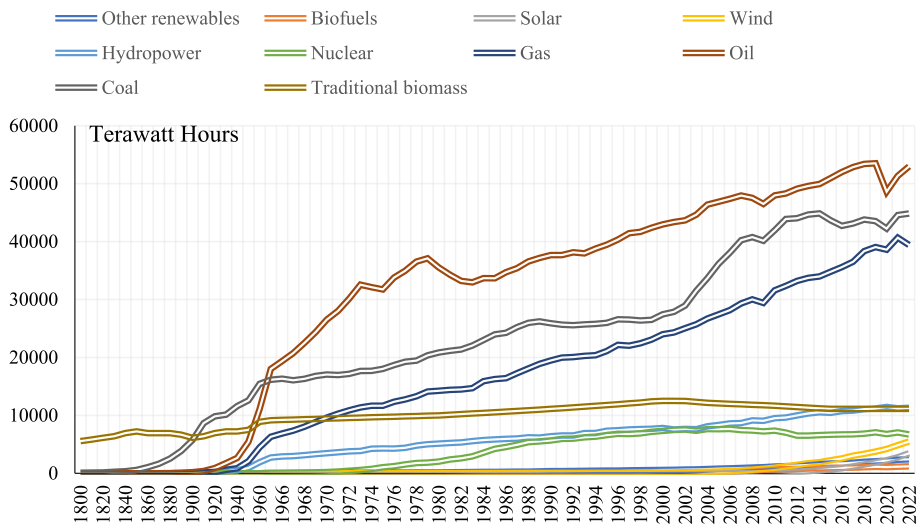

Fig. 2. World Energy Mix. **Note:** Fig. 2 has been created by authors through the data from Our World in Data

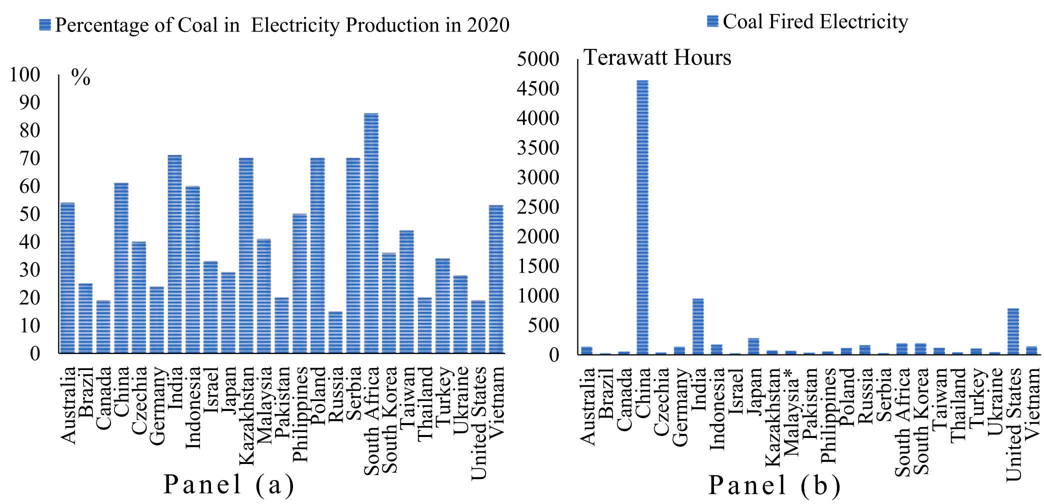

Fig. 3. Coal in Electricity Production in 25 Coal Power Countries, **Note:** Fig. 3 has been created by authors through retrieving related data from EMBER [4].

curve (EKC) by Grossman and Krueger [21], the researchers identified coal as a factor that leads to an increase in CO_2. The EKC curve shows an inverted U-shaped relationship between income and CO_2. Under the EKC hypothesis, researchers consider environmental pollutants such as CO_2, sulfur dioxide and methane gas as dependent variables and analyze the factors that influence them. However, in order to reduce CO_2, it is necessary to directly reduce the elements that are the main source of this pollutant. In this context, analyzing the factors that influence coal becomes important. Societies adopt a coal-based production model in the first phase of their economic development and industrialization. Over time, however, communities whose prosperity and income exceed a certain turning point may abandon coal consumption and turn to fossil fuel sources that are less polluting, such as natural gas, or eco-friendly wind and solar. In this regard, coal can be considered as an environmental pollutant indicator like CO_2 emissions in the EKC hypothesis and analyzed as a dependent variable, and there may be an inverted U-shaped relationship between coal and per capita income. This inverted U-link first reported by Hao et al. [22], and referred to as the coal Kuznets curve (CKC) by Qiao et al. [23]. Taking into account the possible non-linear interaction between income and coal, this study examines the validity of the CKC hypothesis for the 25 largest coal-consuming countries. Whether or not the CKC hypothesis is valid for the top coal consuming countries is important for policymakers with net zero targets, because if income ensures coal reduction, it is ultimately possible to phase out coal with economic development. In this context, this study aims to contribute to the current state of knowledge by investigating whether the highest coal consuming countries can phase out coal in the later stages of their economic development process with the validity of the CKC hypothesis.

The primary objective of this study is to investigate where top coal power countries stand on reducing coal dependence on energy generation through panel data analysis considering the possible emergence of cross-sectional dependence (CD) and provide a future policy projection by estimating the approximate turning point on coal consumption path under the CKC framework. To the best knowledge, this study is the first to determine where top coal power countries stand on coal demand by adopting the CKC framework. Therefore, it has the potential to improve existing literature on the following topics and fill existing gaps in the literature. First, understanding the nature of the coal demand in top coal power countries not only could contribute to establishing efficient policies on reducing coal consumption and ensuring environmental aims determined by international initiatives, such as the SDGs, but also could provide information on the future projection of global coal consumption. Second, having insights into the peak level of coal demand in top coal power countries can give ideas to the policy-makers on where sample countries stand and how the nature of the policies should be determined. Third, investigating possible CD in the estimated models enables researchers to make proper methodology selections and obtain robust estimations and policy inferences.

2. Literature review

The global urgency of the energy transition, particularly in connection with the climate problem, has driven research into aspects of coal energy. In the meantime, the development of coal energy has remained explicitly inexplicable without the theoretical dimension of energy development, as several factors, in addition to climate-related factors, determine the trend and aspect of coal energy.

2.1. Theoretical literature

Following part of the novel work on economic growth proposed by Solow [24], the nexus between energy use and economic prosperity was further developed theoretically in the work of Kraft and Kraft [25]. Subsequently, the links between energy and economic growth have also been described in other frameworks. For instance, by deepening the explanation of the traditional (output) growth model, both economic (productive output) and environmental (undesirable output, such as GHGs) outputs are presented in an explicit description of the output model [26,27].

Before Grossman and Krueger [21] demonstrated how economic growth and environmental indicators, i.e., undesirable outputs are interconnected, Kuznets [28] showed in his work that economic growth and income inequality have an inverted U-shaped relationship, which has now been adapted for the link between ecological quality and the economy. In particular, the EKC perspective, which describes the 'rise and fall' relationship between ecological indicators such as CO_2 and GHGs [29–31], has also been explored in describing the link between energy and GDP. Just as coal energy development can be explained by economic- and socioeconomic-factors, another dimension of coal development (possibly within the transition pathway) could be explained by environmental factors arising mainly from the development of alternative energy sources. A summary of the empirical literature can be found in Table 1, and the following sections examine the earlier literature in detail.

