



Investigating whether the environmental Kuznets curve hypothesis holds for sectoral CO₂ emissions: evidence from developed and developing countries

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Abstract

Carbon dioxide (CO₂) emissions entail a key component of greenhouse gases (GHGs) and are crucial for global warming and climate change issues. Although the environmental Kuznets curve (EKC) pattern of the emissions–income nexus has intrigued many researchers for a long time, few studies cover a wide range of economic sectors and a large number of countries, which calls for the re-investigation of sector-wise EKC arguments. Thereby, we investigate the long-run equilibrium relationship between CO₂ emissions and per capita income in a panel of 86 developing and developed countries for the period from 1990 through 2015. Our findings show that the EKC holds for three sectors: the electricity and heat production sector, the commercial and public services sector, and the other energy industry own use sector with the turning points of approximately 21,000 USD, 3000 USD, and 5000 USD, respectively. Additionally, emissions decrease monotonically for the manufacturing industries and construction sector, the residential sector, and the agriculture, forestry, and fishing sector, whereas they increase monotonically with the development of the transport sector. Policymakers should consider adopting sector-specific environmental policies based on each sector’s unique income–emission relationship, to mitigate CO₂ emissions effectively, and attain sustainable economic growth.

Keywords Sector-wise CO₂ emissions · Environmental Kuznets curve · ARDL

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1 Introduction

Since the pioneering work of Grossman & Krueger (1991), many studies have evaluated the environmental Kuznets curve (EKC) hypothesis to investigate the relationship between economic development and emissions (Alola & Ozturk, 2021; Baloch et al., 2021; Sarkodie & Ozturk, 2020). However, a crucial issue is, the emission–income relationship can differ across economic sectors. From the perspective of carbon dioxide (CO₂) emission dynamics, each economic sector has different features, depending on its energy requirements, variety of available energy resources, technological advancement, economies of scale, and governmental policies. Such diversified features cause different sectors to follow different paths of the structural transformation of energy dynamics during economic development, which could result in different patterns of the emissions–income relationship, across economic sectors. For example, the transportation sector experiences a surge in the movement of people and products, owing to globalization (Sharif et al., 2020); the residential sector experiences energy ladder patterns in the sense that households shift from dirty traditional fuels to clean modern fuels as their income level rises (Hosier & Dowd, 1987; Leach, 1992). Although some studies examine the sectoral emissions–income nexus while focusing on a specific sector, such as the manufacturing, transportation, and residential sectors, and on a specific country, region, or group of countries (Congregado et al., 2016; Raza et al., 2020; Wang et al., 2017; Zhang et al., 2019b), comprehensive studies on a wide range of economic sectors and countries are still scarce. This study attempts to fill this gap by examining the validity of the EKC argument in seven economic sectors, over 86 developed and developing countries.

Today, economies rely on fossil fuel energy, such as coal, oil, and natural gas significantly. This is one of the critical causal factors of higher carbon dioxide (CO₂) emissions in the atmosphere and global warming. The World Bank estimates that per capita CO₂ emissions had accelerated from 1.5 metric tons in 1980 to 7.5 metric tons in 2014. Moreover, the Intergovernmental Panel on Climate Change's (IPCC) Special Report (2019) emphasizes that the global temperature will reach 1.5 °C above pre-industrial levels by 2040 if the uncontrolled emissions of global greenhouse gas continue, emphasizing the threat of environmental issues. Currently, many countries are the parties of the 2016 Paris Agreement to limit global warming well below 2 °C, which has shed light on the importance of curbing CO₂ emissions at the global level. Moreover, as we strive for “achieving universal access to economic, safe and modern energy services by 2030” as stipulated in the Sustainable Development Goals (SDGs), reduction in CO₂ emissions through transitioning to cleaner renewable energy sources, such as hydropower, solar, wind, and geothermal, has become an utmost priority for policymakers.

Many studies have found an association between CO₂ emissions and income level (Apergis & Ozturk, 2015; Boutabba, 2014; Ganda, 2019; Jalil & Feridun, 2011; Kais & Sami, 2016; Ozturk & Acaravci, 2013; Shahbaz et al., 2019). These studies generally provide evidence of an inverted U-shape relationship, the environmental Kuznets curve (EKC) hypothesis, in which CO₂ emissions increase with an increase in the income level until reaching a threshold level, and decline as the income level continues to surge beyond the threshold level. Most studies focus on the aggregate country-level of CO₂ emissions. However, studies have not examined the income–emissions relationship at the sectoral level sufficiently.

Countries are likely to undergo economic and industrial structural changes as they develop, thereby some sectors expand, whereas others shrink. Additionally, each sector

has unique characteristics regarding energy mix, energy intensity, energy alternatives, and technologies. For example, households in the residential sector switch their energy consumption from dirtier (e.g., firewood, charcoal, and bio-wastes) to clean sources (e.g., gas, electricity, and solar) as they achieve higher income levels (Leach, 1992; Saatkamp et al., 2000). The electricity and heat production sector is considered to transform from conventional non-renewable energy sources (e.g., coal, gas, and oil) to renewable energy sources (e.g., hydropower, nuclear power, and wind power) with the attainment of a higher income level (Wang et al., 2017). Such sectoral heterogeneity suggests that different sectors may have different patterns in the income–emissions relationship. This motivates us to investigate the sectoral income–emissions relationship in both developed and developing countries, which will help us implement a uniquely designed environmental regulatory framework for each sector to address environmental quality issues effectively.

Some empirical studies focus on sector-wise CO₂ emissions. However, their coverage is generally limited to specific sectors, countries, or groups of countries. Among these studies, some examined the income–emissions relationship for specific sectors (Hashmi et al., 2020, for the service sector; Zhang et al., 2019b, for the manufacturing and construction sector; Anser et al., 2020, for the residential sector), for specific countries (Wang et al., 2017, for China; Aslan et al., 2018, for the USA; Gokmenoglu & Taspinar, 2018, for Pakistan; Pratiyo et al., 2020, for Indonesia), and a specific group of countries (Pablo-Romero & Sánchez-Braza, 2017, for the European Union; Raza et al., 2020, for 16 emerging countries; Murshed et al., 2020, for the Organization of the Petroleum Exporting Countries (OPEC) countries). In contrast, our study investigates the income–emissions relationship by covering a wide range of sectors and numerous developed and developing countries. In this respect, our study explores the prominent features of the diversity of sectoral emissions and reveals distinct income–emission patterns in multiple economic sectors, which is a novel contribution to the existing literature in the context of environment and development studies. Following the classification of the International Energy Agency (IEA), we consider CO₂ emissions for seven economic sectors¹: (i) electricity and heat production, (ii) manufacturing industries and construction, (iii) residential, (iv) transport, (v) agriculture, forestry, and fishing; (vi) commercial and public services; and (vii) other energy industry own use. We use panel data from 86 developed and developing countries from 1990 to 2015. Our analysis allows us to evaluate whether the EKC hypothesis holds for each sector comprehensively.

We examine the long-run income–emissions relationship with their short-run dynamics using a panel autoregressive distributed lag (ARDL) model proposed by Pesaran et al. (1999). Our analysis shows clear differences in the income–emissions relationship across sectors. The EKC hypothesis holds for three sectors (electricity and heat production, commercial and public services, and other energy industry own use). Regarding these three sectors, at the early stage of development, sector-wise CO₂ emissions increase with an increase in income level. Once the income level reaches a threshold level, sector-wise CO₂ emissions start declining. The results also show that as the income level increases, the commercial and public services sector first reaches its threshold income level, followed by the other energy industry own use sector and the electricity and heat production sector. In contrast, our study does not observe EKC patterns for the other four sectors (manufacturing industries and construction, residential, transport, agriculture, forestry, and fishing).

¹ For the details, see International Energy Agency (2021).

Sector-wise CO₂ emissions are negatively linked with the income level of the manufacturing industries and construction sector, the residential sector, and the agriculture, forestry, and fishing sector. However, these are positively associated with the income level in the transport sector. Several sensitivity tests were performed to confirm the consistency of the main results.

