



What does the EKC theory leave behind? A state-of-the-art review and assessment of export diversification-augmented models

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Abstract Over the past three decades, researchers have extensively examined the environmental Kuznets curve (EKC) hypothesis. Despite their early focus on the ecological impacts of anthropogenic development, associated conclusions differ and often conflict. In this study, we conducted a state-of-the-art review of this topic and shed light on the methodological challenges that the literature attempted to overcome so far. Since China is going through structural economic changes and environmental reforms, we relied on this illustrative case and developed an augmented-EKC framework to investigate whether

this hypothesis holds between export product diversification and environmental pollution, stratifying by carbon energy content: renewable (Model 1) and fossil energy (Model 2). Quarterly data are collected over the most available and recent period (i.e., 1990Q1–2018Q4) and computed by applying the Quadratic Match-Sum Method (QMS) on annual series. Besides, per capita income and foreign direct investments are included as additional factors to the baseline models specifications. The empirical analysis comprises the Clemente–Montanes–Reyes unit root test with structural break and additive outlier, the autoregressive distributed lag (ARDL) bounds test for cointegration, the Granger causality test, and dynamic (DOLS) and fully modified OLS (FMOLS) estimators, followed by robustness checks confirming the stability of the coefficients exhibited in the two autoregressive settings. For both models, empirical results failed to support the existence of an inverted-U-shaped relationship among export product diversification and carbon release from fuel combustion in China. Also, as income grows, low-carbon resources seem improving export diversification and vice versa. Related findings are thought to bring robust inferences able to complement the existing literature and open a fruitful research direction.

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Introduction

Climate change arose as a major risk to be addressed. The rise in global surface average temperature is largely attributable to the elevated levels of greenhouse gas (GHG) pollutants, which are directly driven by the combustion of fossil fuels for human activity purposes (Zhang et al., 2011; Intergovernmental Panel on Climate Change (IPCC), 2007, 2011, 2014; Özokcu & Özdemir, 2017). As a response, growing attention has been paid to expanding the concept of sustainability and sustainable development (SD) (Awan et al., 2020; Dhir et al., 2021; Madanaguli et al., 2021). Early, this concept took a multifaceted dimension. First initiated by the World Commission on Environment and Development (WCED), this concept aimed at offering a definition of what should be a desirable development process (i.e., “*as one that meets present needs, while allowing future generations to address their own*”) (Hajar et al., 2020). Far from promoting a strict decline of aggregate income, SD supports the idea behind which a climate-compatible economic path is possible, reframing thus the long antagonist human-nature relationship (Schneider & Sprout, 2021). It relates to an old debate rooted around the elaboration of a development model deemed suitable to balance the marginal costs and benefits of anthropogenic activity (Holtz-Eakin & Selden, 1995). From a theoretical standpoint, this concept sheds light on three pillars (i.e., economic prosperity, social equity, and environmental protection) which are thought to rethink the well-established human activities-environmental degradation relationship (Sauvé et al., 2016). Empirically, such a relationship has been extensively inspected through the influential environmental Kuznets curve (EKC) framework, by reference to the pioneer theory of Simon Kuznets (1967) on inequalities. The origins of this analysis can be traced back to Grossman and Krueger (1991) who examined NAFTA’s effect on a set of pollutant concentrations. It argues that environmental pollution initially increases with economic development, reducing afterward at the turning point, whereas economic activity leads to environmental pollution reduction (Liu et al., 2019). Thus, this postulates that economic activity may exhibit an inverted U-shaped relationship with atmospheric pollutants. But beyond that, this de-linking dynamic underlines the encouraging plausibility that economic and environmental targets may be simultaneously achievable.¹

While the literature on this topic is extensive, the existence of the EKC and its practical policy implications failed to generate a consensus (Jaunky, 2011). Besides, existing studies mostly relied on a reduced-bivariate-EKC-form, using gross domestic product (GDP) to proxy “*economic activity*,” thus neglecting other fundamental components, and notably export product diversification. It is worth noticing that such a topic becomes critical in the current environmental context, as the UK government has recently hosted COP 26 in Glasgow between 31st October and 12th November 2021. While it initially aimed at building progress in four key areas (coal, cars, cash, and trees), problems rose among parties when attempting to get agreement on the first two: rapid phase-out of coal-based power and heating plants, and progressive shift from fossil-fuelled towards low-carbon driven automobiles (Schneider, 2022; Smith et al., 2021). Since 1995, besides the legally binding 1997 Kyoto Protocol, 25 COP meetings occurred along with other international agreements. Over the same period, atmospheric CO₂ emissions, the principal anthropogenic GHG component, increased from 360 to 420 ppm in 2020 (Rees, 2021). Therefore, non-negligible critics have been expressed towards the standard approach to global warming, which mainly consists in alleviating the constraints on economic growth while enabling a continuous technological development thought suitable to compensate environmental damages. Acceptable approaches include wind turbines, solar photovoltaic panels, lithium batteries, hydrogen, and carbon capture and storage technologies, with the underlying massive need for resources and mineral components. But beyond the yet critical risk for biodiversity, it involves the development of competitive industrial sectors with adequate trade agreements and export promotion policies to ensure low-carbon technologies transfer across countries and sustain economic growth. Displaying far-reaching policy implications, the present study examines whether the EKC hypothesis holds between export product diversification and

¹ The basic philosophy of the EKC-theory is outlined in Beckerman (1992, p.482)’s vision: “although economic growth usually leads to environmental deterioration in the early stages of the process, in the end, the best and probably the only-way to attain a decent environment in most countries is to become rich.”

atmospheric pollution. To do so, an innovative step-wise empirical methodology will be conducted.