2.2. Empirical literature

In the literature, CO_2 emissions [46,47], the ecological footprint [48,49], and, more recently, the load capacity factor [50]are mentioned as indicators of ecological degradation. A large part of these indicators consists of CO_2 emissions, and coal is the energy type with the highest carbon intensity. Therefore, this section discusses the literature that analyzes the economic impact of coal consumption and the substitution possibilities of coal and other forms of energy.

2.2.1. Economic and socioeconomic drivers of coal energy development

In a general context, the inter-relationship between energy and GDP has been widely presented from the perspective of neutrality, feedback, energy-saving/conservation, growth hypotheses, and even the EKC hypothesis [22,23,34,36,38,35,51,52]. Qiao et al. [23] implement a panel data analysis by obtaining datasets for 30 Chinese provinces to test the validity of the CKC. While the entire panel and subpanel results show that the CKC hypothesis is valid, similar to the outcome in Hao et al. [22], the results for the province-specific study are mixed. In particular, the results indicate that coal consumption has not yet peaked, i.e., the CKC hypothesis is not valid in the coal-dependent developing regions of the country, which is in contrast to the valid observation of the CKC hypothesis in the other regions. This investigation implies that coal consumption in China is unlikely to peak uniformly as far as provincial factors are concerned.

The impact of economic growth on coal consumption patterns has also been examined for different scenarios, such as the largest coal consumer countries and developed/developing economies [33,32]. In testing this relationship over the period from 2000 to 2010, Lei et al. [32] implemented the Granger causality approach to a panel of the six largest consumers of coal energy in the world. The empirical revelation from the investigation shows that causality between coal consumption and economic output is bidirectional in Germany, Japan, and Russia. Importantly, in China, economic growth Granger causes coal consumption without a feedback effect, but there is no statistical evidence of causation between these indicators in India and the USA. In order to provide empirical evidence of the relationship between coal utilization and economic performance, Jin-ke et al. [33] show that the causality between coal consumption and economic performance is different in major industrialized countries and major developing countries using the

Table 1
Former literature on the drivers of coal demand.

Author(s)	Sample/Period	Method	Result(s)
Lei et al. [32]	China, Germany, India, Japan, Russia, the United States of America/ 2000 through 2010	Granger Causality	M
Jin-ke et al. [33].	Developed and Developing Countries, 1980 to 2005	Granger Causality	M
Apergis and Payne [34]	OECD Countries/ 1980–2005	Vector Error Correction Method	Coal Consumption↔GDP
Wolde-Rufael [35]	Major Coal Consuming Countries/ 1965–2005	vector autoregressive Framework	M
Li and Leung [36]	23 Regions of China/1985–2008	Panel Causality Methods	M
Michieka and Fletcher [37]	China/1971–2009	Granger Causality	GDP→Coal Consumption Urbanization*
Hao et al. [22]	China/1995 to 2012	First-Generation Panel Data Methods	CKC is valid.
Chai et al. [38]	China/1965–2016	Partial Least Squares	CKC is valid.
Qiao et al. [23]	Chinese provinces/ 2000–2016	Set of Panel Data Methods	CKC is valid.
Guidolin and Alpcan [39]	Australia	Diffusion Model	Renewable Energy (−)
Raza and Shah [40]	Pakistan/ 1981–2017	Vector Error Correction Method	Coal Consuption↔GDP
Wang et al. [41]	China	Grey Prediction Model	The peak year for coal consumption in China is 2027
Wang et al [42].	Guangdong Province	Logarithmic Mean Divisia Index	GDP (+) Energy Intensity (−) Fixed Capital Formation (+) Exports (+)
Raza and Lin [43]	Pakistan/ 1986–2019	Logarithmic Mean Divisia Index	Energy Intensity (−) Economic Activitiy (+)
Zaghdoudi et al. [44]	China/Q1-1992-Q3-2021	Fourier ARDL	Oil Price (+)
Tang et al. [45]	Pakistan/ 2001–2020	Laspeyres Index Of Decomposition	GDP (+)

Notes: +: Positive Impact, -: Negative Impact, *: Statistically Insignificant Impact, ↔: Bidirectional Causal Nexus, →: Unidirectional Causal Nexus, M: Mixed.

corresponding data sets for the period from 1980 to 2005. Raza and Lin [43] have shown for Pakistan from 1986 to 2019 that an increase in economic activity can lead to an increased demand for coal. Tang et al. [45] have shown that economic development from 2001 to 2020 has a positive effect on coal demand in Pakistan.

The role of other economic factors, such as population, trade, and industrialization, in coal consumption has also been widely examined [37,53,54]. Kurniawan and Managi [53] attempt to validate the existence of CKC in Indonesia from 1970 to 2015. The result indicates that the CKC is valid for the examined case and that trade openness and urbanization positively influence coal energy use. Michieka and Fletcher [37] investigate China over the period 1971–2009 and report that economic output causes coal consumption, but there is no causality from urbanization to coal consumption. To show whether coal consumption in China has peaked, Wang et al. [41] combine data analysis with a grey prediction model and find that 2027 (with an estimate of 437.8 million tons) is the likely peak year for coal consumption in China. Wang et al. [41] show that coal consumption in the country is most strongly influenced by economic growth, followed by the industrial structure, while the population growth rate exerts the slightest effect. Raza and Shah [40] uncover a bidirectional causal interaction between population and coal utilization in Pakistan from 1981 to 2017.

2.2.2. Alternative energy as a driver of coal energy development

Wang et al. [42] investigate the supply- and demand-side drivers of coal consumption, using the example of the rapidly developing Chinese regions (Guangdong province), which account for most of the country's CO_2 emissions resulting from the dominant use of coal energy. They confirm that economic growth is the most crucial supply-side factor positively influencing coal consumption in Guangdong Province, while energy intensity hinders coal consumption. Notably, the study establishes that the industrial structure exerts a contrasting effect on coal consumption at different phases of development. Meanwhile, demand factors, including fixed capital formation, urban households, and exports increase coal consumption due to international and interprovincial trade. Zaghdoudi et al. [44] investigate whether the oil price exerts an asymmetric influence on coal consumption in terms of the impact of alternative energies on coal consumption. The result confirms a non-linear relationship between coal energy consumption and the oil price, such that coal consumption is positively affected in the short term when there is a positive shock in the oil price.

Guidolin and Alpcan [39] examine the competing role of renewable energy sources in the use of coal energy in Australia. The study shows that the uptake of renewable energy sources hinders coal consumption. However, the relationship between renewable energy sources and natural gas is complementary in nature. According to Tiewsoh et al. [55], the share of primary energy utilization in India is dominated by coal energy. In a data analysis for the period between 2000 and 2013, they report that the total annual primary energy consumption doubled during this period. Tiewsoh et al. [55] point out that the share of coal consumption increased from 49 to 54 percent during the period studied (2000–2013), while the share of oil consumption fell from 36 to 30 percent and the share of natural gas consumption remained unchanged at 8 percent. According to Man et al. [56] and Li et al. [57], coal energy can play a role in substituting natural gas and oil energy, but more so for natural gas. Through a critical analysis of a forecasting model based on the optimistic scenario, the baseline scenario, and the cautious scenario, Li et al. [57] found that China's potential surge in coal energy demand can reduce the country's dependence on imported oil, natural gas, and primary energy by ~70 percent, ~40 percent, and ~20 percent, respectively. The study thus supports that coal energy is a potential substitute for alternative energy sources.