These findings make some key contributions to the design and implementation of environmental policies. First, developing countries should focus more on the sectors in which the EKC hypothesis holds (electricity and heat production, commercial and public services, and other energy industry own use) to mitigate the environmental degradation associated with economic progress. Second, both developed and developing countries could benefit from expediting the pace of emissions reduction in sectors where the emissions are negatively linked with the income level (manufacturing industries and construction, residential, agriculture, forestry, and fishing) by implementing appropriate policy measures. Third, both developed and developing countries should prioritize the transport sector in their national plans and programs to improve environmental quality, as this sector is vulnerable to the increase in emissions as their economies develop.

The rest of the paper is organized as follows. Section 2 comprises the literature review. Section 3 describes the empirical analysis, which encompasses data and model specifications. Section 4 presents the empirical results and related discussions. Section 5 concludes the study and provides policy suggestions.

2 Literature review

2.1 The environmental Kuznets curve hypothesis

The environmental Kuznets curve (EKC) is the hypothesized association between economic development and environmental degradation. EKC is named after Kuznets (1955), who first conceptualized the bell-shaped relationship between income inequality and economic development. The EKC concept emerges following Grossman & Krueger's (1991) study, which shows that the relationship between pollution and economic growth resembles an inverted U-shaped curve. Environmental degradation and pollution increase in the early stages of economic development. However, they subside with further economic growth after reaching a certain income level.

Grossman (1995) presented three possible channels for a bell-shaped EKC pattern: the scale effect, composition effect, and technique effect. First, at the early stage of development, a country experiences a scale effect in which the pollution level rises along with increased economic activities. At this stage, environmental quality continues to deteriorate as policymakers overlook environmental issues, and people have a greater tolerance for pollution. Second, as the country enters a more advanced stage of development, the economy undergoes a structural transformation from dirtier to cleaner economic activities, including the movement of resources from the polluting industrial sector to the cleaner service sector as well as the establishment of cleaner industries, which is considered the composition effect. Third, technological progress accelerates at the final stage of economic development as governments implement environment-saving policies, and citizens demand a healthier and cleaner environment, resulting in a lower level of environmental degradation under the technique effect. Many empirical studies support the concept of nonlinear relationships (Chen et al., 2019, for China;

Usman et al., 2019, for India; Sun et al., 2020, for the Organization for Economic Cooperation and Development (OECD) region and Belt and Road region; Churchill et al., 2020, for Australian states and territories; Alola & Ozturk, 2021, for the USA; Baloch et al., 2021, for the OECD countries; Sarkodie & Ozturk, 2020, for Kenya). Some studies extend the EKC concept even further by incorporating other macroeconomic variables, such as industrial structure and urbanization. For example, Wang & Wang (2021a) investigated the nonlinear effects of population aging on CO₂ emissions in 137 countries by employing a panel threshold regression (PTR) model, and indicated that the associations between industrial structure and CO₂ emissions with the increase in population aging are positive, negative, and have an inverted U-shaped in high-income, upper-middle-income, and low-income countries, respectively. Additionally, following the increase in population aging, the associations between urbanization and CO₂ emissions in high-income countries have an inverted U-shape, whereas the associations in the upper-middle, lower-middle, and low-income groups are nonlinear and positive.

Although many empirical studies support the EKC hypothesis, they have often been criticized for various issues (Kaika & Zervas, 2013). First, the assumption of a normal distribution of world income level in the EKC hypothesis has been criticized as it may result in an inaccurate estimate of the turning point for the EKC. This is attributed to the fact that a significantly larger number of people are below the world's mean income level, which causes world income distribution to be highly skewed (Stern et al., 1996; Stern, 2004a). Second, it is often argued that developing countries cannot reduce pollutant emissions at a later stage of development compared with what developed countries had achieved in the past. This is attributed to the fact that developed countries take advantage of developing countries with less strict regulations by relocating their domestic pollution-intensive industries to developing countries, and the developing countries are not in a position to outsource their pollution-intensive industries to other countries any further (Cole, 2004; Stern et al., 1996). Third, even if developed countries reduce production-based pollution through technological advancement and structural changes, their consumption remains pollution-intensive (Wagner, 2010). Therefore, the overall effect may cause higher environmental degradation, which the EKC hypothesis may not reflect (Kaika & Zervas, 2013). Fourth, some empirical studies claim that the EKC hypothesis does not hold for pollutants that have long-term effects on human health and the quality of life and a comparatively high abatement cost (Arrow et al., 1995; Dinda, 2004). Finally, several studies criticize the previous empirical findings related to the EKC hypothesis for the limited coverage and poor quality of data (Stern et al., 1996), assuming that every country would follow a similar EKC pattern in the panel data, ignoring the heterogeneity of countries in nature (De Bruyn et al., 1998), omitted variable bias (Stern, 2004b), problems of using a mixture of stationary and non-stationary series leading to misleading inferences in panel unit root tests (Lee & Lee, 2009), and the assumption of unidirectional causality running from income to environmental quality (Arrow et al., 1995; Stern et al., 1996).

Several related studies do not provide clear evidence of the EKC hypothesis. For example, Zoundi (2017) investigated 25 selected African countries over the period from 1980 through 2012, and showed that the EKC hypothesis does not hold. Using data that spanned from 1857 to 2007, Esteve & Tamarit (2012) failed to observe the EKC relationship between per capita CO₂ and per capita income for the Spanish economy. Some studies also verify different shapes of the nonlinear relationship between income and CO₂ emissions, such as N- and U-shaped relationships (e.g., an N-shaped EKC by Lorente & Álvarez-Heranz, 2016, for 17 OECD countries; Bekun et al., 2021a, for 10 sub-Saharan African countries; a U-shaped EKC by Ozcan, 2013, for 12 Middle East countries), and argue that the

income–emissions relationship may be more complicated than what the EKC hypothesis assumes.

Existing related studies also discuss the role of other macroeconomic indicators, such as trade openness, energy consumption, renewable energy, and urbanization, in relation to CO₂ emissions in various regions and countries. For example, Adedoyin et al. (2021a) showed that sustainable and alternative energy are negatively associated with CO₂ emissions, while trade openness and income are positively associated with CO₂ emissions in 27 European Union countries. Nathaniel et al. (2021) found that CO₂ emissions are positively related to urbanization, natural resources, economic growth, and globalization, while human capital is negatively related to CO₂ emissions in 18 Latin American and Caribbean countries. Several studies also showed that CO₂ emissions are negatively associated with economic growth, trade openness, and economic policy uncertainty (Adedoyin et al., 2021b; Udemba et al., 2021; Wada et al., 2021).

2.2 Sector-wise CO₂ emissions and the income level

Recently, in the wake of climate change issues, studies on the EKC hypothesis for the income–pollution nexus in different economic sectors have received attention. Most of these studies provide evidence of the EKC hypothesis for sectoral CO₂ emissions. For example, Congregado et al. (2016) investigated the existence of the EKC hypothesis for the income–pollution nexus in five economic sectors (commercial, electrical, industrial, residential, and transport sectors) in the USA, by applying the dynamic ordinary least squares (DOLS) method with structural breaks for the period from 1973Q1 to 2015Q2, and proved that the EKC holds in all sectors except the industrial sector. Using panel data and panel fixed effects regression, Wang et al. (2017) examined the relationship between economic growth and industrial CO₂ emissions in three sectors, including the mining, manufacturing, electricity, and heat production sectors in China spanning from 2000 through 2013, and found evidence of the EKC hypothesis in the electricity and heat production sector. Zhang et al. (2019b) examined the nexus between income and CO₂ emissions in the manufacturing and construction industry sector of 121 countries throughout 1960–2014, using the panel fixed effects estimation and confirmed that the EKC hypothesis can be validated in 95 out of 121 countries, during the stated study period. Employing fully modified ordinary least squares (FMOLS) for the panel data of 16 emerging economies, Raza et al. (2020) found the validity of the EKC hypothesis in the residential sector.