Occurring at the first stage of the development, the effective role of export diversification has been the subject of important theoretical disagreements. Early theories predicted a monotonic relationship between income and sectoral concentration. Operating a break with this view, Imbs and Wacziarg (2003) demonstrated that the diversification of exports rises with per capita GDP until a turning point and after which, export concentration becomes a more predominant economic development-enabler. Accordingly, it is supported that securing long-term economic growth may be conditional to the shift from an export diversification process to a concentration strategy (Agosin et al., 2012; Cadot et al., 2011; Klinger & Lederman, 2004). Later, such inverted U-shaped evidence found support in Klinger and Lederman (2006), Cadot et al. (2011, 2013), and Gozgor and Can (2016a), while Parteka and Tamberi (2013) showed that diversification opportunities are determined by per capita income and features influencing the size of the accessible markets. As a matter of fact, in the early stages of economic emergence, countries usually exploit their comparative advantage and resource endowment. Hence, often they display a standard basket of limited products (Gozgor, 2017). Thus, this suggests that the diversification strategy is the most likely to enhance growth (Imbs & Wacziarg, 2003). Going one step further, the seminal contribution from Melitz (2003) showed that an increase in export variety — which is at the core of export diversification — may enhance productivity because the only most productive firms can bear the cost of export. Furthermore, export diversification is suggested to lower the exposure to external shocks and enable a secure growth path (Lederman & Maloney, 2007; Haddad et al., 2010). On the other hand, a pioneer theory led by Krugman (1991) and outlined in Neary (2001) showed that economic activity in economies experiencing integration processes tends to be growingly agglomerated. Therefore, concentration dynamics may also occur at the sector level, which could explain the nature of the productivity channel in trade-oriented emerging economies (Imbs & Wacziarg, 2003). Thus, in a later stage of development, avoiding specializing in capital and knowledge-intensive product may adversely affect the growth of income, pointing out to the existence of a negative

correlation between the level of sectoral diversification and income levels (Apergis et al., 2018).

By contrast, the underlying mechanisms operating into the export diversification-environmental pollution nexus appear much more overlooked and thereby call here for more explanations. The nature of the trade-environment interactions can be decomposed into three fundamental forces: scale, composition, and technique effects (Cole, 2004; Copeland & Taylor, 1995a, 1995b; Liu et al., 2019). Above all, the scale effect is defined by a state of the economy where a level of pollution emitted translates into a higher income level, *ceteris paribus*. By contrast, any adjustment along the industrial composition affects the pollution intensity of the production process, which in turn is thought to significantly impact the level of emissions. This is known as the composition effect. Finally, the technique effect refers to the changes in emission intensity of the production, resulting from the adoption of low-carbon technologies along the supply chain for instance. Omitting the intermediate energy variable while outlining the trade-pollution interactions might lead to a sporadic discussion. Although the literature on this topic remains seminal (i.e., the first empirical demonstration that export diversification and demand for energy improve each other is traced back to Shahbaz et al. (2019) for the US case), crucial linkages are known to be shared among indicators. Regarding the polluting side, the export diversification stage requires important energy needs, necessary for the competitive development of industries (Gozgor & Can, 2016b). This booming energy demand reverbs into a growing environmental pressure exerted on the environment during the export diversification stage (Paramati et al., 2016). Known as the “*pollution havens*” hypothesis, important critics have also been raised against the last globalization wave (i.e., taking the form of multilateral reductions of tariffs and non-tariff barriers to trade flows) as it may enable the transfer of polluting-concentration industry (such as including steel, petrochemicals, fertilizers, and paper) from advanced to developing countries (Akbostanci et al., 2007; Liu et al., 2018). Looking at the mitigating side, the concentration of the export basket may reduce energy needs as it promotes more efficient usage of energy, which in turn, boosts economic growth. Therefore, lowering the energy demand is decidedly linked to the energy-saving potential of manufacturing products and should drive the promotion/outsourcing decisions

of the less polluting/most environmentally harmful industries (Shahbaz et al., 2019). In-between, learning-by-exporting, and spillover channels are thought to plant the seeds of endogenous growth (Barro, 1997).

Providing clearer and finer information than standard economic volumes (i.e., GDP and trade flows), export diversification data faithfully reflect the trade structure of a given economy (Liu et al., 2019). Defined by Ali et al. (1991) as an export content change of a given economy, the concept of export diversification results either from the scale-increase of the existing export content (i.e., exporting a larger quantity of each good, referring to the intensive margin) or an increase in the number of distinctive products (exporting a wider set of goods, referring to the extensive margin) (Can et al., 2020; Hummels & Klenow, 2005). When merged with carbon data, it points out that environmental sustainability might find its roots within the economic structure (and specialization pattern) rather than the trade volumes (Liu et al., 2019). Accordingly, employing export diversification as an indicator is here of high interest since it allows for the elaboration of important environmental insights concerning the trade structure determinant. Now, readily available statistics allow for an in-depth assessment of a single case because related results could bring valuable information regarding the “*polluting*” or “*mitigating*” effect of export structure on environmental pollution.

In this paper, we intended to focus on China for several reasons. Having undergone rapid economic growth since 1978 (opening-up reforms), China has become one of the largest economies worldwide, mostly because of a strong export-led (oriented) growth engine. As Brazil and India, China is now on the path of joining the ranks of the five world’s largest economies within the next half-century (Naudé & Rossouw, 2011), although the possibility of an incipient deindustrialization process is now discussed (Wei & Wang, 2019). As of 2020, China holds a nominal gross domestic product (GDP) of 14.86 trillion US dollars, constituting around 16% of the entire global economy (Li et al., 2021). Looking at trade figures, China exported approximately 2.6 trillion US dollars worth of goods while ICT rose from 2.2% of service exports in 2000 to 16.5% in 2020 (WDI, 2020). Meanwhile and for obvious reasons, Chinese energy needs for industrial and domestic purposes have skyrocketed. Thus, it became the biggest air polluter