3. Theoretical underpinnings, model, data & methodology

3.1. Theoretical underpinnings, model & data

Coal has historically played a central role in the Industrial Revolution and contributed to the rapid economic development that has dominated the global economy since the 18th century. It has powered industrial activities requiring vast amounts of energy, such as the iron and mining industry, increased the volume of industrial activities, and boosted economic growth [58], while rising industrialization and economic growth has brought with it an increase in energy demand [59].

The use of coal has a dramatic impact on modern urban services such as powering buildings and heating. Therefore, there is an interaction between coal consumption, the modern economic structure, and economic growth. In fact, the technological advances through the Industrial Revolution have helped to break the vicious circle between population growth and famine because of insufficient food production [60]; thus, population growth has accelerated at an unprecedented rate [61]. Population growth in the peripheries of cities has historically led to a surplus of labor, and the development of industry and manufacturing in the cities has caused a mass exodus from rural areas. Therefore, population concentration in urban areas has increased significantly [62]. The rise in population density has inevitably changed the energy demand in urban areas. One group of researchers has claimed that population density can reduce energy demand by facilitating urban services and increasing productivity, while another group of researchers has uncovered that an increase in energy demand and ecological pressures in urban areas may be inevitable due to the increase in density [29,63,64]. The debate on how population density can affect energy demand is therefore still ongoing.

The volume of international trade has increased immensely in the last three centuries, which has also boosted the demand for energy in all dimensions [53]. The primary source for meeting the increasing energy demand in the economy in earlier phases was coal power. Some researchers have argued that increasing trade relations among nations have enabled them to import know-how alongside manufactured goods, leading to technological advances and productivity gains. Thus, the energy intensity of production and energy demand have declined [23]. The interaction between trade and energy demand is therefore a controversial topic among researchers.

Since the industrial revolution, coal has been considered one of the most important causes of GHGs and global warming. Considering that some of the world's largest economies, such as China, are highly dependent on coal [65], reducing coal dependence in the energy supply of the global economy is considered an effective policy to avoid the worst consequences of climate change [66]. In this context, reducing the share of coal by promoting alternative energy sources has always been considered one of the most effective policy alternatives. To this end, renewable energy and natural gas have been seen as substitutes for coal [67,68]. Renewable energies and natural gas have therefore had a significant impact on the demand for coal around the globe.

Considering the above theoretical explanations and rationale, the following linear-logarithmic models are used in Eqs. (1)–(5) in the top coal-dependent countries,[1] listed in Table 2 for the period from 1997 to 2021:

$$\ln COAL_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln PD_{it} + \varepsilon_{it1} \tag{1}$$

$$\ln COAL_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln PD_{it} + \beta_4 \ln IND_{it} + \varepsilon_{it2} \tag{2}$$

[1] Normally, EMBER (2021b) reports the top 25 coal-dependent countries. However, Israel, Serbia, South Korea, and Taiwan were excluded because of missing observations.

Table 2
List of analyzed top coal-dependent countries.

Australia	Indonesia	Russia
Brazil	Japan	South Africa
Canada	Kazakhstan	Thailand
China	Malaysia	Turkiye
Czechia	Pakistan	Ukraine
Germany	Philippines	United States
India	Poland	Vietnam

$$\ln COAL_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln PD_{it} + \beta_4 \ln TRD_{it} + \varepsilon_{it3} \tag{3}$$

$$\ln COAL_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln PD_{it} + \beta_4 \ln NG_{it} + \varepsilon_{it4} \tag{4}$$

$$\ln COAL_{it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln PD_{it} + \beta_4 \ln REN_{it} + \varepsilon_{it5} \tag{5}$$

where COAL denotes coal consumption, GDP and GDP[2] denote gross domestic product (GDP) and GDP squared, respectively; PD implies population density, IND is the industrial value added used as a proxy for industrialization, TRD represents trade openness, NG denotes natural gas consumption, and REN shows renewable energy consumption. The data on COAL, NG, and REN are retrieved from Our World in Data, while the data on GDP, PD, IND, and TRD are obtained from the World Bank, World Development Indicators..

Detailed explanations and descriptive statistics for the dataset used can be found in Table 3. The descriptive statistics show that GDP has the highest maximum and minimum levels, while IND has the lowest maximum level, and NG has the lowest minimum levels. GDP has the highest mean over the time horizon, while REN has the lowest mean level. PD has the highest standard deviation, while REN has the lowest. Therefore, PD follows a more fluctuating pattern compared to the data set, while REN has a relatively stable pattern over the time horizon.

3.2. Methodology

It is well known that methods for estimating panel data can often lead to biased estimates when CD occurs. Therefore, investigating whether CD occurs in the estimated models is crucial to avoid distorted estimations and policy inferences. For this purpose, the CD method developed by Chudik and Pesaran [69] is applied to test the CD properties of the models. Following the CD test, the integration levels of the variables are tested using the Im-Pesaran-Shin (IPS) unit root method proposed by Im et al. [70]. After determining the order of integration of the variables, the empirical estimates are continued using cointegration tests, namely the Pedroni test and the variance ratio test proposed by Pedroni [71] and Westerlund [72], respectively.

Table 3
Explanations and descriptive statistics for the variables.

Variable	Explanation	Mean	Max.	Min.	Std. Dev.
COAL	Coal Consumption per capita (Kwh)	8.587	10.380	5.029	1.283
GDP	Per capita (Constant, 2015 US$)	8.942	11.032	6.500	1.203
PD	Population density (people per sq. km of land area)	4.223	6.160	0.875	1.485
IND	Industry (including construction), value added (% of GDP)	3.390	3.882	2.843	0.238
TRD	Trade (% of GDP)	4.083	5.395	2.800	0.569
NG	Natural Gas (% equivalent primary energy)	2.760	3.997	−4.057	1.032
REN	Renewables (% equivalent primary energy)[2]	1.850	3.886	−1.450	0.992

The empirical strategy adopted is visualized step-by-step in Fig. 4. After testing the cointegration properties of the utilized models denoted in Eqs. (1)–(5), the long-run elasticity estimates of the regressors are performed using the panel ARDL method proposed by Pesaran et al. [73]. In addition, the robustness of the empirical results is checked using the panel FMOLS developed by Pedroni [74] and panel DOLS by Pedroni [75]. The FMOLS and DOLS estimators provide elasticity calculations that are resistant to autocorrelation and endogeneity, and these estimators are effective in the absence of CD. Since the study does not detect CD in the panel data in the first phase, it uses FMOLS and DOLS methods.

4. Empirical results and robustness checks

The study conducts a CD test for the initial assessment of the unit root, cointegration, and cointegration estimator determination, and the empirical results are reported in Table 4. According to the CD estimation results, the null hypothesis of no CD is accepted at different statistical significance levels. It can be inferred that the first generation techniques can be used to estimate panel data to investigate the level of integration of variables, cointegration relations, and esimations of long-run coefficients. The IPS unit root test, Pedroni and variance ratio cointegration tests, panel ARDL, FMOLS and DOLS tests are used for these purpose.