Among related studies on sector-wise CO₂ emissions, some fail to provide evidence of the EKC hypothesis, while others observe various shapes of the nonlinear income–emissions relationship. For example, Fujii & Managi (2013) identified the N-shaped pattern between income level and CO₂ emissions in nine industries in the OECD from 1970 to 2005, using a panel regression analysis. Moutinho et al. (2020) confirmed the U-shaped relationship between economic development and sectoral CO₂ emissions in three sectors (agriculture, forestry, and fisheries; construction; remaining activities) out of seven sectors of 12 oil-producing and exporting countries (OPEC) from 1992 to 2015, using the panel-corrected standard error (PCSE) model. Erdoğan et al. (2020) could not prove the existence of the EKC hypothesis in the energy, transport, and other sectors of 14 G20 countries during the period from 1991 to 2017.

Although many studies examine the linkage between sector-wise CO₂ emissions and income level, the scope of their studies is limited to a specific sector, country, or group of countries. To the best of our knowledge, this study is the first to examine the existence

of the EKC pattern of the income–emissions relationships, incorporating both developed and developing countries, and covering a comprehensive range of economic sectors. By addressing the distinguished features of sectoral heterogeneity representing different income–emission nexuses in multiple economic sectors, our study could make a valuable contribution to the existing literature in the context of environment and development studies. Furthermore, evaluating the presence of the EKC pattern for each sector enables environmental regulators to plan and implement effective environmental policies to mitigate pollution issues in different economic sectors.

3 Methodology and data

3.1 Data

This study employs yearly panel data from 86 developing and developed countries from 1990 to 2015.² Table 1 presents a list of the sample countries. We use the database of the International Energy Agency (IEA) on CO₂ emissions from fuel combustion to obtain sector-wise CO₂ emissions. Our study analyzes the total CO₂ emissions and seven sectors (components) of (i) electricity and heat production; (ii) manufacturing industries and construction; (iii) residential; (iv) transport; (v) commercial and public services; (vi) agriculture, forestry, and fishing; and (vii) other energy industry own use³ (International Energy Agency, 2021) to ascertain the relationships between sector-wise CO₂ emissions and per capita income level. We use the World Development Indicators (WDI) of the World Bank to acquire other variables such as per capita GDP, total final energy consumption, and total renewable energy share.

Table 2 presents the descriptive statistics of the variables used in the analysis. Regarding sector-wise CO₂ emissions, the electricity and heat production sector produces the largest share of CO₂ emissions on average, followed by the transport sector. The other energy industry own use sector produces the smallest share of CO₂ emissions. Table 3 presents the correlation matrix of the variables. As expected, CO₂ emissions positively correlate with the total energy consumption and negatively correlate with renewable energy share. Additionally, CO₂ emissions are positively correlated with income levels.

3.2 Model specification

This study aims to investigate the nonlinear relationship between income level and sector-wise CO₂ emissions. To identify the relationships, we consider the following model specifications for each sector⁴:

² Owing to data unavailability, the coverage of the commercial and public services sector, the agriculture, forestry, and fishing sector, and the other energy industry own use sector is 57, 60, and 61 countries, respectively.

³ It is worth noting that other energy industry own use sector contains emissions from fuel combusted in oil refineries, for the manufacture of solid fuels, coal mining, oil and gas extraction and other energy-producing industries. Any CO₂ emissions from the use of electricity or heat generation are included in the electricity and heat production sector. The manufacturing industries and construction sector comprise CO₂ emissions from the combustion of fuels in the industry only.

⁴ Additionally, we estimate the linear model specification.

Table 1 Sample countries

Developed countries	Developing countries
Australia	Algeria
Austria	Bangladesh
Bahamas, The	Bolivia
Barbados	Botswana
Belgium	Brazil
Canada	Bulgaria
Chile	Burkina Faso
Cyprus	Burundi
Denmark	Cameroon
Finland	China
France	Colombia
Germany	Costa Rica
Greece	Cote d'Ivoire
Hong Kong SAR, China	Dominica
Iceland	Dominican Republic
Ireland	Ecuador
Italy	Egypt, Arab Rep
Japan	El Salvador
Korea, Rep	Eswatini
Luxembourg	Ethiopia
Macao SAR, China	Fiji
Mauritius	Gabon
Netherlands	Guatemala
New Zealand	Haiti
Norway	Honduras
Panama	India
Poland	Indonesia
Portugal	Jamaica
Romania	Jordan
Saudi Arabia	Kenya
Singapore	Malawi
Slovenia	Malaysia
Spain	Mauritania
Sweden	Mexico
Switzerland	Morocco
UK	Nigeria
USA	Pakistan
Uruguay	Peru
	Philippines
	Senegal
	South Africa
	Sri Lanka
	Sudan
	Tanzania
	Thailand
	Tunisia
	Turkey
	Zambia

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln Y_{it} + \beta_2 (\ln Y_{it})^2 + \sum_k \beta_k X_{k,it} + u_{it} \quad (1)$$

where $\ln CO_{2it}$ is the log of sector-wise CO₂ emissions (kt of CO₂) in country i in year t , $\ln Y_{it}$ is the log of the income level, $X_{k,it}$'s are other control variables expected to relate to CO₂ emissions, and u_{it} is the error term. The design of the empirical model specification

Table 2 Descriptive statistics

	Variable	Countries	Obs	Mean	Max	Min	Std. Dev
CO ₂ emissions (kt)							
Total		86	2236	237,337	9,188,381	61	833,923
Electricity and heat production		86	2236	97,000	4,347,398	3	371,606
Manufacturing industries and construction		86	2236	46,340	3,038,400	3	212,458
Residential		86	2236	16,956	385,853	6	49,981
Transport		86	2236	51,384	1,807,722	39	184,240
Agriculture/Forestry/Fishing		60	1482	5,751	114,706	3	13,461
Commercial and public services		57	1560	11,009	234,242	3	32,123
Other energy industry own use		61	1586	17,754	395,550	2	44,814
GDP per capita	Y	86	2236	16,881	111,968	164	20,322
Total final energy consumption	TFEC	86	2236	2,644,432	73,183,147	823	7,928,592
Renewable energy share in total	REC	86	2236	0.32	0.98	0.00	0.28
Total natural resource rent (% of GDP)	TNRR	86	2236	4.56	55.34	0.00	7.68
Trade openness (trade as % of GDP)	TRADE	86	2236	60.67	621.38	2.56	60.84

Table 3 Correlation matrix

	Y	TFEC	REC	TNRR	TRADE
Y	1.00				
TFEC	0.23	1.00			
REC	-0.68	-0.22	1.00		
TNRR	-0.31	0.01	0.31	1.00	
TRADE	0.52	-0.08	-0.37	-0.20	1.00
CO ₂ emissions (kt)					
Total	0.42	0.93	-0.52	-0.12	0.05
Electricity and heat production	0.41	0.80	-0.63	-0.18	0.08
Manufacturing industries and construction	0.37	0.93	-0.47	-0.09	0.00
Residential	0.34	0.91	-0.47	-0.13	-0.05
Transport	0.40	0.95	-0.45	-0.09	0.00
Agriculture/forestry/fishing	0.49	0.83	-0.52	-0.26	0.04
Commercial and public services	0.35	0.80	-0.46	-0.28	-0.03
Other energy industry own use	0.36	0.87	-0.44	-0.01	0.05

The sectoral CO₂ emissions, Y, and TFEC are expressed in the logarithmic form

and the selection of explanatory variables are based on the existing literature (Ganda, 2019; Liu et al., 2017; Sugiawan & Managi, 2016; Zoundi, 2017). The quadratic specification of income level is extensively used in research related to the EKC hypothesis of the income–emissions relationship. The quadratic model specification captures the nonlinear linkage between sector-wise CO₂ emissions and per capita income level. This study uses real GDP per capita as a measure of a country’s income level. Additionally, we incorporate the log of the total final energy consumption (terajoules) and the share of renewable energy in the total final energy consumption for other control variables into the model.

We employ a panel ARDL model to estimate the short- and long-run dynamics of the relationship between income level and CO₂ emissions. The panel ARDL model is more advantageous than other dynamic panel models, such as the fixed effects and the generalized methods of moment (GMM) estimators introduced by Anderson & Hsiao (1981, 1982), Arellano (1989), and Arellano & Bover (1995). It can be used to investigate a long-run relationship regardless of whether the variables are stationary at the level, at the first difference, or an integration of both (Pesaran et al., 2001). Furthermore, the ARDL estimates are unbiased, despite some regressors being endogenous (Harris & Sollis, 2003; Jalil & Ma, 2008). Additionally, the ARDL model is reliable for small samples (Haug, 2002).