with total emissions covering about 29.3% of global GHG levels in 2017 (Publication Office of the European Union (POEU), 2018). While the issues of air pollution and natural resource depletion have long been overlooked, the Chinese government recently endorsed major energy and environmental reforms. First, it confirmed its mitigation targets set by the 2015 Paris Climate Change Conference and agreed to reduce global emissions by 43% (below 2005 levels) in 2030 (Dong et al., 2017). In the wake of the president’s call for an “*energy revolution*,” the structure of the electricity sector drastically shifted towards low-carbon energies. Between 2000 and 2018, decarbonized energies (i.e., hydro, wind, and solar) increased 7 times from 21,770 thousand tons of oil equivalent (ktoe) to 169,510 ktoe (International Energy Agency (IEA), 2020a, b, c). At the disaggregated level, electricity generation-based wind grew from 615 GWh to 295,023 GWh whereas solar PV experienced a historical expansion from 22 GWh in 2000 to 130,658 GWh in 2018 (IEA, 2020a, b, c). And this dynamic is not expected to stop. China is now considered the largest low-carbon energy investor, and it is expected to account for 40% of the world’s capacity expansion by 2024. For this reason, the International Energy Agency (IEA) designated China as one of the three renewable energy leaders of the twenty-first century (Spratt et al., 2014; IEA, 2020a, b, c). Far from being a coincidence, such a decarbonization process aims at deploying a secure supply of low-carbon electricity to meet its growing industry needs in the long run. This is congruent with the recent declaration of Chinese president Xi Jinping (September 23rd, 2020), highlighting that China would officially achieve carbon-neutral by 2060 (Pollitt, 2020). In line with this background, there is a point in selecting China as an illustrative case and assessing whether the EKC hypothesis holds among export diversification and carbon dioxide (CO₂) emissions from fuel combustion.

An extensive survey of the literature underlines five major elements. First, empirical assessments of the export diversification-environmental pollution relationship are quite recent. Up to now, the analysis from Gozgor and Can (2016b) on the Turkish case remains one of the most seminal contributions on this topic. Second, past studies examining such a relationship in the context of the EKC considered large and heterogeneous samples of countries (see

Apergis et al. (2018) for 19 advanced economies; Liu et al. (2019) for 125 economies; Can et al. (2020) for 84 developing economies; Mania (2020) for 98 economies; Shahzad et al. (2020) for 63 emerging countries; Wang, Chang, et al. (2020) for G-7 countries). Although they are promising, these analyses must be further extended to single cases as it is not clear that panel results can be generalized to other economies, regions, or income groups. Third, one must admit that related findings sometimes conflict notably because of data and methodological choices. For instance, while Mania (2020) applied the long-run pooled mean group (PMG) estimation method, Liu et al. (2019) and Apergis et al. (2018) employed a fixed effects (FE) and a panel quantile regression model, respectively. Again, this contrasts with Can et al. (2020) who performed the autoregressive distributed lag (ARDL) bounds test and also differs from the error correction model (ECM) approach adopted in Liu et al. (2018). Thus, this calls for further inquiry into this nexus with the most advanced empirical procedures now available in the domain. Fourth, the Chinese-related literature is scarce and sporadic. Most of the time, Chinese data have been included within large panels, avoiding thus the design of country-specific insights. Also, we noticed that Liu et al. (2018) did not follow the conventional panel approach and conducted a comparative nexus analysis among Korea, Japan, and China. Finally, up to now, no previous study has investigated the export diversification-CO₂ emissions nexus for the single Chinese case, indicating evidence of a critical lack in the literature. Fifth, the contributing role of other factors into the carbon pollution curbing dynamic (notably population and foreign direct investments) remains merely overlooked and calls for further inquiry using the most accurate available data.

In light of the above considerations, this paper seeks to extend the literature in four distinct manners. Above all, this research draws researchers' attention to current methodological issues and conducts a state-of-the-art survey of the EKC topic, starting by outlining the main features of past empirical analyses, and drawing an analytical review of the field, with conclusions thought to enlarge the research field and suggest new alternatives. Second, since China is experiencing profound industrial and trade structure mutations, we took this case as an illustration and performed a complete analysis of its export

diversification-environmental pollution nexus within the context of the EKC. As Chinese president Xi Jinping recently set a carbon neutrality target by 2060, an in-depth analysis of the Chinese case is thought to bring valuable country- and sector-specific insights useful for both economic and environmental purposes. Hence, to the best we know, this paper is the first to assess the causal linkage between export product diversification and CO₂ emissions from fuel combustion for the single case of China. A third novelty aspect is that this paper contrasts with previous ones as it adopts a multivariate approach and incorporates income, population, and FDI within the non-linear specification. Also, the sensitivity of the export diversification-environmental pollution nexus to the inclusion of polluting and low-carbon energies (i.e., exhaustible fossil and low-carbon resources, respectively) is tested by developing two distinct specifications, and where the dependent (carbon emissions) and remaining independent (GDP, low-carbon and fossil energy, FDI) variables are constant. Fourth and finally, this study displays a last competitive edge as it conducts a complete causality testing framework. We assessed the stationarity properties of the series using the Clemente–Montanes–Reyes unit root test with structural break and additive outlier. For both models, the ARDL bounds test to cointegration is performed, followed by the Granger causality tests, and fully modified ordinary least square (FMOLS) and dynamic ordinary least square (DOLS) estimators to capture the long and short-run relationships among variables. Finally, traditional diagnosis and robustness checks related to the stability of the coefficients are conducted.

In sum, beyond conducting an in-depth review of the EKC topic, this paper aims at enriching the EKC discipline with trade-related knowledge. Thus, this work incorporates export product diversification within an EKC framework for China. Herein, we ask whether the environmental Kuznets curve (EKC) hypothesis holds between export product diversification and environmental pollution for the illustrative case of China. Using data covering the 1990Q1-2018Q4 period (and obtained by applying the quadratic match-sum method on annual series), a complete causality testing framework is applied to investigate the linkages operating among export diversification, per capita income, energy demand, and carbon release from fuel combustion for the

Chinese economy. Two distinct model specifications are set: incorporating renewable and fossil energy, respectively. If it is confirmed that export diversification and environmental pollution share a negative quadratic curve, then trade liberalization efforts and technical innovations within industrial sectors would substantially drive CO₂ emissions reduction. Inversely, if a linear effect among indicators is established, it indicates that controlling the rising release of harmful polluting particles in China cannot be achieved without limiting the diversification of exporting sectors within the economy. With several novelty aspects, this research strives to represent a relevant contribution to the literature, helpful for Asian policymakers in the current COP context. Finally, it strives to expand our econometrics knowledge of the EKC and highlight new directions for this debated field of environmental research.