Table 5 presents the IPS test results. The empirical outcomes denote that all variables follow a non-stationary process at the level in the model with constant, constant, and trend, while they become stationary at the first difference. It can therefore be established that all variables follow the I (1) process and a cointegration test can be applied in this situation.

The results of the Pedroni cointegration test in Table 6 show that the null hypothesis of no cointegration is accepted at various levels of statistical significance when the modified Phillips-Perron statistic is considered, while it can be rejected when the Phillips-Perron and modified Dickey-Fuller test statistics are considered. Furthermore, the results of the variance ratio cointegration test show that the null hypothesis of no cointegration is clearly rejected in all models. This leads to the conclusion that there is a long-term trade-off between coal consumption and the regressors. The long-term elasticity estimates are therefore carried out using the panel ARDL method.

The panel ARDL estimation results are reported in Table 7. The empirical outcomes for Model 1 imply that GDP growth increases coal

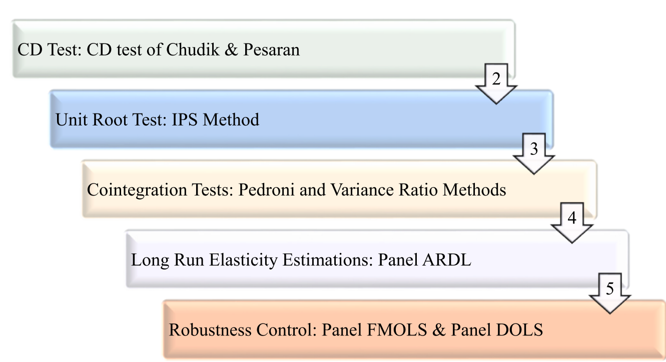

Fig. 4. Empirical strategy.

[2] Renewables includes hydropower, solar, wind, geothermal, and bioenergy.

Table 4
CD test results for variables.

Test	Model 1	Model 2	Model 3	Model 4	Model 5
CD	−1.470 (0.141)	0.218 (0.828)	−0.768 (0.443)	−1.255 (0.209)	−2.070 (0.038)

Notes: Probability values have been denoted in parenthesis.

Table 5
Unit root test results.

Variables	Constant		Constant & Trend	
	Level	First Difference	Level	First Difference
COAL	4.400 (0.999)	−15.890 (0.000)	−0.677 (0.249)	−16.104 (0.000)
GDP	−0.837 (0.201)	−3.887 (0.000)	0.428 (0.665)	−2.464 (0.006)
GDP^2	−0.175 (0.430)	−4.093 (0.000)	0.077 (0.530)	−2.439 (0.007)
PD	−0.262 (0.396)	−1.815 (0.034)	−0.463 (0.321)	−2.696 (0.003)
IND	0.331 (0.630)	−6.551 (0.000)	−0.815 (0.207)	−3.887 (0.000)
TRD	−1.173 (0.120)	−9.691 (0.000)	−0.012 (0.495)	−7.804 (0.000)
GAS	0.416 (0.661)	−4.980 (0.000)	−0.763 (0.222)	−3.783 (0.000)
REN	4.309 (0.999)	−6.688 (0.000)	1.827 (0.966)	−6.487 (0.000)

Note: See Table 3.

consumption, while GDP^2 reduces it. Besides, population density upsurges coal consumption. Moreover, similar empirical outcomes are obtained in the remaining models in terms of GDP, GDP,^{2} and PD. In light of these empirical outcomes, it can be inferred that there is an inverted-U-shaped nexus between coal consumption and economic development in the top coal-dependent countries. Therefore, the CKC is valid in the sample countries.

Industrialization and trade upsurges coal demand in Models 3 and 4. The consumption of natural gas and renewable energy mitigates coal demand in Models 4 and 5, respectively. Thus, an increase in industrialization and trade boosts demand for coal, while an increase in the demand for substitute energy sources, namely natural gas and renewable energy, reduces the demand for coal. In addition, the turning points of coal demand in relation to economic development are estimated and shown in Table 6 for each model. Considering the estimated outcomes, the average income level for the turning point is about US$ 11,664.

The robustness check of the estimated empirical results is performed using the panel FMOLS and DOLS, and the results are reported in Table 8. The empirical outcomes of FMOLS and DOLS in all models have proved that GDP has a positive impact on coal demand, while GDP^2 has a negative impact on it. Therefore, the FMOLS estimation results confirm the existence of CKC. The DOLS outcomes and the majority of the FMOLS outcomes for population density show that the increase in population density boosts the demand for coal. The FMOLS and DOLS findings confirm that industrialization is driving up coal demand, while natural gas consumption and renewable energy consumption are helping to reduce coal demand.

The FMOLS outcomes also denote that trade restricts coal demand, while the DOLS estimation results show that trade increases coal use. Considering the majority of empirical results, it can be concluded that trade boosts coal demand. It can be argued that DOLS and FMOLS estimation results remarkably confirm the ARDL estimation outcomes. It can be concluded that the findings are robust.

The validity of the CKC is an important point of discussion, as coal-dependent countries can displace coal with the benefits of economic expansion. Natural gas and renewables can also be used as important displacement instruments for this purpose, and possible scenarios are discussed in the following section.

5. Discussion

One of the biggest obstacles to improving ecological quality is seen in the consumption of fossil fuels. Burning energy sources such as coal and oil releases large amounts of CO_2 emissions, which exacerbate the adverse effects of global warming. The CO_2-increasing and harmful effects of coal consumption on the environmental conditions of countries have been demonstrated in various studies (see e.g., Ref. [76–78]). As coal combustion contains more carbon molecules, it produces more CO2 per unit of energy than oil and natural gas [79]. Coal threatens human health as it releases large amounts of CO_2. The use of coal causes serious health problems such as cancer, arsenicosis, premature births, and respiratory diseases [80]. The use of coal is a significant obstacle to sustainable development due to its negative impact on the environment and human health. Therefore, coal consumption should be reduced for a sustainable future and healthy societies. In this regard, the NZE targets require the gradual decommissioning of coal-fired power plants without interruption by 2040 [15].

Although previous researchers considered and still consider sustainable development in the context of the EKC [81,82] or focused directly on the impact of coal on CO_2 emissions (see e.g. Ref. [20]), the reduction of CO_2 in coal consumption is based on minimization. However, studies analyzing the determinants of coal consumption are quite

Table 7
ARDL estimation results.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
GDP	14.182 (0.000)	8.218 (0.000)	12.794 (0.000)	11.863 (0.000)	7.561 (0.000)
GDP^2	−0.788 (0.000)	−0.440 (0.000)	−0.734 (0.000)	−0.643 (0.000)	−0.377 (0.000)
PD	2.218 (0.000)	4.564 (0.000)	2.818 (0.000)	0.474 (0.021)	3.616 (0.000)
IND	–	0.306 (0.000)	–	–	–
TRD	–	–	0.316 (0.000)	–	–
GAS	–	–	–	−0.452 (0.000)	–
REN	–	–	–	–	−0.070 (0.000)
ECT	−0.299 (0.000)	−0.400 (0.000)	−0.293 (0.000)	−0.347 (0.000)	−0.358 (0.000)
Turning Point	8092	11,368	6095	10,137	22,629

Note: See Table 3.

Table 6
Cointegration results.