To estimate the short-run and long-run associations between income level and CO₂ emissions, this study considers a panel ARDL model for Eq. (1), which takes the following error correction form:

$$\Delta \ln CO_{2it} = \varphi_i ECT_{it} + \sum_{j=1}^{p-1} \alpha_{ij}^* \Delta \ln CO_{2it-j} + \sum_{j=0}^{q-1} \Delta Z_{it-j} \beta_{ij}^* + \varepsilon_{it} \tag{2}$$

$$ECT_{it} = \ln CO_{2it-1} - Z_{it} \theta_i \tag{3}$$

where Δ is the difference operator, $\ln CO_{2it}$ is the log of sector-wise CO₂ emissions (kt), Z_{it} is the vector of explanatory variables (the log of GDP per capita and its squared value, the log of GDP per capita square, the log of total final energy consumption, and renewable energy share), ECT_{it} is the error correction term, and ε_{it} is the error term. The coefficient $\varphi_i = \left(1 - \sum_{j=1}^p \alpha_{ij}\right)$ on the error correction term captures the speed of convergence to the long-run equilibrium. The coefficient of the error correction term must be significantly negative (i.e., $\varphi_i < 0$), so that the system converges to the long-run equilibrium. The long-run coefficient is given by $\theta_i = -\frac{\sum_{j=0}^q \beta_{ij}}{\varphi_i}$. The coefficients of the short-run dynamics are given by $\alpha_{ij}^* = -\sum_{d=j+1}^p \alpha_{i,d}$ and $\beta_{ij}^* = -\sum_{d=j+1}^p \beta_{i,d}$. A panel ARDL model estimation can be performed using the mean group (MG) or panel mean group (PMG) estimator (Pesaran & Smith, 1995; Pesaran et al., 1999). The MG estimator allows parameters to differ across countries, while the PMG estimator imposes a homogeneity restriction on the long-run coefficients. However, it allows short-run coefficient and error variances to vary across countries. We perform the Hausman test to ascertain whether the MG or PMG estimator is appropriate for our panel ARDL model.

Table 4 Cross-section dependence test

Variables	Pesaran (2004) CD statistics
CO ₂ emissions	
Total	113.06***
Electricity and heat production	90.96***
Manufacturing industries and construction	20.14***
Residential	18.75***
Transport	189.35***
Commercial and public services	8.03***
Agriculture/forestry/fishing	16.79***
Other energy industry own use	28.58***
GDP per capita	216.05***
Total final energy consumption	164.61***
Renewable energy share (% of total)	12.01***
Total natural resource rent (% of GDP)	79.35***
Trade openness (trade as % of GDP)	141.62***

Null hypothesis: No cross-section dependence (correlation)

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

4 Results

4.1 Panel unit root tests

The panel ARDL model requires that all the variables are stationary at the level or the first difference (Pesaran et al., 1999, 2001). Previous studies examined the stationarity of variables using traditional unit root tests, such as Levin et al. (2002), Breitung (2000), Im et al. (2003), and Hadri (2000). However, these traditional unit root tests assume cross-sectional error independence in the panel data and are likely to suffer bias and inconsistencies (Banerjee et al., 2004; Phillips & Sul, 2003). Therefore, we need to ascertain whether the variables have cross-sectional dependence or independence in testing the stationarity of the variables. To verify the presence of cross-section dependence, we apply the cross-section dependence (CD) test introduced by Pesaran (2004). It is applicable to various panel data models, including stationarity and unit root dynamic heterogeneous panels with short periods and large cross-section units. Moreover, it is robust to the presence of unit roots and structural breaks. Table 4 presents the results of the CD test statistics, which confirm the presence of cross-section dependence for all the variables at the 1% significance level. Once all the variables are cross-sectionally dependent, we examine the stationarity of each variable using the cross-sectionally augmented IPS (CIPS) test of Pesaran (2007), allowing for heterogeneity and cross-sectional dependence. The test is based on an extended version of standard augmented Dickey–Fuller (ADF) regressions with the cross-sectional averages of lagged levels and first differences of the individual time series. Table 5 shows the CIPS test statistics, which confirm that all the variables are stationary at the level or the first difference at the 1% significance level. This result allows us to proceed with the analysis of panel cointegration and ARDL estimation.

Table 5 Unit root tests

Variables	Pesaran (2007)	
	CIPS t-stat (level)	CIPS t-stat (difference)
CO ₂ emissions		
Total	-2.01	-3.46***
Electricity and heat production	-1.94	-3.82***
Manufacturing industries and construction	-2.21**	-3.72***
Residential	-1.77	-3.57***
Transport	-1.90	-3.03***
Commercial and public services	-1.66	-3.77***
Agriculture/forestry/fishing	-2.34***	-4.09***
Other energy industry own use	-2.20**	-3.89***
GDP per capita	-2.26***	-2.62***
Total final energy consumption	-1.92	-3.64***
Renewable energy share (% of total)	-1.11	-3.32***
Total natural resource rent (% of GDP)	-2.70***	-3.64***
Trade openness (trade as % of GDP)	-2	-3.24***

Null hypothesis: The series is non-stationary

Note: ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

4.2 Panel cointegration test

Most studies consider cointegration tests that are based on residual-based cointegration tests as proposed by Engle & Granger (1987), Kao (1999), and Pedroni (2004), which require the long-run cointegrating vector at levels equal to the short-run adjustment process in their differences. This restriction is considered a common-factor restriction. Failure to comply with such a restriction results in a loss of power for residual-based cointegration tests (Banerjee et al., 1998; Kremers et al., 1992). The loss of power may result in a failure to reject the null hypothesis of no-cointegration, even in cases where cointegration is significantly suggested by theory (Westerlund, 2007).

Westerlund (2007) developed panel cointegration tests based on structural dynamics rather than relying on common-factor restrictions. This cointegration test provides better size accuracy and higher power than other residual-based cointegration tests. Westerlund (2007) proposed four test statistics: group mean statistics (G_{τ} and G_{α}) and panel statistics (P_{τ} and P_{α}). The group mean statistics are designed to test whether at least one cross section is cointegrated. In contrast, the panel statistics are designed to test whether the entire panel is cointegrated. The test statistics of the cointegration tests in Table 6 show that the G_{τ} and P_{τ} statistics (except the agriculture, forestry, and fishing sector) are statistically significant, which implies that there is a cointegration or long-run relationship among the variables.

Table 6 Cointegration tests

	Group mean statistics						Panel statistics					
	G_{τ}			G_{α}			P_{τ}			P_{α}		
	Value	Z-value	P-value	Value	Z-value	P-value	Value	Z-value	P-value	Value	Z-value	P-value
CO ₂ emissions												
Total	-2.77***	-5.24	0.00	-9.43	2.03	0.98	-31.3***	-12.76	0.00	-11.82***	-6.17	0.00
Electricity and heat production	-2.89***	6.50	0.00	-7.73	4.27	1.00	-23.21***	-5.11	0.00	-7.65	-0.26	0.40
Manufacturing industries and construction	-3.07***	-8.18	0.00	-6.95	5.29	1.00	-21.36***	-3.36	0.00	-6.9	0.80	0.79
Residential	-3.16***	-9.16	0.00	-8.42	3.36	1.00	-25.94***	-7.69	0.00	-9.39***	-2.73	0.00
Transport	-2.92***	-6.74	0.00	-8.48	3.28	1.00	-23.51***	-5.39	0.00	-9.36***	-2.69	0.00
Agriculture/forestry/fishing	-3.05***	-6.52	0.00	-7.12	4.13	1.00	-15.21	-0.67	0.25	-6.27	1.37	0.91
Commercial and public services	-3***	-6.32	0.00	-7.08	4.28	1.00	-18.87***	-3.78	0.00	-8.21	-0.88	0.19
Other energy industry own use	-2.88***	-5.37	0.00	-5.81	5.73	1.00	-19.62***	-4.37	0.00	-9.23**	-2.11	0.02

Null hypothesis: No cointegration

The optimal lag/lead is decided by Akaike's information criterion (AIC). ***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

4.3 ARDL estimation

After the completion of the stationarity and cointegration tests, we estimate the ARDL model. As suggested by Pesaran & Smith (1995) and Pesaran et al. (1999), we perform the Hausman test to select the MG or PMG estimator. The Hausman test statistics are insignificant for all sectors, implying that the PMG estimator is preferable to the MG estimator (Table 7). Therefore, we adopt the PMG-ARDL model to estimate the income–emissions relationship for each sector.