The rest of this paper is organized as follows. “[State-of-the-art review](#)” section presents the state-of-the-art of the EKC topic. “[Data collection, ekc theory, and econometric framework](#)” section describes the data specification, EKC theory, and presents the econometric framework. “[Empirical results](#)” section displays the empirical results. In “[Discussion of the results: what insights can we draw?](#)” section, findings are discussed. Lastly, “[Conclusions and policy recommendations](#)” section reports concluding remarks, practical implications but also prospects for future research.

State-of-the-art review

First developed in Grossman and Krueger (1991), the EKC theory has been abundantly studied and extended to various cases and issues. In this section, a systematic review² is presented. It consists in first outlining the EKC baseline (i.e., GDP-environmental degradation nexus) “[Economic growth and environmental pollution: the EKC baseline](#)”. Then, a specific focus is brought on the export product diversification-environmental pollution nexus, under the

context of the EKC “[Export product diversification and environmental pollution: a modified EKC application](#)”. Finally, a discussion is elaborated based on the insights drawn from this state-of-the-art review “[The EKC approach: insights from the empirical literature](#)”. While crucial methodological issues are highlighted, potential improvement paths are suggested to address them. Overall, having underlined the key gaps in the literature, a research proposal is formulated in an ideal illustrative case: China. For an exhaustive overview of the EKC concept, see Kaika and Zervas (2013) and Sarkodie and Strezov (2019).

Economic growth and environmental pollution: the EKC baseline

A range of studies has shed light on the non-linear pattern of the growth-pollution relationship. While a strand of the literature relied on various multi-country approaches, the share of country-specific examinations has substantially increased these recent years. This sub-section aims at presenting the most relevant and recent studies of the EKC between GDP and environmental degradation. Also, an exhaustive review of the EKC literature can be found in Bilgili et al. (2016), Sarkodie and Strezov (2019), and Schneider (2020).

A strand of the empirical literature validated the existence of the EKC while dealing with wide samples of economies. Upon the most relevant ones, one found Shafik and Bandyopadhyay (1992) for 149 economies; Panayotou (1993) for 68 countries; Selden and Song (1994) for 30 economies; Dinda et al. (2000) for 33 economies; Stern and Common (2001) for 73 countries; York et al. (2003) for 142 countries; Cole (2004) for OECD countries; Dijkgraaf and Vollebergh (2005) for 24 countries; Apergis and Payne (2009) for 6 central American countries; Lean and Smyth (2010) for 5 ASEAN countries; Leitão (2010) for 94 countries; Castiglione et al. (2012) for 28 countries; Iwata et al. (2012) for 11 OECD countries; Ben Jebli et al. (2013) for 25 OECD economies; Bilgili et al. (2016) for 17 OECD economies; Kais and Sami (2016) for 58 economies; Zaman and Abd-el Moemen (2017) for 90 countries; Haseeb et al. (2018) for BRICS countries; Sarkodie (2018) for 17 African economies; Alshubiri and Elheddad (2019) for 32 OECD countries; Dogan and Inglesi-Lotz (2020) for 7 EU countries; Kong and Khan (2019) for 14 developed and 15 developing

² For in-depth inputs regarding the concept of systematic review applied on neighboring topics, relevant examples can be found in Kushwah et al. (2019), Khanra et al. (2020), Sahu et al. (2020), Tandon et al. (2020), Dhir et al. (2020), and Chauhan et al. (2021)

countries; Le (2019) for 10 ASEAN countries; Adeel-Farooq et al. (2020) for 6 ASEAN economies; Leal and Marques (2020) for 20 OECD economies; Murshed et al. (2021) for 6 Asian countries.

Conversely, other multi-country studies failed to validate this theory. Upon them, one finds Moomaw and Unruh (1997) for 16 transition economies; Agras and Chapman (1999) for 34 economies; Gangadharan and Valenzuela (2001) for 51 countries; Acaravci and Ozturk (2010) for 19 EU economies; Narayan and Narayan (2010) for 43 developing economies; Arouri et al. (2012) for 12 MENA economies; Baek (2015a) for 12 major nuclear energy-consuming economies; Baek (2015b) for Arctic countries; Heidari et al. (2015) for 5 ASEAN countries; Lin et al. (2016) for 5 African countries; Antonakakis et al. (2017) for 106 countries; Aye and Edoja (2017) for 31 developing countries; Cai et al. (2018) for G-7 economies; Hu et al. (2018) for 25 developing countries; Moutinho et al. (2020) for 12 OPEC countries; Pata and Aydin (2020) for 6 hydropower generating nations.

Finally, mixed evidence has been reported in Lee et al. (2010) as results pointed out the presence of an inverted U-shaped relation between growth and pollution in America and Europe, but not in Africa, Asia, and Oceania. Similarly, Akadiri et al. (2021) validated the presence of the EKC only in the long run for BRICS countries. Besides, some new empirical approaches attempted to test this theory using more elaborated and inclusive metrics. For instance, Al-Mulali et al. (2015), Ozturk et al. (2016), and Ulucak and Bilgili (2018) used ecological footprint as an indicator of environmental degradation; Luzzati and Orsini (2009) inspected the energy-EKC hypothesis; Katz (2015) applied the EKC theory on the water use-economic growth link; Bimonte and Stabile (2017) explored the land consumption-income relationship under the context of the EKC; Mehmood and Tariq (2020) supported the presence of a U-shaped curve between globalization and CO₂ emissions for 8 South Asian countries; Dogan and Inglesi-Lotz (2020) analyzed the impact of economic structure on environmental degradation using the EKC framework; Wang, Gao, et al. (2020) tested the validity of the EKC between urbanization and air pollution; Magazzino et al. (2020a) examined the municipal solid waste (MSW) production-income per capita nexus using the EKC approach. Table 1 outlines the information on this literature.