Test	Statistic	Model 1	Model 2	Model 3	Model 4	Model 5
Pedroni	**Modified Phillips-Perron**	0.175 (0.430)	1.3162 (0.094)	1.411 (0.079)	1.298 (0.097)	1.317 (0.093)
	Phillips-Perron	−4.411 (0.000)	−4.618 (0.000)	−3.988 (0.000)	−4.443 (0.000)	−4.245 (0.000)
	Modified Dickey-Fuller	−4.752 (0.000)	−4.867 (0.000)	−4.189 (0.000)	−5.061 (0.000)	−4.783 (0.000)
Westerlund	**Variance Ratio**	−3.244 (0.000)	−2.781 (0.000)	−2.830 (0.002)	−2.903 (0.001)	−2.909 (0.001)

Note: See Table 3.

Table 8
FMOLS and DOLS estimations for robustness check.

Variables	Model 1		Model 2		Model 3		Model 4		Model 5	
	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS	FMOLS	DOLS
GDP	37.413	5.876	39.065	7.998	6.001	8.451	21.573	6.989	38.874	4.444
	(0.000)	(0.004)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
GDP^2	−1.653	−0.289	−1.724	−0.448	−0.327	−0.479	−0.823	−0.343	−1.736	−0.218
	(0.000)	(0.017)	(0.000)	(0.000)	(0.000)	(0.000)	(0.013)	(0.000)	(0.000)	(0.000)
PD	−0.214	2.377	1.075	0.769	1.116	0.599	−0.290	5.1821	0.817	2.166
	(0.601)	(0.057)	(0.014)	(0.017)	(0.000)	(0.017)	(0.468)	(0.000)	(0.028)	(0.004)
IND	–		0.484	0.852	–	–	–	–	–	–
			(0.000)	(0.000)						
TRD	–		–		−0.294	0.064	–	–	–	–
					(0.000)	(0.035)				
GAS	–		–		–	–	−0.505	−0.089	–	–
							(0.000)	(0.000)		
REN	–		–		–	–	–	–	−0.191	−0.057
									(0.000)	(0.033)

Note: See Table 3.

limited. For example, Lin and Raza [83] found that coal consumption in Pakistan is widespread due to the expansion of the economy. Tang et al. [45] proved that economic development spurs coal utilization, while Raza and Lin [43] uncovered that increasing economic activities can boost coal demand.

Rare studies have found that there is an inverted U-shaped relationship between coal and income, such as EKC, and described this relationship as the CKC. Hao et al. [22] supported the validity of CKC for China. Kurniawan and Managi [53] verified the CKC for Indonesia. Qiao et al. [23] validated the CKC for 30 provinces in China. Tran et al. [84] confirmed an inverted U-shaped link between coal and income in Vietnam. The results of the present study confirm the validity of the CKC for the top 21 coal-consumer countries. Previous literature has generally analyzed the CKC for one country. For the countries that consume the most coal in the world, it is essential to minimize their overall coal consumption in order to achieve net zero targets. In this context, the validity of CKC shows that these countries need to increase their environmental investments by channeling their income gains into technologies that reduce coal consumption (e.g. increasing energy efficiency).

Population density is a factor that increases coal consumption. Regions with increasing population density require more energy, and these regions increase their coal consumption in the first phase of development. Population density is a factor that produces more coal for heating and for use in the industrial sector, thus releasing CO_2. This finding is consistent with Chen et al. [85]. It is also known that there is a close relationship between the industrial sector and coal demand. Udi et al. [54] noted that there is a unidirectional causality from industrialization to coal demand. Some studies show that industrialization is taking place in countries such as Bangladesh [86], China [87], South Korea [88] and Argentina [89], which increases CO_2 emissions in these developing countries.

The findings of the current study support this: Coal is called the king of the Industrial Revolution, but it is not part of the modern economy. The air pollution caused by coal utilization can ultimately be a barrier to economic growth [90]. Therefore, it is necessary for the top coal countries to change their energy mix for sustainable development. However, a reduction in coal consumption is possible either by increasing energy efficiency or by using substitute energy sources. In order to analyze this situation, the CO_2-reducing effects of natural gas and renewable energies are examined for the top coal consumer countries.

The results show that natural gas and renewable energies help to reduce coal demand in the countries with the highest coal consumption. The results on the role of renewables in mitigating CO_2 by reducing possible ecologically harmful energy utilization can be found in Fareed et al. [91], Erdogan et al. [92], and Karlilar et al. [93]. Although natural gas is sometimes considered as ecologically harmful as other hydrocarbon sources, such as coal and oil, it has been shown that whether natural gas can be harmful to ecology depends on the combustion technique. Therefore, natural gas is considered an excellent alternative to pollutant power sources, such as coal, as it emits fewer GHGs [94].

Mohammad et al. [95] emphasize that natural gas is the best source for substituting coal during the transition to renewables due to its competitiveness with coal. It can also be easily integrated into the renewable energy ecosystem. It is well known that renewable energy will become more affordable as technological innovation in renewable technologies advances. Therefore, natural gas can be a strong support for technological advances. However, it should be noted that a permanent alternative and long-term solution to reduce coal dependency and achieve decarbonization in the sample countries could be achieved through the diffusion of renewable energy [92], which is crucial for tackling climate change and achieving climate goals, such as the SDGs and the NZE. The results of the analysis show that natural gas can contribute more to reducing coal consumption than renewables. The main reason for this is probably that natural gas is an excellent alternative to coal for heating purposes. In contrast to Martins et al. [96], the role of natural gas in supporting carbon neutrality by reducing coal demand is consistent with the results of Dong et al. [97].

Policy options arising from these findings include increasing natural gas investment in top coal consumer countries, encouraging households to heat with natural gas, and supporting businesses that use natural gas through tax exemptions such as the alternative fuel excise tax credit. It is possible that the top coal consumer countries will reap the benefits of CKC and provide a better environment for their societies through the expansion of natural gas.

6. Conclusion and policy recommendations

6.1. Conclusion

The global economic system is at a critical juncture when it comes to combating climate change and improving environmental sustainability worldwide. In this context, shifting the energy mix by reducing dependence on fossil fuels and utilizing clean energy sources is seen as an effective way to combat climate change. To this end, policymakers are paying particular attention to reducing coal consumption. Coal has fueled the global economy for decades, but cannot be considered part of sustainable development as it is one of the most polluting fossil fuels. It is sometimes assumed that the use of high-quality coal can increase energy efficiency, which, in turn reduces coal use and GHGs concentration. However, in some cases, not even the quality of coal plays a significant role in ensuring energy efficiency [98], which is important for reducing resource utilization. Therefore, reducing coal dependency has become a significant task for policymakers in terms of sustainable development.

To find out where coal-dependent countries stand on cutting coal dependence, this study examines the validity of the CKC hypothesis in the 21 largest coal-consuming countries, taking into account the impact of trade, population density, natural gas, renewables, and industrialization on coal consumption. The study uses various panel cointegration tests and panel ARDL, FMOLS, and DOLS estimators, as there is no CD in the panel data. The results of the study show that CKC is valid; population density and industrialization increase coal consumption, while natural gas and renewables are substitutes that reduce the consumption of dirty energy.