Table 7 presents the long-run and short-run coefficients of the PMG-ARDL models with linear and quadratic specifications for the total CO₂ emissions and sector-wise CO₂ emissions. Regarding the model with total CO₂ emissions as the dependent variable, the estimates show that the final energy consumption is positively related to the total CO₂ emissions, and renewable energy share is negatively related to the total CO₂ emissions. The long-run coefficients of the log of real GDP per capita and its square term are significantly positive and negative, respectively, confirming the validity of an inverted U-shaped environmental Kuznets curve for the income–emissions relationship. CO₂ emissions increase at the beginning of the development stage of a country and decline after reaching a certain threshold income level (also known as the turning or reversal point). The threshold income level is approximately 16,000 USD for the total CO₂ emissions. Our results for the inverted U-shaped income–emission relationship for the total CO₂ emissions are consistent with the findings of recent studies such as Alola & Ozturk (2021), Baloch et al. (2021), Bekun et al. (2021b), and Sarkodie & Ozturk (2020).

More importantly, considering sector-wise CO₂ emissions as the dependent variable of the ARDL model, we observe the apparent heterogeneity of the income–emissions relationship across sectors. Based on the estimated long-run coefficients of the log of real GDP per capita and its square term, all the sectors can generally be divided into three groups: (i) the sectors supporting the EKC hypothesis, (ii) the sectors with a negative income–emissions relationship, and (iii) the sectors with a positive income–emissions relationship. Figure 1 presents a summary of the main results.

The first group supporting the EKC hypothesis encompasses three sectors: the electricity and heat production sector, the commercial and public services sector, and the other energy industry own use sector. In these sectors, the estimated long-run coefficients of the log of real GDP per capita and its square term are significantly positive and negative, respectively, similar to the case of the total CO₂ emissions. Given the large share of CO₂ emissions from the electricity and heat production sector, the nonlinear pattern of the income–emissions relationship in the sector could be a source of the EKC pattern for the total CO₂ emissions. The estimated turning point for the electricity and heat production sector is approximately 21,000 USD, which is close to that for the total CO₂ emissions. Additionally, the estimated threshold income level for the commercial and public services sector and the other energy industry own use sector is approximately 3,000 USD and 5,000 USD, respectively, which are significantly lower than those for the electricity and heat production sectors. Regarding the three sectors that exhibit the EKC pattern, sector-wise CO₂ emissions increase at the early stage of the development of a country. However, CO₂ emissions peak out first for the commercial and public services sector, then for the other energy industry own use sector, and finally for the electricity and heat production sector.

Our results regarding the electricity and heat production sector are consistent with the findings of Aslan et al. (2018), showing that the EKC holds in the electrical sector in the USA. However, they are in contrast to the findings of Akbar et al. (2021) who showed that

Table 7 PMG-ARDL estimates

	Total		Electricity and heat production		Manufacturing industries and construction		Residential		Transport		Agriculture/forestry/fishing		Commercial and public services		Other energy industry own use	
	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic
(A) Long-run estimates																
log(Income)	-0.067*** (0.017)	0.775*** (0.105)	2.107*** (0.277)	0.277*** (0.059)	-0.678*** (0.04)	1.093*** (0.294)	-0.477*** (0.048)	-1.063*** (0.274)	0.259*** (0.029)	0.776*** (0.165)	-0.616*** (0.065)	0.854** (0.359)	-0.891*** (0.08)	1.283** (0.583)	-0.301*** (0.084)	1.077** (0.499)
log(Income) ²		-0.04*** (0.005)	-0.106*** (0.015)			-0.093*** (0.015)		0.04*** (0.014)		-0.028*** (0.008)		-0.064*** (0.017)		-0.08*** (0.03)		-0.064** (0.027)
log(final energy consumption)	0.967*** (0.018)	0.864*** (0.022)	0.733*** (0.048)	0.72*** (0.052)	1.202*** (0.037)	1.183*** (0.034)	0.937*** (0.044)	0.947*** (0.044)	0.931*** (0.023)	0.939*** (0.024)	0.658*** (0.063)	0.642*** (0.075)	1.478*** (0.11)	1.062*** (0.123)	1.144*** (0.069)	1.015*** (0.078)
Renewable energy share	-1.513*** (0.047)	-1.339*** (0.055)	-1.356*** (0.142)	-1.558*** (0.142)	-1.619*** (0.124)	-1.476*** (0.138)	-0.87*** (0.136)	-1.101*** (0.162)	-1.484*** (0.059)	-1.432*** (0.071)	-1.999*** (0.143)	-0.701*** (0.138)	-1.469*** (0.255)	-0.29 (0.415)	0.256 (0.273)	0.004 (0.292)
(B) Short-run estimates																
Error correction term	-0.231*** (0.025)	-0.27*** (0.028)	-0.248*** (0.024)	-0.291*** (0.026)	-0.246*** (0.022)	-0.308*** (0.024)	-0.225*** (0.025)	-0.267*** (0.029)	-0.243*** (0.025)	-0.283*** (0.026)	-0.224*** (0.028)	-0.245*** (0.031)	-0.283*** (0.036)	-0.32*** (0.037)	-0.254*** (0.03)	-0.286*** (0.031)
log(Income)	0.163* (0.091)	1.048 (6.415)	0.699** (2.325)	0.542 (12.325)	0.279 (0.175)	-17.143* (9.517)	-0.245* (0.143)	2.488 (11.413)	-0.024 (0.093)	11.07* (6.297)	0.175 (0.257)	3.013 (17.636)	-0.4 (0.393)	13.514 (37.259)	0.508 (0.338)	5.492 (11.422)
log(Income) ²		0.017 (0.343)	0.061 (0.778)		0.838 (0.531)		-0.218 (0.678)		0.413*** (0.344)	-0.58* (0.344)	0.099 (1.004)		0.94*** (2.239)	0.244 (0.687)	0.166 (0.687)	
log(final energy consumption)	0.298** (0.14)	0.315*** (0.1)	-0.953 (1.008)	-0.953 (1.008)	1.503*** (0.227)	1.249*** (0.246)	-0.078 (0.463)	0.004 (0.492)	0.413*** (0.126)	0.321*** (0.124)	0.009 (0.559)	-0.156 (0.649)	0.94*** (0.343)	0.696 (0.537)	0.244 (0.38)	0.166 (0.371)
Renewable energy share	-2.613*** (0.668)	-2.689*** (0.747)	-5.093*** (1.245)	-5.809*** (1.727)	-4.088*** (1.579)	-4.802*** (1.591)	1.53 (3.465)	2.102 (3.616)	-0.778 (0.745)	-4.482 (0.785)	-2.803** (1.329)	-2.892** (1.372)	-0.347 (1.258)	0.061 (1.816)	-3.134 (5.753)	-2.919 (5.57)
Constant	-0.28*** (0.031)	-1.137*** (0.123)	-0.635*** (0.087)	-3.009*** (0.29)	-0.221*** (0.035)	-2.739*** (0.212)	-0.064* (0.037)	0.448*** (0.06)	-1.168*** (0.12)	-2.058*** (0.187)	0.965*** (0.147)	-0.93*** (0.124)	-1.277*** (0.182)	-3.928*** (0.463)	-1.32*** (0.152)	-2.997*** (0.323)
Hausman test statistics (p-value shown in the parentheses)	0.92 (0.82)	2.33 (0.67)	1.75 (0.63)	3.27 (0.51)	0.07 (0.99)	0.93 (0.92)	1.76 (0.62)	0.88 (0.93)	6.07 (0.11)	3.30 (0.51)	1.24 (0.74)	1.13 (0.89)	2.88 (0.41)	1.57 (0.81)	1.17 (0.76)	1.37 (0.85)