Subsequently, far-reaching investigations have been performed at the country level. Results validating the EKC theory can be found in Jalil and Mahmud (2009), Sarkodie et al. (2020) and Sun et al. (2021) for China; Fodha and Zaghoud (2010), and Shahbaz et al. (2014) for Tunisia; Iwata et al. (2010) for France; Baek and Kim (2013) for Korea; Shahbaz et al. (2013) for Romania; Saboori et al. (2016) for Malaysia; Pata (2018) for Turkey; Isik et al. (2019a, b) for the USA (50 and 10 US States, respectively); Rana and Sharma (2019) for India; Sarkodie and Ozturk (2020) for Kenya; Ongan et al. (2021) for the USA.

Nonetheless, this hypothesis has been rejected in Soytaş et al. (2007) for the USA; Fei et al. (2011), Wang et al. (2016), and Pata and Caglar (2021) for China; Alam et al. (2011), Yang and Zhao (2014), and Ahmad et al. (2016) for India; Balibey (2015) for Turkey; Mikayilov et al. (2018) for Azerbaijan; Iskandar (2019) for Indonesia; Hasanov et al. (2019) for Kazakhstan; Koc and Bulus (2020) for Korea; Minlah and Zhang (2021) for Ghana; Shikwambana et al. (2021) for South Africa. Table 2 underlines key elements of this literature.

Export product diversification and environmental pollution: a modified EKC application

Analyses on the nexus between export product diversification and environmental pollution are quite recent, and thus very seminal. While fruitful papers attempted to analyze the above-mentioned nexus under the context of the EKC, the scope of research possibilities remains large and promising.

Above all, the first empirical investigation can be traced back to Gozgor and Can (2016b) on the Turkish case. The authors tested the impacts of export diversification and energy use on carbon dioxide concentration using the DOLS estimation and data covering the 1971–2010 period. Obtained results claimed evidence that there exists a critical level of export diversification after which the effective impact of this latter variable on pollution becomes negative. This finding corroborates those of Apergis et al. (2018) who supported the EKC hypothesis for 19 advanced economies and used ARDL and quantile panel regression (QPR) estimation. Besides, Liu et al. (2018) inspected the relationship between export diversification and ecological footprint for Korea, Japan, and China, and conducted a comparative study. VECM evidence brought strong support to

Table 1 Summary of EKC studies on the growth-pollution nexus: multi-country approach

Author(s)	Countries	Period	Methodology	Energy data	EKC
Grossman and Krueger (1991)	42 economies	1977–1988	FE	Ø	Yes
Shafik and Bandyopadhyay (1992)	149 economies	1960–1990	FE	Ø	Yes
Panayotou (1993)	68 economies	1988	OLS	T	Yes
Selden and Song (1994)	30 economies	1979–1987	RE, FE	Ø	Yes
Moomaw and Unruh (1997)	16 transition economies	1950–1992	OLS, FE	Ø	No
Agras and Chapman (1999)	34 economies	1971–1991	FE	T	No
Dinda et al. (2000)	33 economies	1979–1990	OLS	Ø	Yes
Gangadharan and Valenzuela (2001)	51 economies	1998	OLS and 2SLS	T	No
Stern and Common (2001)	73 economies	1960–1990	FE, RE	Ø	Yes
York et al. (2003)	142 economies	1996	STIRPAT	Ø	Yes
Cole (2004)	OECD economies	1980–1997	FE and RE	Ø	Yes
Dijkgraaf and Vollebergh (2005)	24 economies	1960–1997	OLS	Ø	Yes
Acaravci and Ozturk (2010)	19 EU economies	1960–2005	ARDL	T	No
Apergis and Payne (2009)	6 central American economies	1971–2004	VECM	T	Yes
Lean and Smyth (2010)	5 ASEAN economies	1980–2006	DOLS	T	Yes
Leitão (2010)	94 economies	1981–2000	FE, RE	T	Yes
Lee et al. (2010)	97 economies	1980–2001	GMM	Ø	Mixed
Narayan and Narayan (2010)	43 developing economies	1980–2004	Panel cointegration	Ø	No
Jaunky (2011)	36 high-income economies	1980–2005	GMM and VECM	Ø	Yes
Arouri et al. (2012)	12 MENA economies	1981–2005	CCE	T	No
Castiglione et al. (2012)	28 economies	1996–2008	OLS	T	Yes
Iwata et al. (2012)	11 OECD economies	1960–2003	ARDL	NE	Yes
Ben Jebli et al. (2013)	25 OECD economies	1980–2009	FMOLS, DOLS	R	Yes
Baek (2015a)	12 nuclear energy consuming economies	1980–2009	FMOLS, DOLS	NE	No
Baek (2015b)	Arctic economies	1960–2010	ARDL	T	No
Heidari et al. (2015)	5 ASEAN economies	1980–2008	PSTR	T	No
Bilgili et al. (2016)	17 OECD economies	1977–2010	FMOLS, DOLS	R	Yes
Kais and Sami (2016)	58 economies	1990–2012	GMM	T	Yes
Lin et al. (2016)	5 African economies	1980–2011	STIRPAT	T	No
Antonakakis et al. (2017)	106 economies	1971–2011	VAR, IRF	T	No
Aye and Edoja (2017)	31 developing economies	1971–2013	DHC, DPTR	T	No
Zaman and Abd-el Moemen (2017)	90 economies	1975–2015	GMM	T	Yes
Cai et al. (2018)	G-7 economies	1965–2015	ARDL	RE	No
Sarkodie (2018)	17 African economies	1971–2013	RE, FE, WC, ECM	T	Yes
Haseeb et al. (2018)	BRICS economies	1993–2013	WC, DHC	T	Yes
Hu et al. (2018)	25 developing economies	1996–2012	OLS, DOLS	R	No
Alshubiri and Elheddad (2019)	32 OECD economies	1990–2015	GMM, FE	Ø	Yes
Kong and Khan (2019)	14 developed and 15 developing economies	1977–2014	VECM, GMM	Ø	Yes
Le (2019)	10 ASEAN economies	1993–2014	FE, RE	Ø	Yes
Dogan and Inglesi-Lotz (2020)	7 EU economies	1980–2014	PPC, FMOLS	T	Yes
Adeel-Farooq et al. (2020)	6 ASEAN economies	1985–2012	MG, PMG	Ø	Yes
Leal and Marques (2020)	20 OECD economies	1990–2016	ARDL	F/R	Yes
Moutinho et al. (2020)	12 OPEC economies	1992–2015	PCSE	T	No