6.2. Policy recommendations

The validity of CKC shows that the top coal consumer countries can switch to alternative and clean energy sources as their income levels rise. It is expected that an increasing economic development process will help the countries on the upward trend of the CKC to cut their coal dependence as long as economic development increases. However, the countries in the downward trend of the CKC should prohibit the increase of coal demand and reduce the current utilization level to transform the energy mix. How coal should be substituted is a significant policy question for policymakers. In this context, empirical evidence shows that renewables and natural gas are two good alternatives.

According to the results of the analysis, natural gas is more capable of reducing dependence on coal than renewables. For this reason, the top coal consumer countries may consider using more natural gas in the short term to ensure energy security and drive economic activity, while increasing the share of renewable energy utilization in the overall energy mix. To ensure a cleaner energy mix, renewables that are cleaner than natural gas, should be the ultimate goal. To this end, policymakers should prioritize the promotion of green energy investments in both public and private investments.

In addition, leading coal countries should minimize the negative impact of industrialization and population density on coal consumption through green urban planning and a green transformation in the industrial sector. Thus, achieving carbon neutrality and NZE for 2050 will be easier to achieve thanks to the reduction of carbon-intensive energy in the countries with the highest coal consumption. In this context, the top coal-consuming countries should provide more funding and tax breaks to producers and utilities to finance natural gas and invest in renewable energy. To achieve a more eco-friendlier trade mix in the top coal-dependent countries, policymakers could also consider expanding environmental taxes on trade to reduce the share of polluting goods and internalize the negative externalities of trade on environmental quality.

6.3. Limitation and future research

The study has some research limitations. First, the study analyzes a panel data sample that includes a mix of developed and developing countries. Future studies may analyze the validity of CKC in developed and developing top coal countries separately. The second limitation of the study is that it considers aggregated renewables and natural gas as clean energy. Future studies can analyze the impact of nuclear, solar, wind, and biomass on coal displacement separately. The third limitation of the study is related to the method, as the analysis only considers the characteristics of the time domain. In the future, researchers could also analyze the validity of CKC using frequency domain modeling. Finally, in the future, researchers could also analyze the environmental impact of the service sector as a determinant of CKC. In this way, more detailed information can be obtained on minimizing coal consumption.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] J. Turner, What can we learn from the role of coal in the Industrial Revolution?, 2021 Retrieved from https://www.economicsobservatory.com/what-can-we-learn-from-the-role-of-coal-in-the-industrial-revolution. (Accessed 1 January 2024).
[2] P. Riden, The output of the British iron industry before 1870, Econ. Hist. Rev. 30 (3) (1977) 442–459.
[3] E.A. Wrigley, Energy and the English industrial revolution, Phil. Trans. Math. Phys. Eng. Sci. 371 (1986) (2013) 20110568.
[4] EMBER, Top 25 coal power countries in 2020, 2021 Retrieved from https://ember-climate.org/insights/research/top-25-coal-power-countries-in-2020/. (Accessed 1 January 2024).
[5] International Energy Agency, Global coal demand set to remain at record levels in 2023, 2023 Retrieved from https://www.iea.org/news/global-coal-demand-set-to-remain-at-record-levels-in-2023. (Accessed 1 January 2024).
[6] M.Y. Raza, M. Cucculelli, Sustainable energy changeover in Pakistan: prospects, progress, and policies, Environ. Sci. Pollut. Control Ser. 31 (5) (2024) 6610–6627.
[7] Q. Wang, X. Song, Y. Liu, China's coal consumption in a globalizing world: insights from Multi-Regional Input-Output and structural decomposition analysis, Sci. Total Environ. 711 (2020) 134790.
[8] United Nations. Causes and Effects of Climate Change. 2024.Retrieved from https://www.un.org/en/climatechange/science/causes-effects-climate-change#:~:text=Fossil%20fuels%20–%20coal%2C%20oil%20and,of%20all%20carbon%20dioxide%20emissions. (Accessed 22 April 2024).
[9] M. Jakob, J.C. Steckel, F. Jotzo, B.K. Sovacool, L. Cornelsen, R. Chandra, T. Nace, The future of coal in a carbon-constrained climate, Nat. Clim. Change 10 (8) (2020) 704–707.
[10] S. Erdogan, U.K. Pata, M.T. Kartal, Exploring the Cost of decarbonizing the United States: a proposal for a green Sacrifice ratio, Environ. Model. Assess. (2024), https://doi.org/10.1007/s10666-024-09952-2.
[11] International Energy Agency, Net zero roadmap: a global pathway to keep the 1.5 °C goal in reach-2023 update, 2023 Retrieved from https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach/executive-summary. (Accessed 2 February 2024).
[12] IBISWorld, Global Coal Mining - Market Size, Industry Analysis, Trends and Forecasts (2024-2029), 2024 Retrieved from https://www.ibisworld.com/global/market-research-reports/global-coal-mining-industry/#IndustryStatisticsAndTrends. (Accessed 2 February 2024).
[13] EMBER, Global Electricity Review 2021, 2021 Retrieved from https://ember-climate.org/app/uploads/2021/03/Global-Electricity-Review-2021.pdf. (Accessed 11 February 2024).
[14] P. Jiang, H. Yang, X. Ma, Coal production and consumption analysis, and forecasting of related carbon emission: evidence from China, Carbon Manag. 10 (2) (2019) 189–208.
[15] IEA, Coal. https://www.iea.org/energy-system/fossil-fuels/coal, 2024. (Accessed 28 April 2024).
[16] ClientEarth, 2022. Retrieved from https://www.clientearth.org/latest/news/fossil-fuels-and-climate-change-the-facts/#:~:text=Coal%20is%20a%20fossil%20fuel,the%20world's%20total%20carbon%20emissions. (Accessed 28 April 2024).
[17] O.B. Adekoya, O.T. Kenku, J.A. Oliyide, M.A.S. Al-Faryan, On the COP26 and coal's phase-out agenda: striking a balance among the environmental, economic, and health impacts of coal consumption, J. Environ. Manag. 328 (2023) 116872.
[18] H. Hou, B. Xie, Y. Cheng, Analysis of carbon emissions and emission reduction from coal-fired power plants based on dual carbon targets, Sustainability 15 (9) (2023) 7369.