Table 7 (continued)

	Total		Electricity and heat production		Manufacturing industries and construction		Residential		Transport		Agriculture/forestry/fishing		Commercial and public services		Other energy industry own use		
	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	Linear	Quadratic	
No. of groups	86	86	86	86	86	86	86	86	86	86	57	57	60	60	61	61	
No. of obs	2150	2150	2150	2150	2150	2150	2150	2150	2150	2150	1425	1425	1500	1500	1525	1525	
Threshold value of income level (constant 2010 USD)	16,115			20,716													4,510

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

For the manufacturing industries and construction sector and the agriculture, forestry, and fishing sector the estimated coefficients of the log of real GDP per capita and its square term are significantly positive and negative with the small threshold income level, which suggests that the income–emissions relationship is negative

For the residential sector, the estimated coefficients of the log of real GDP per capita and its square term are significantly negative and positive with the large threshold income level, which suggests that the income–emissions relationship is negative

For the transport sector, the estimated coefficients of the log of real GDP per capita and its square term are significantly positive and negative with the large threshold income level, which suggests that the income–emissions relationship is positive

the economic growth drives the aggregate demand for energy in the belt and road initiative (BRI) countries, resulting in an elevated level of CO₂ emissions in the electricity and heat production sector. Concerning the commercial and public services sector, our results coincide with the findings of Hashmi et al. (2020) regarding the service sector in Pakistan, and those of Azizalrahman and Hasyimi (2019) regarding the commercial sector of upper-middle-income countries. However, Aslan et al. (2018) failed to confirm the existence of the EKC phenomenon in the commercial sector in the USA, implying that the USA is unsuccessful in using environmentally friendly technologies in the commercial sector.

The difference in turning points across sectors may relate to the argument of Grossman (1995) that the EKC pattern comes from three channels: scale, composition, and technique effects. Compared to the other two sectors, the electricity and heat production sector is likely to have a more substantial scale effect owing to the argument that countries at the early stages of development focus on increasing electricity demand along with economic growth. In contrast, the commercial and public services sector and the other energy industry own use sector tend to experience the composition effect associated with the transformation from dirtier to cleaner economic activities and the technique effect associated with the adoption of advanced technology and the clean energy-oriented regulations of governments.

The second group, supporting a negative income–emissions relationship, comprises three sectors: the manufacturing industries and construction sector, the residential sector, and the agriculture, forestry, and fishing sector.⁵ In these sectors, we observe that sector-wise CO₂ emissions monotonically decline with rising income levels. The negative relationship generally implies that the composition and technique effects offset the scale effect in these sectors. At the early stage of the development of manufacturing industries and construction sector, CO₂ emissions are relatively high owing to the high dependency on inefficient technology and traditional forms of energy sources such as burning wood, charcoal, and bio-waste. This sector further undergoes a transformation process toward modern technology with high energy efficiency as the manufacturing and construction industries develop, resulting in a reduction in CO₂ emissions. Our results in the manufacturing industries and construction sector are inconsistent with the findings of previous studies, showing the validity of the EKC hypothesis (Fujii & Managi, 2013, for three industrial sectors, including the construction industry in the OECD member countries; Fujii & Managi, 2016, for the industrial sector in 39 developing countries; Xu & Lin, 2016 for the manufacturing industry in China).

The negative income–emissions relationship in the residential sector can be explained by the fuel-switching behavior of households proposed by the ‘energy ladder model’ (Hosier & Dowd, 1987; Leach, 1992). According to the energy ladder model, households in the residential sector often switch fuels from dirtier to cleaner ones, driven mainly by income level and fuel costs (Saatkamp et al., 2000). Our findings are in line with those of Ma et al. (2019), in which the transition from coal to electricity in the residential building sector of China is driven by economic development, resulting in a reduction in CO₂

⁵ The estimated coefficients of the log of real GDP per capita and its square term are significantly positive and negative, respectively, for the manufacturing industries and construction sector and the agriculture, forestry, and fishing sector. However, the threshold income level is very small, so the income–emissions relationship is negative. Additionally, regarding the residential sector, the estimated coefficients of the log of real GDP per capita and its square term are significantly negative and positive with the large threshold income level, which implies that the income–emissions relationship is negative.

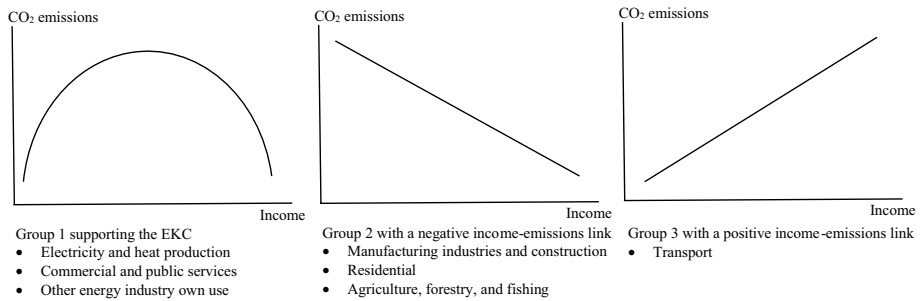


Fig. 1 Results

intensity over the past decade. However, our findings are inconsistent with the findings of Anser et al. (2020), which confirm the existence of a U-shaped income–emission relationship in the residential sector in the South Asian Association for Regional Cooperation (SAARC) member countries. Moreover, the monotonically declining property of CO₂ emissions in the agriculture, forestry, and fishing sector with an increase in the income level suggests that the composition and technique effects dominate the scale effect in the process of economic development, similar to the case of the manufacturing industries and construction sector. Our results regarding the agriculture, forestry, and fishing sector are inconsistent with the findings of Zhang et al. (2019a), which showed an inverted U-shape income–emissions relationship in the agriculture, forestry, and fishing sector in China’s main grain-producing areas, suggesting that the improvement in energy-saving technologies in this sector will be apparent at a later stage of development.

The transport sector falls under the third group, in which CO₂ emissions monotonically increase with economic development.⁶ Although energy efficiency in the transport sector improves through composition and technique effects along with economic development, our results show a positive income–emissions relationship. This is partly attributed to the argument that economic development is generally associated with globalization, and triggers greater movements of people and products, including business trips, tourism, and trade of goods and services. In this case, the scale effect associated with increased demand for transport services dominates the composition and technique effects, causing CO₂ emissions to surge along with economic development. Our results regarding the transport sector are consistent with the findings of Habib et al. (2021) and Wang and Wang (2021c) in G20 countries and China, respectively. However, our results contrast with the findings of Kharbach & Chfadi (2017) and Godil et al. (2020), which show a negative relationship between income and CO₂ emissions in the transportation sector of the Morocco and US economies, respectively, implying that the transportation systems of these countries are fuel-efficient with clean energy use.

4.4 Robustness checks

The previous subsection revealed that three sectors follow the EKC patterns of the income–emissions relationships, three sectors follow the monotone decreasing pattern, and one sector follows the monotone increasing pattern. In this subsection, we validate these

⁶ The estimated coefficients of the log of real GDP per capita and its square term are significantly positive and negative with the large threshold income level, which suggests that the income–emissions relationship is positive.

results using the sensitivity tests. Some studies, such as Stern et al. (1996), criticize the assumption that the normal distribution of world income level may derive unreliable estimates in the EKC argument as a significantly larger number of people are below the world's mean income level. Therefore, we divide our sample countries into two groups of developed and developing countries and estimate the model with the linear, rather than the quadratic, specification for each group. Applying the World Bank's income classification, countries in the high-income category are considered developed, and those in the other income categories (upper-middle, lower-middle, and low-income categories) are considered developing.