Table 1 (continued)

Author(s)	Countries	Period	Methodology	Energy data	EKC
Pata and Aydin (2020)	6 hydropower consuming economies	1965–2016	ARDL	R	No
Akadiri et al. (2021)	BRICS countries	1995–2018	PMG-ARDL	F	Yes (LR)
Murshed et al. (2021)	6 South Asian countries	1980–2016	AMG, CCE-MG	F	Yes

T, F, and R refer to total energy consumption, fossil fuel energy consumption, and renewable energy consumption, respectively. \emptyset indicates that no energy consumption data were included in the estimation model. “Yes” indicates that the EKC hypothesis is supported, while “No” refers to its empirical rejection. LR corresponds to Long-Run. 2SLS 2 stages least squares, AMG augmented mean group, ARDL autoregressive distributed lag bounds, CCE-MG common correlated effects mean group estimator, DHC Dumitrescu-Hurlin causality test, DOLS dynamic ordinary least squares, ECM error correction model, FE fixed effects, FMOLS fully modified ordinary least squares, GMM generalized method of moments, IRF impulse response function, MG mean group, OLS ordinary least squares, PCSR panel corrected standard errors, PMG-ARDL pooled mean group-autoregressive distributed lag model, PPC Pedroni panel cointegration, PSTR panel smooth transition regression, RE random effects, STIRPAT stochastic regression on population, affluence, and technology, VAR vector auto-regressive, VECM vector error correction model, WC Westerlund cointegration

the EKC hypothesis for Korea and Japan, while China does not display the same tendency. By contrast, to deal with this research question, Liu et al. (2019) developed an econometric specification incorporating Driscoll and Kraay standard errors. Based on a series covering 125 countries, obtained results end up being mixed. While the sample of low-income countries illustrates a surprising U-shaped pattern, OECD countries display an inverted U-shaped curve, providing evidence of the EKC only for this income group. Furthermore, Can et al. (2020) re-visited this nexus for 84 developing countries. ARDL, DOLS, and FMOLS results revealed that the EKC hypothesis holds for the whole sample. Applying GMM and pooled mean group estimators on a sample of 98 developed and developing countries, Mania (2020) found that the EKC is valid between export diversification and CO₂ emissions. Finally, in Shahzad et al. (2020), the authors empirically demonstrated that all three metrics proxying export diversification sharply lower pollution. To do so, they collected data on 63 developing economies and adopted a FE and GMM approach. Lastly, Wang et al. (2020) asked whether low-carbon innovation and export diversification can control CO₂ considering G-7 countries. Thus, they assessed the export diversification-pollution nexus and applied the cross-sectional augmented autoregressive distributed lags (CS-ARDL). Findings showed that export diversification significantly mitigates environmental pollution. Nonetheless, the magnitude of this effect declines with the degree of environmental innovation. Khan et al. (2021) conducted a slightly similar

assessment for Regional Comprehensive Economic Partnership (RCEP) signatories using the CS-ARDL model over the 1987–2017 period. Associated results gave support to the EKC hypothesis between export diversification and pollution trend, which is in line with Ali et al. (2022) for India. While Jiang et al. (2022) did not incorporate a quadratic export diversification term within their common correlated effects mean group (CCE-MG) estimates specification, they showed how environmental pollution is significantly triggered by export diversification. Table 3 highlights key elements of this emerging literature.

The EKC approach: insights from the empirical literature

This state-of-the-art review highlights important points. Above all, while the EKC literature is extensive, results differ and sometimes conflict. Thus, as concluded by Kaika and Zervas (2013), no clear conclusion has been drawn so far, perhaps because the income-CO₂ emissions nexus remains highly sensitive to the use of energy, which, in turn, is a non-avoidable industrial input. More generally, the ways authors addressed the economic-environment relationship diverge in several ways. Upon them, the diversity of methodologies employed, the heterogeneity of samples of countries considered, and the variety of model specifications adopted.

First, existing studies demonstrated a strong capacity to apply a range of different quantitative tools to a

Table 2 Summary of EKC studies on the growth-pollution nexus: single-country approach

Author(s)	Countries	Period	Methodology	Energy data	EKC
Soytas et al. (2007)	US	1960–2004	GC	T	No
Jalil and Mahmud (2009)	China	1975–2005	ARDL	T	Yes
Fodha and Zaghdoud (2010)	Tunisia	1961–2004	VECM	∅	Yes
Iwata et al. (2010)	France	1970–2003	ARDL	NE	Yes
Fei et al. (2011)	China	1985–2007	OLS	T	No
Alam et al. (2011)	India	1971–2016	GC, TYC, IRF	T	No
Baek and Kim (2013)	Korea	1971–2007	ARDL	F/R/N	Yes
Shahbaz et al. (2013)	Romania	1980–2010	ARDL, VECM, GC	T	Yes
Shahbaz et al. (2014)	Tunisia	1971–2010	VECM	∅	Yes
Yang and Zhao (2014)	India	1970–2008	GC	T	No
Balibey (2015)	Turkey	1974–2011	VAR, IRF	∅	No
Ahmad et al. (2016)	India	1971–2014	ARDL, GC	F	No
Saboori et al. (2016)	Malaysia	1980–2009	ARDL	∅	Yes
Wang et al. (2016)	China	1990–2012	VECM, IRF, GC	T	No
Mikayilov et al. (2018)	Azerbaijan	1992–2013	DOLS, FMOLS	T	No
Pata (2018)	Turkey	1974–2014	ARDL, FMOLS	R	Yes
Hasanov et al. (2019)	Kazakhstan	1992–2013	FMOLS	∅	No
Isik et al. (2019a)	US (50 States)	1980–2015	AMG	F	Yes
Işık et al. (2019b)	US (10 States)	1980–2015	FE, CCE	R	Yes
Iskandar (2019)	Indonesia	1981–2016	ARDL	∅	No
Rana and Sharma (2019)	India	1982–2013	TYC	∅	Yes
Koc and Bulus (2020)	Korea	1971–2017	ARDL	T/R	No
Minlah and Zhang (2021)	Ghana	1960–2014	RWGC	∅	No
Pata and Caglar (2021)	China	1980–2016	ARDL	R	No
Sarkodie and Ozturk (2020)	Kenya	1971–2013	ARDL, ECM	T/R	Yes
Sarkodie et al. (2020)	China	1961–2016	ARDL	F/R	Yes
Sun et al. (2021)	China	1990–2017	VAR, GC	T	Yes
Ongan et al. (2021)	US	1991–2019	DA	F/R	Yes
Shikwambana et al. (2021)	South Africa	1994–2019	SQMK	∅	No