[19] N. Maamoun, R. Kennedy, W. Peng, D. D'souza, M. Gray, S. Lavelle, J. Urpelainen, Multi-dimensional and region-specific planning for coal retirements, iScience 26 (6) (2023) 106739.
[20] U.K. Pata, A. Kumar, The influence of hydropower and coal consumption on greenhouse gas emissions: a comparison between China and India, Water 13 (10) (2021) 1387.
[21] G.M. Grossman, A. Krueger, Environmental Impacts of a North American Free Trade Agreement, 1991. Working paper No. 3914.
[22] Y. Hao, Z.Y. Zhang, H. Liao, Y.M. Wei, China's farewell to coal: a forecast of coal consumption through 2020, Energy Pol. 86 (2015) 444–455.
[23] H. Qiao, S. Chen, X. Dong, K. Dong, Has China's coal consumption actually reached its peak? National and regional analysis considering cross-sectional dependence and heterogeneity, Energy Econ. 84 (2019) 104509.
[24] R.M. Solow, A contribution to the theory of economic growth, Q. J. Econ. 70 (1) (1956) 65–94.
[25] J. Kraft, A. Kraft, On the Relationship between Energy and GNP, The Journal of Energy and Development, 1978, pp. 401–403.
[26] R. Färe, S. Grosskopf, C.K. Lovell, C. Pasurka, Multilateral productivity comparisons when some outputs are undesirable: a nonparametric approach, Rev. Econ. Stat. (1989) 90–98.
[27] J. Rahko, A.A. Alola, Examining green productivity amidst climate change technological development and spillovers in the Nordic economies, J. Clean. Prod. 434 (2024) 140028.
[28] S. Kuznets, Economic growth and income inequality, Am. Econ. Rev. 45 (1955) 1–28.
[29] S. Erdogan, On the impact of natural resources on environmental sustainability in African countries: a comparative approach based on the EKC and LCC hypotheses, Resour. Pol. 88 (2024) 104492.
[30] R. Li, Q. Wang, L. Li, S. Hu, Do natural resource rent and corruption governance reshape the environmental Kuznets curve for ecological footprint? Evidence from 158 countries, Resour. Pol. 85 (2023) 103890.
[31] U.K. Pata, S. Karlilar, The integrated influence of energy security risk and green innovation on the material footprint: an EKC analysis based on fossil material flows, J. Clean. Prod. 435 (2024) 140469.
[32] Y. Lei, L. Li, D. Pan, Study on the relationships between coal consumption and economic growth of the six biggest coal consumption countries: with coal price as a third variable, Energy Proc. 61 (2014) 624–634.
[33] L. Jin-ke, W. Feng-hua, S. Hua-ling, Differences in coal consumption patterns and economic growth between developed and developing countries, Procedia Earth and Planetary Science 1 (1) (2009) 1744–1750.
[34] N. Apergis, J.E. Payne, Coal consumption and economic growth: evidence from a panel of OECD countries, Energy Pol. 38 (3) (2010) 1353–1359.
[35] Y. Wolde-Rufael, Coal consumption and economic growth revisited, Appl. Energy 87 (1) (2010) 160–167.
[36] R. Li, G.C. Leung, Coal consumption and economic growth in China, Energy Pol. 40 (2012) 438–443.
[37] N.M. Michieka, J.J. Fletcher, An investigation of the role of China's urban population on coal consumption, Energy Pol. 48 (2012) 668–676.
[38] J. Chai, M. Du, T. Liang, X.C. Sun, J. Yu, Z.G. Zhang, Coal consumption in China: how to bend down the curve? Energy Econ. 80 (2019) 38–47.
[39] M. Guidolin, T. Alpcan, Transition to sustainable energy generation in Australia: interplay between coal, gas and renewables, Renew. Energy 139 (2019) 359–367.
[40] M.Y. Raza, M.T.S. Shah, Analysis of coal-related energy consumption in Pakistan: an alternative energy resource to fuel economic development, Environ. Dev. Sustain. 22 (2020) 6149–6170.
[41] C. Wang, F. Wang, X. Zhang, Y. Wang, Y. Su, Y. Ye, H.O. Zhang, Dynamic features and driving mechanism of coal consumption for Guangdong province in China, J. Geogr. Sci. 32 (3) (2022) 401–420.
[42] W. Wang, X. Kao, Z. Lin, Y. Zhang, Has China's coal consumption really peaked?—prediction and scenario analysis of China's coal consumption peak under the double-carbon target, Front. Environ. Sci. 10 (2022) 974763.
[43] M.Y. Raza, B. Lin, Coal efficiency, carbon reduction, and future policy perspective in Pakistan's economic growth: a decomposition and decoupling approach, Front. Energy Res. 11 (2023) 1275221.
[44] T. Zaghdoudi, K. Tissaoui, M.H. Maaloul, Y. Bahou, N. Kammoun, Asymmetric connectedness between oil price, coal and renewable energy consumption in China: evidence from Fourier NARDL approach, Energy 285 (2023) 129416.
[45] S. Tang, M.Y. Raza, B. Lin, Analysis of coal-related energy consumption, economic growth and intensity effects in Pakistan, Energy 130581 (2024).
[46] Q. Wang, Y.E. Zeng, B.W. Wu, Exploring the relationship between urbanization, energy consumption, and CO2 emissions in different provinces of China, Renew. Sustain. Energy Rev. 54 (2016) 1563–1579.
[47] R. Li, L. Li, Q. Wang, The impact of energy efficiency on carbon emissions: evidence from the transportation sector in Chinese 30 provinces, Sustain. Cities Soc. 82 (2022) 103880.
[48] B.S. Eweade, H. Güngör, S. Karlilar, The determinants of ecological footprint in the UK: the role of transportation activities, renewable energy, trade openness, and globalization, Environ. Sci. Pollut. Control Ser. 30 (58) (2023) 122153–122164.
[49] C. Aytun, S. Erdogan, U.K. Pata, O. Cengiz, Associating environmental quality, human capital, financial development and technological innovation in 19 middle-income countries: a disaggregated ecological footprint approach, Technol. Soc. 76 (2024) 102445.
[50] Q. Wang, J. Sun, R. Li, U.K. Pata, Linking trade openness to load capacity factor: the threshold effects of natural resource rent and corruption control, Gondwana Res. 129 (2024) 371–380.
[51] Q. Wang, F. Zhang, R. Li, Revisiting the environmental kuznets curve hypothesis in 208 counties: the roles of trade openness, human capital, renewable energy and natural resource rent, Environ. Res. 216 (2023) 114637.
[52] Q. Wang, T. Yang, R. Li, Does income inequality reshape the environmental Kuznets curve (EKC) hypothesis? A nonlinear panel data analysis, Environ. Res. 216 (2023) 114575.
[53] R. Kurniawan, S. Managi, Coal consumption, urbanization, and trade openness linkage in Indonesia, Energy Pol. 121 (2018) 576–583.
[54] J. Udi, F.V. Bekun, F.F. Adedoyin, Modeling the nexus between coal consumption, FDI inflow and economic expansion: does industrialization matter in South Africa? Environ. Sci. Pollut. Control Ser. 27 (2020) 10553–10564.
[55] L.S. Tiewsoh, M. Sivek, J. Jirásek, Traditional energy resources in India (coal, crude oil, natural gas): a review, Energy Sources B Energy Econ. Plann. 12 (2) (2017) 110–118.
[56] Y. Man, Y. Han, Y. Hu, S. Yang, S. Yang, Synthetic natural gas as an alternative to coal for power generation in China: life cycle analysis of haze pollution, greenhouse gas emission, and resource consumption, J. Clean. Prod. 172 (2018) 2503–2512.
[57] J. Li, Y. Tian, X. Yan, J. Yang, Y. Wang, W. Xu, K. Xie, Approach and potential of replacing oil and natural gas with coal in China, Front. Energy 14 (2020) 419–431.
[58] G. Clark, D. Jacks, Coal and the industrial revolution, 1700–1869, Eur. Rev. Econ. Hist. 11 (1) (2007) 39–72.
[59] K.B. Medlock III, R. Soligo, Economic development and end-use energy demand, Energy J. 22 (2) (2001) 77–105.
[60] E. Boserup, The impact of scarcity and plenty on development, J. Interdiscipl. Hist. 14 (2) (1983) 383–407.
[61] J. Komlos, Nutrition, population growth, and the industrial revolution in England, Soc. Sci. Hist. 14 (1) (1990) 69–91.
[62] P. Sapkota, U. Bastola, Foreign direct investment, income, and environmental pollution in developing countries: panel data analysis of Latin America, Energy Econ. 64 (2017) 206–212.
[63] S. Erdogan, Linking natural resources and environmental sustainability: a panel data approach based on the load capacity curve hypothesis, Sustain. Dev. (2023). https://doi.org/10.1002/sd.2836.
[64] O. Mindali, A. Raveh, I. Salomon, Urban density and energy consumption: a new look at old statistics, Transport. Res. Pol. Pract. 38 (2) (2004) 143–162.
[65] Z. Jia, B. Lin, How to achieve the first step of the carbon-neutrality 2060 target in China: the coal substitution perspective, Energy 233 (2021) 121179.
[66] United Nations, Cut the Coal, 2024 Retrieved from https://www.un.org/en/climate-action/cut-coal. (Accessed 22 April 2024).
[67] K. Hayhoe, H.S. Kheshgi, A.K. Jain, D.J. Wuebbles, Substitution of natural gas for coal: climatic effects of utility sector emissions, Climatic Change 54 (2002) 107–139.
[68] M.D. Leonard, E.E. Michaelides, D.N. Michaelides, Substitution of coal power plants with renewable energy sources–Shift of the power demand and energy storage, Energy Convers. Manag. 164 (2018) 27–35.
[69] A. Chudik, M.H. Pesaran, Common correlated effects estimation of heterogeneous dynamic panel data models with weakly exogenous regressors, J. Econom. 188 (2) (2015) 393–420.
[70] K.S. Im, M.H. Pesaran, Y. Shin, Testing for unit roots in heterogeneous panels, J. Econom. 115 (1) (2003) 53–74.
[71] P. Pedroni, Critical values for cointegration tests in heterogeneous panels with multiple regressors, Oxf. Bull. Econ. Stat. 61 (S1) (1999) 653–670.
[72] J. Westerlund, New simple tests for panel cointegration, Econom. Rev. 24 (3) (2005) 297–316.
[73] M.H. Pesaran, Y. Shin, R.P. Smith, Pooled mean group estimation of dynamic heterogeneous panels, J. Am. Stat. Assoc. 94 (446) (1999) 621–634.
[74] P. Pedroni, Fully modified OLS for heterogeneous cointegrated panels, Adv. Econom. 15 (2000) 93–130.
[75] P. Pedroni, Purchasing power parity tests in cointegrated panels, Rev. Econ. Stat. 83 (4) (2001) 727–731.
[76] U.K. Pata, The influence of coal and noncarbohydrate energy consumption on CO_2 emissions: revisiting the environmental Kuznets curve hypothesis for Turkey, Energy 160 (2018) 1115–1123.
[77] K. Cheng, H.P. Hsueh, O. Ranjbar, M.C. Wang, T. Chang, Urbanization, coal consumption and CO2 emissions nexus in China using bootstrap Fourier Granger causality test in quantiles, Letters in Spatial and Resource Sciences 14 (2021) 31–49.
[78] C. Magazzino, M. Mele, N. Schneider, A machine learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO2 emissions, Renew. Energy 167 (2021) 99–115.
[79] MIT, Why does burning coal generate more CO2 than oil or gas?. https://climate.mit.edu/ask-mit/why-does-burning-coal-generate-more-co2-oil-or-gas, 2022. (Accessed 25 February 2024).
[80] M. Hendryx, K.J. Zullig, J. Luo, Impacts of coal use on health, Annu. Rev. Publ. Health 41 (2020) 397–415.
[81] A.A. Alola, U.T. Donve, Environmental implication of coal and oil energy utilization in Turkey: is the EKC hypothesis related to energy? Manag. Environ. Qual. Int. J. 32 (3) (2021) 543–559.
[82] R. Li, Q. Wang, J. Guo, Revisiting the environmental Kuznets curve (EKC) hypothesis of carbon emissions: exploring the impact of geopolitical risks, natural resource rents, corrupt governance, and energy intensity, J. Environ. Manag. 351 (2024) 119663.
[83] B. Lin, M.Y. Raza, Coal and economic development in Pakistan: a necessity of energy source, Energy 207 (2020) 118244.