Table 8 shows the results of the subsampling sensitivity analyses. The total CO₂ emissions and sector-wise CO₂ emissions in the electricity and heat production sector and the other energy industry own use sector are positively related to the income level for developed countries but negatively related to the income level for developing countries. This finding is consistent with the EKC hypothesis for the two sectors. Contrasting to the baseline findings in the previous subsection, the estimation shows that the commercial and public services sector fails to exhibit the EKC pattern. The sector has a negative income–emissions relationship for both developed and developing countries, although the negative relationship is less substantial for developing countries. Moreover, consistent with the previous baseline findings, the manufacturing industries and construction sector, the residential sector, and the agriculture, forestry, and fishing sector exhibit a negative income–emissions relationship, irrespective of developed and developing countries, while the transport sector has a positive income–emissions relationship. Therefore, the results of the sensitivity tests are generally consistent with the main results.⁷

5 Conclusion

This study investigates the long-run equilibrium relationship between income level and sectoral CO₂ emissions in the context of the EKC hypothesis for the panel data of 86 countries, using the PMG-ARDL model. Our empirical results confirm that the income–emissions relationship follows the EKC pattern upon considering the total CO₂ emissions at the aggregate level. More importantly, we present some clear pictures of the income–emissions relationships for different sector-wise CO₂ emissions. First, the three sectors (electricity and heat production, commercial and public services, and other energy industry own use) follow the EKC patterns. Among these three sectors, CO₂ emissions peak out first for the commercial and public services sector, followed by the other energy industry own use sector and the electricity and heat production sector. As a country develops, the composition and technique effects dominate the scale effect in these sectors. Second, the three sectors (manufacturing industries and construction, residential, and agriculture, forestry, and fishing) do not follow the EKC patterns but exhibit a negative income–emissions relationship, where economic development is associated with the reduction in CO₂ emissions, partly

⁷ Additionally, we perform two additional sensitivity tests. First, we use per capita CO₂ emissions as the dependent variable. Second, we introduce two additional control variables: total natural resource rent (% of GDP) and total trade (% of GDP). Some studies emphasize the crucial roles of natural resource rents and trade openness in relation to CO₂ emissions (Bekun et al., 2019; Wang and Wang, 2021b; Wang and Zhang, 2021a, 2021b). We obtain the data of total natural resource rent and the total trade from the World Development Indicators and the Penn World Table, respectively. These sensitivity tests are performed using the nonlinear quadratic specification. The results are presented in Table 9 of Appendix.

Table 8 Sub-sample sensitivity tests

	Total		Electricity and heat production		Manufacturing industries and construction		Residential		Transport		Agriculture/forestry/fishing		Commercial and public services		Other energy industry own use	
	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing	Developed	Developing
<i>(A) Long-run estimates</i>																
log(Income)	-0.095*** (0.015)	0.186*** (0.025)	-0.082* (0.046)	0.591*** (0.084)	-0.616*** (0.043)	-0.538*** (0.104)	-0.401*** (0.06)	-0.846*** (0.078)	0.235*** (0.047)	0.312*** (0.041)	-0.283*** (0.053)	-0.646*** (0.088)	-1.374*** (0.145)	-0.278*** (0.1)	-0.461*** (0.064)	0.427*** (0.098)
log(total final energy consumption)	0.979*** (0.02)	0.817*** (0.024)	1.002*** (0.029)	0.803*** (0.057)	1.172*** (0.045)	1.601*** (0.08)	1.078*** (0.061)	1.077*** (0.054)	0.827*** (0.044)	0.919*** (0.028)	0.22*** (0.079)	0.881*** (0.113)	2.183*** (0.216)	0.946*** (0.126)	0.575*** (0.087)	0.68*** (0.073)
Renewable energy share in total	-1.486*** (0.055)	-1.264*** (0.067)	-2.338*** (0.22)	-1.232*** (0.212)	-1.875*** (0.158)	-1.77*** (0.173)	-0.263* (0.155)	-2.979*** (0.268)	-1.389*** (0.114)	-1.39*** (0.079)	-1.01*** (0.13)	-1.799*** (0.363)	-0.507 (0.365)	-1.47*** (0.454)	2.159*** (0.452)	-0.313 (0.345)
<i>(B) Short-run estimates</i>																
Error correction term	-0.119 (0.048)	-0.21*** (0.03)	-0.287*** (0.043)	-0.238*** (0.028)	-0.294*** (0.035)	-0.203*** (0.03)	-0.228*** (0.045)	-0.217*** (0.036)	-0.225*** (0.039)	-0.276*** (0.033)	-0.253*** (0.047)	-0.244*** (0.04)	-0.245*** (0.046)	-0.318*** (0.054)	-0.245*** (0.041)	-0.298*** (0.046)
g(Income)	-0.119 (0.154)	0.381*** (0.102)	-0.12 (0.37)	1.224*** (0.387)	0.367 (0.275)	0.057 (0.217)	-0.794*** (0.194)	0.133 (0.178)	-0.072 (0.17)	-0.007 (0.103)	0.008 (0.277)	0.186 (0.426)	-0.755** (0.322)	-0.072 (0.722)	0.704** (0.279)	0.163 (0.63)
log(total final energy consumption)	0.626*** (0.066)	-0.059 (0.28)	0.606* (0.361)	-2.417** (1.068)	1.345*** (0.197)	1.602*** (0.364)	1.089*** (0.199)	-1.1 (0.746)	0.48*** (0.074)	0.34 (0.221)	0.584*** (0.205)	-0.574 (1.031)	1.144*** (0.293)	0.339 (0.695)	0.208 (0.165)	0.279 (0.73)
Renewable energy share in total	-1.794 (1.093)	-3.42*** (0.925)	-3.521*** (1.06)	-5.476*** (1.783)	-3.481 (2.628)	-3.977*** (1.246)	8.648 (7.872)	-4.087*** (1.411)	2.192 (2.123)	-2.419*** (0.756)	-2.87*** (1.1)	-3.344 (2.288)	1.548 (1.89)	-2.659* (1.594)	-9.215 (10.732)	2.539 (4.021)
Constant	-0.298*** (0.048)	-0.307*** (0.052)	-0.797*** (0.152)	-1.409*** (0.183)	-0.119*** (0.03)	-1.605*** (0.239)	-0.53*** (0.127)	0.254*** (0.059)	-0.829*** (0.147)	-1.351*** (0.161)	1.966*** (0.362)	0.148 (0.109)	-1.82*** (0.337)	-1.135*** (0.188)	1.158*** (0.223)	-1.512*** (0.236)
No. of groups	38	48	38	48	38	48	38	48	38	48	27	30	30	30	30	31
No. of obs	988	1248	988	1248	988	1248	988	1248	988	1248	702	780	780	780	780	806

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

because the composition and technique effects are substantial from the early stage of development. Third, the transport sector also fails to show the EKC patterns but exhibits a positive income–emissions relationship since the scale effect might be dominant at any stage of economic development.

Previous studies examined the income–emissions relationship at the aggregate level of CO₂ emissions or sectoral level in a specific country or region. However, the generalization of these findings for policy formulation might be inappropriate since sector-specific characteristics, such as energy requirement, technological advancement, resource endowment, and alternative energy sources, could make each sector's income–emissions relationship differ. Considering this fact, we investigate the income–emissions relationship in seven economic sectors for a large panel of developed and developing countries. Our findings provide some important policy implications. First, the electricity and heat production sector, the commercial and public services sector, and the other energy industry own use sector with an inverted U-shaped income–emissions pattern suggest that these sectors require well-crafted environmental policy interventions by the governments of developing countries, especially the electricity and heat production sector, as it has the highest threshold value. Second, a monotonically declining income–emissions relationship in the manufacturing industries and construction sector, the residential sector, and the agriculture, forestry, and fishing sector suggests that emissions decline with economic growth in developed and developing countries. Both developed and developing countries could expedite the pace of emissions reduction along the economic development path by implementing appropriate policy measures. Third, a monotonically increasing income–emissions association in the transport sector indicates that the environmental degradation caused by the sector further exacerbates as a country develops. Therefore, unlike other sectors, the transportation sector requires a swift transition toward modern renewable energy sources to enhance energy efficiency and reduce environmental costs.