T, F, NE, and R refer to total energy consumption, fossil fuel energy consumption, nuclear energy consumption, and renewable energy consumption, respectively. ∅ indicates that no energy consumption data were included in the estimation model. “Yes” indicates that the EKC hypothesis is supported, while “No” refers to its empirical rejection. *AMG* augmented mean group, *ARDL* autoregressive distributed lag bounds, *CCE* common correlated effects, *DA* decomposition analysis, *FMOLS* fully modified ordinary least squares, *GC* Granger causality test, *IRF* impulse response function, *OLS* ordinary least squares, *RWGC* rolling window Granger causality, *SQMK* sequential Mann–Kendall test, *TYC* Toda–Yamamoto causality test, *VAR* vector auto-regressive, *VECM* vector error correction model

single research question. On the one hand, statistical assumptions may differ across tests and procedures, making the results less reliable and comparable. On the other hand, using more powerful data techniques is thought to bring more consistent findings, especially when applied in complement to the standard procedure. While early papers relied on standard panel estimators (i.e., fixed effects; random effects panel estimators), others employed modified panel

version (i.e., dynamic ordinary least square; fully modified ordinary least squares), and even innovative estimators (i.e., generalized method of moments; panel quantile regression; Driscoll–Kraay standard errors). More recently, one can also notice the new utilization of advanced panel procedures allowing for heterogeneity (mean group estimator; augmented mean group estimator) and cross-sectional dependence among the series (i.e., common correlated

Table 3 Summary of EKC studies on the export diversification-pollution nexus

Author(s)	Countries	Period	Methodology	Energy data	EKC
Gozgor and Can (2016b)	Turkey	1971–2010	DOLS	T	Yes
Apergis et al. (2018)	19 advanced countries	1962–2010	ARDL, QPR	∅	Yes
Liu et al. (2018)	Japan, Korea, and China	1990–2013	VECM	∅	Yes (Japan and Korea only)
Liu et al. (2019)	125 countries	2000–2014	FE, DKSE	∅	Mixed
Can et al. (2020)	84 developing countries	1971–2014	ARDL, DOLS, FMOLS	T	Yes
Mania (2020)	98 countries	1995–2013	GMM, PMG	∅	No
Shahzad et al. (2020)	63 developing countries	1971–2014	FE, GMM	T	-
Wang et al. (2020)	G-7 countries	1990–2017	CS-ARDL	RE	-
Khan et al. (2021)	RCEP signatories	1987–2017	WC, CS-ARDL	RE	Yes
Jiang et al. (2022)	96 countries	1991–2018	CCE-MG, FMOLS, DOLS	∅	-
Ali et al. (2022)	India	1965–2017	STIRPAT	∅	Yes

T refers to total energy consumption. ∅ indicates that no energy consumption data were included in the estimation model. “Yes” indicates that the EKC hypothesis is supported, while “No” refers to its empirical rejection. “Mixed” indicates that the authors concluded to mixed evidence regarding the effective validity of the EKC. “-” indicates that investigating the validity of the EKC was not the explicit aim of the paper. *ARDL* autoregressive distributed lag bounds, *CCE-MG* common correlated effects mean group estimator, *CS-ARDL* cross-sectionally augmented autoregressive distributed lag, *DKSE* Driscoll-Kraay standard errors, *DOLS* dynamic ordinary least squares, *FE* fixed effects, *FMOLS* fully modified ordinary least squares, *GMM* generalized method of moments, *PMG* pooled mean group, *STIRPAT* stochastic impact regression on population, affluence and technologies, *QPR* quantile panel regression, *WC* Westerlund cointegration test

effects mean group estimator). Often supplemented by cointegration techniques (Johansen cointegration test; Pedroni panel cointegration), various macro-econometric tools have been employed to inspect the short- and long-run interactions between economic and environmental indicators (autoregressive distributed lag bounds; vector error correction model). Finally, one must not avoid the non-negligible role accorded to causality tests along with modern EKC testing procedures. Starting with the standard one (i.e., Granger causality test), researchers employed more innovative versions (Toda-Yamamoto causality test; Dumitrescu-Hurlin causality test). Overall, a prominent place is now dedicated to variance analyses (i.e., forecast error variance decomposition; impulse response function), widely used to check the validity of the causal inference ahead of the sample period.

Second, an important insight drawn from the EKC literature is that most of the multi-country studies referenced here were conducted on large and heterogeneous samples of countries. This is laudable if the study aims at performing a global (or regional) scale assessment, but less intuitive in the case of a panel elaborated with data from countries belonging

to different stages of development. Naturally, we do not avoid the data availability constraint that economists faced in the past. However, we argue that the literature lacks single-country examinations which in turn, might limit the design of adequate policy recommendations.

Third, another diverging point stands in the various approaches that researchers adopted so far. To investigate the empirical relevance of the EKC hypothesis between economic growth and environmental pollution, past papers frequently relied on bivariate or trivariate models³ (i.e., they added energy data as a unique additional factor). Similarly, export diversification-CO₂ emission frameworks have often been enriched with aggregate income data, avoiding thus the inclusion of other fundamental determinants. Although they are easier to implement, we hereby considered that relying on such a model is limited because including a unique additional factor cannot

³ Trivariate models contrast to bivariate frameworks as they incorporate an energy determinant within their econometric specification. Ahead three variables, a model is considered a multivariate.

sufficiently control for omitted variable bias. Therefore, this is of high interest to analyze which other sub-factors may lead to an EKC relationship since incorporating multiple confounding factors is thought to substantially limit statistical interferences, biased estimations, and misleading interpretations (Lütkepohl, 1982). This corresponds to the strategy adopted in more recent papers such as Can et al. (2020) and Shahzad et al. (2020) for instance.