[84] N.D. Tran, N.C. Sahu, P. Kumar, Income, coal consumption, and the environmental Kuznets curve in Vietnam, Environ. Sci. Pollut. Control Ser. 30 (20) (2023) 58200–58212.
[85] J. Chen, Q. Xian, J. Zhou, D. Li, Impact of income inequality on CO2 emissions in G20 countries, J. Environ. Manag. 271 (2020) 110987.
[86] M. Shahbaz, G.S. Uddin, I.U. Rehman, K. Imran, Industrialization, electricity consumption and CO2 emissions in Bangladesh, Renew. Sustain. Energy Rev. 31 (2014) 575–586.
[87] X. Liu, J. Bae, Urbanization and industrialization impact of CO2 emissions in China, J. Clean. Prod. 172 (2018) 178–186.
[88] M.J. Song, Y.J. Seo, H.Y. Lee, The dynamic relationship between industrialization, urbanization, CO2 emissions, and transportation modes in Korea: empirical evidence from maritime and air transport, Transportation 50 (6) (2023) 2111–2137.
[89] L.C. Voumik, M. Ridwan, Impact of FDI, industrialization, and education on the environment in Argentina: ARDL approach, Heliyon 9 (1) (2023) e12872.
[90] Economics Observatory, What can we learn from the role of coal in the Industrial Revolution?. https://www.economicsobservatory.com/what-can-we-learn-from-the-role-of-coal-in-the-industrial-revolution, 2021. (Accessed 27 February 2024).
[91] Z. Fareed, S. Salem, T.S. Adebayo, U.K. Pata, F. Shahzad, Role of export diversification and renewable energy on the load capacity factor in Indonesia: a Fourier quantile causality approach, Front. Environ. Sci. 9 (2021) 770152.
[92] S. Erdogan, U.K. Pata, S.A. Solarin, Towards carbon-neutral world: the effect of renewable energy investments and technologies in G7 countries, Renew. Sustain. Energy Rev. 186 (2023) 113683.
[93] S. Karlilar, M. Balcilar, F. Emir, Environmental sustainability in the OECD: the power of digitalization, green innovation, renewable energy and financial development, Telecommun. Pol. 47 (6) (2023) 102568.
[94] United Nations Environmental Programme, Is natural gas really the bridge fuel the world needs?. https://www.unep.org/news-and-stories/story/natural-gas-really-bridge-fuel-world-needs, 2023. (Accessed 22 April 2024).
[95] N. Mohammad, W.W. Mohamad Ishak, S.I. Mustapa, B.V. Ayodele, Natural gas as a key alternative energy source in sustainable renewable energy transition: a mini review, Front. Energy Res. 9 (2021) 625023.
[96] T. Martins, A.C. Barreto, F.M. Souza, A.M. Souza, Fossil fuels consumption and carbon dioxide emissions in G7 countries: empirical evidence from ARDL bounds testing approach, Environ. Pollut. 291 (2021) 118093.
[97] K. Dong, X. Dong, X. Ren, Can expanding natural gas infrastructure mitigate CO2 emissions? Analysis of heterogeneous and mediation effects for China, Energy Econ. 90 (2020) 104830.
[98] A. Jindal, R. Nilakantan, Falling efficiency levels of Indian coal-fired power plants: a slacks-based analysis, Energy Econ. 93 (2021) 105022.