Although this study investigates the sectoral income–emissions relationship in the context of the EKC hypothesis in developed and developing countries, there are some limitations. For example, our study does not incorporate the relationship between CO₂ emissions and other macroeconomic variables in the context of the EKC hypothesis. Several studies have examined the relationship between emissions and other macroeconomic indicators, such as tourism revenue (Paramati et al., 2017; Zhang & Gao, 2016), renewable energy (Bento & Moutinho, 2016), financial development (Ozatac et al., 2017), urbanization (He et al., 2017; Pata, 2018; Wang et al., 2016), and the recovery of economic growth and energy consumption in the context of the COVID-19 pandemic (Wang & Zhang, 2021c). Similarly, the EKC analysis can be undertaken with various pollutant indicators such as greenhouse gas (GHG) emissions, CO₂, methane (CH₄), nitrous oxide (N₂O), ecological footprint (Ali et al., 2021), methane emissions (Adeel-Farooq et al., 2020), nitrogen oxide emissions (Murshed, 2021), and deforestation rates (Ozatac et al., 2017). Our study only considers CO₂ emissions for sectoral EKC analyses. Therefore, the investigation with the inclusion of other macroeconomic and pollutant indicators might help create a more comprehensive understanding of the pattern of the sectoral EKC phenomenon, which could be conducted in future research.

Appendix

See Table 9.

Table 9 Additional sensitivity tests

Sector-wise CO ₂ emissions	Total		Electricity		Manufacturing industries and construction		Residential		Transport		Agriculture/Forestry/Fishing		Commercial and public services		Other energy industry own use	
	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control
(A) Long-run estimates																
log(Income— GDP per capita)	0.091	0.771***	2.148***	2.52***	0.785***	1.213***	-1.081***	-0.517*	1.323***	0.833***	0.571*	0.621*	0.847	-0.623	1.135**	3.119***
log(Income) ²	(0.117)	(0.071)	(0.233)	(0.231)	(0.269)	(0.291)	(0.269)	(0.297)	(0.179)	(0.186)	(0.34)	(0.337)	(0.603)	(0.5)	(0.484)	(0.433)
log(Income) ³	-0.01	-0.04***	-0.103***	-0.12***	-0.075***	-0.106***	0.038***	0.007	-0.055***	-0.029***	-0.045***	-0.049***	-0.057*	0.001	-0.069***	-0.176***
log(total final energy consumption)	(0.006)	(0.004)	(0.014)	(0.011)	(0.014)	(0.015)	(0.014)	(0.015)	(0.009)	(0.01)	(0.017)	(0.017)	(0.031)	(0.024)	(0.026)	(0.023)
lnTFEC	0.941***	0.8***	0.515***	0.51***	1.323***	1.219***	0.976***	0.968***	0.833***	0.936***	0.344***	0.637***	1.078***	1.398***	1.144***	0.932***
Renewable energy share in total	(0.021)	(0.019)	(0.055)	(0.053)	(0.046)	(0.026)	(0.05)	(0.048)	(0.028)	(0.025)	(0.074)	(0.058)	(0.144)	(0.11)	(0.09)	(0.067)
REC	-1.463***	-1.439***	-1.094***	-2.007***	-1.494***	-1.476***	-1.134***	-0.839***	-1.306***	-1.46***	-1.117***	-0.736***	-0.52	-0.35	-0.012	0.087
TNR	(0.058)	(0.043)	(0.124)	(0.137)	(0.127)	(0.136)	(0.161)	(0.171)	(0.07)	(0.075)	(0.137)	(0.124)	(0.401)	(0.402)	(0.285)	(0.242)
Total natural resource rent (% of GDP)	-0.001	-0.001	-0.009***	-0.009***	-0.004**	-0.004**	-0.002	-0.002	-0.002**	-0.002**	-0.005	-0.005	-0.055***	-0.055***	0.018***	0.018***
TRADE of GDP	(0.001)	(0.001)	(0.003)	(0.003)	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)	(0.006)	(0.006)	(0.008)	(0.008)	(0.004)	(0.004)
	0.109***	0.109***	0.333***	0.333***	0.191***	0.191***	0.069***	0.069***	-0.012	-0.012	-0.137***	-0.137***	0.3***	0.3***	0.175***	0.175***
	(0.011)	(0.011)	(0.03)	(0.03)	(0.045)	(0.045)	(0.03)	(0.03)	(0.028)	(0.028)	(0.046)	(0.046)	(0.033)	(0.033)	(0.051)	(0.051)
(B) Short-run estimates																
ECT	-0.276***	-0.273***	-0.3***	-0.301***	-0.311***	-0.304***	-0.264***	-0.258***	-0.287***	-0.266***	-0.25***	-0.241***	-0.318***	-0.333***	-0.281***	-0.285***
ΔlnY	(0.028)	(0.03)	(0.028)	(0.028)	(0.025)	(0.025)	(0.029)	(0.029)	(0.024)	(0.025)	(0.035)	(0.038)	(0.037)	(0.041)	(0.032)	(0.034)
ΔlnY ²	-0.134	-0.186	3.89	2.497	-16.953*	-18.883**	0.177	5.444	12.037**	6.951	5.583	-7.981	11.501	32.399	1.686	11.581
	(6.442)	(5.607)	(11.669)	(12.554)	(9.458)	(9.086)	(12.183)	(11.655)	(6.13)	(5.044)	(18.171)	(25.854)	(37.451)	(37.646)	(11.504)	(13.16)
ΔlnTFEC	0.096	0.08	-0.139	-0.05	0.843	0.952*	-0.099	-0.472	-0.66**	-0.404	0	0.708	-0.653	-1.995	-0.317	-0.905
	(0.347)	(0.309)	(0.723)	(0.808)	(0.531)	(0.498)	(0.722)	(0.674)	(0.334)	(0.286)	(1.041)	(1.51)	(2.254)	(2.337)	(0.697)	(0.76)
ΔlnTFEC	0.221	0.292**	-9.768	-2.009	2.098**	1.243***	-0.597	-0.121	0.633**	0.297*	0.987	-0.283	1.562**	1.238**	0.261	-0.003
	(0.159)	(0.148)	(8.9)	(1.5)	(0.813)	(0.288)	(1.125)	(0.545)	(0.284)	(0.154)	(0.8)	(0.753)	(0.638)	(0.542)	(0.452)	(0.401)

Table 9 (continued)

Sector-wise CO ₂ emissions	Total		Electricity		Manufacturing industries and construction		Residential		Transport		Agriculture/Forestry/Fishing		Commercial and public services		Other energy industry own use	
	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control	Per-capita	Additional Control
ΔBEC	-2.571*** (0.733)	-2.97*** (0.912)	-13.79 (9.043)	-6.454*** (2.222)	-3.618** (1.411)	-4.78*** (1.484)	1.763 (3.835)	0.959 (2.601)	-0.267 (0.773)	-0.664 (0.793)	-2.174* (1.178)	-2.596* (1.46)	2.065 (2.068)	-0.188 (2.125)	-2.083 (5.864)	-3.391 (5.87)
ΔTNR	-0.896 (1.266)	-21.597 (20.467)			3.24 (6.923)			-4.648 (7.996)		-1.773 (2.495)		-0.683 (0.561)		9.041 (6.247)	0.563 (0.836)	0.563 (0.836)
$\Delta TRADE$	0.026 (0.032)	-0.13 (0.163)			0.051 (0.081)		0.039 (0.08)		0.039 (0.049)		0.27 (0.377)		-0.027 (0.208)		0.114 (0.273)	0.114 (0.273)
C	-0.455*** (0.045)	-0.902*** (0.104)	-2.884*** (0.276)	-2.954*** (0.313)	-2.669*** (0.211)	-2.902*** (0.226)	0.385*** (0.059)	-0.239*** (0.044)	-2.606*** (0.219)	-2.023*** (0.188)	-0.175*** (0.071)	-0.642*** (0.111)	-3.248*** (0.39)	-2.149*** (0.28)	-3.358*** (0.372)	-5.303*** (0.623)
No. of groups	86	86	86	86	86	86	86	86	86	86	57	57	60	60	61	61
No. of obs	2150	2150	2150	2150	2150	2150	2150	2150	2150	2150	1425	1425	1500	1500	1525	1525
Threshold value of income level (constant 2010 USD)	95	15.329	33.765	36.316	187	305	1,504,068	1.1×10 ¹⁶	167,255	1,727,298	569	565	1,686	1.9×10 ¹⁵	3,732	7,050

***, **, and * denote significance at 1%, 5%, and 10% levels, respectively

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