All in all, no clear picture has emerged for policymakers since evidence on the existence and the robustness of the EKC seem having diverged rather than converged across time. The reason stands in the chronology of these investigations and the development of new econometric tools across decades.

- From the 1990s to 2000s, the first wave of empirical papers has relied on the conventional approach: large sample of countries, data corresponding to multi-pollutants, bivariate⁴ GDP/environmental pollution models, and standard econometric regression methodologies (i.e., ordinary least squares, fixed effects, and random effects) (see Shafik and Bandyopadhyay (1992), Selden and Song (1994), Stern and Common (2001)).
- In the 2010s, the second wave of studies has been characterized by the EKC analysis of a single pollutant (i.e., typically using CO₂ emissions as a proxy for environmental degradation) using series covering large groups of countries but over relatively small periods (see Acaravci and Ozturk (2010), Lee et al. (2010), Leitão (2010), Narayan and Narayan (2010)).
- Over the recent 2010–2020 period, studies shifted from multi- to single-country approaches, notably because of newly available time-series data over long periods (see Alam et al. (2011), Shahbaz et al. (2014), Işık et al. (2019a, b)). In response to the limitations caused by simple growth-pollution frameworks, this third wave of studies has been accompanied by new multivariate model specifications incorporating production factors (i.e., gross fixed capital formation; labor or population),

energy inputs (i.e., total energy use, low-carbon energy use or fossil energy use), trade indicators (i.e., trade openness or trade volumes), but also financial indicators (i.e., foreign direct investments). Also, accurate methodologies (cointegration and causality tests, variance analysis) emerged as a complement to standard regressions. Besides, more advanced panel procedures have also been developed and applied along with EKC investigations (allowing for heterogeneity within the sample and cross-sectional dependence among the series, notably).

Also, we noticed that no previous analysis has explored the export diversification-environmental pollution nexus for the specific case of China. This is surprising since the growth-pollution nexus in China has been the subject of intense (but conflicting) examinations (see Fei et al. (2011), Wang et al. (2016), and Pata and Caglar (2021) for the EKC rejection; and Jalil and Mahmud (2009), Sarkodie et al. (2020), and Sun et al. (2021) for the empirical validation of the EKC). To date, Liu et al. (2018) remain the only study that brought export diversification evidence on the Asian region, although related results have been drawn from a conventional trivariate estimation model. Underlining a critical gap in the literature, it appears crucial to take the Chinese case as an illustration. While its booming emergence has been mostly driven by export-led-growth mechanisms, this economy is also the world's largest polluter. Thus, China will have to commit to environmental efforts shortly by targeting its most energy-intensive sectors with adequate reforms. Launched recently (i.e., September 23rd, 2020), the carbon-neutrality objective set by Chinese President Xi Jinping is a fair illustration of this ambitious low-carbon economy goal.

Based on this state-of-the-art review, this paper seeks to add to the empirical domain by addressing the above-mentioned concerns separately. Thus, we took the Chinese case as an illustration and examine whether the EKC hypothesis holds between export product diversification and carbon emissions from fuel combustion. Since the Chinese manufacturing sector is undergoing profound mutations, a good understanding of the trade structure-environmental degradation nexus is believed to bring high information value to policymakers. To do so, this paper employs a complete causality testing framework

⁴ Bivariate models contain an economic variable and an environmental variable describing economic growth and environmental degradation, respectively.

and relies on a consistent time-series strategy. Data cover the 1990Q1-2018Q4 period and are obtained by applying the quadratic match-sum method on the annual series. Regarding the empirical strategy followed, we include in the same study different approaches for robustness check. We start by studying stationarity and cointegration through both the Johansen cointegration test and the ARDL error correction regression procedure. Afterward, we include Granger causality analysis, finishing with FMOLS and DOLS methodologies, following previous literature, in particular, Can et al. (2020), whereas presenting a more complete empirical analysis. Finally, to remedy econometric issues, this study employs a multivariate approach, including per capita income, export diversification, and foreign direct investments variables into the model. All in all, the sensitivity of the export diversification-environmental pollution nexus to the inclusion of polluting and low-carbon energy resources (i.e., fossil energy use and low-carbon energy consumption, respectively) is tested. To the best of our knowledge, this study is the first to assess the dynamic link between export product diversification and CO₂ emissions within an EKC framework and for the single case of China.

Data collection, EKC theory, and econometric framework

Besides the "Data collection", this section presents the standard EKC theory "Theoretical EKC framework". Then, the econometric framework is displayed and designed following our export diversification research question "Econometric framework".

Data collection

To perform our empirical investigation, we collected series on China for the following variables: export product diversification (index), CO₂ emissions from fuel combustion (thousand tons), per capita GDP (PPP, constant 2017 international US dollar \$), fossil fuel energy consumption (kilo tons of oil equivalent (ktoe)), renewable energy consumption (kilo tons of oil equivalent (ktoe)), foreign direct investments (FDI, net inflows, BoP, current US dollar \$). Accordingly, fossil and renewable energy consumption are used as a proxy for fossil and renewable energy

demand, respectively. CO₂ emissions are used as a proxy for environmental degradation. For all variables, the series covers the most recent and available period of data: 1990Q1-2018Q4. Those were computed by applying the Quadratic Match-Sum Method (QMS) on the annual series. Per capita GDP and FDI data are taken from the World Development Indicators database (WDI, 2020). Data on export product diversification are taken from the UNCDAT Database (2020).⁵ Fossil information and renewable energy consumption are taken from the OECD Environment Statistics database (2020).⁶ Finally, CO₂ emissions from fuel combustion data are taken from the IEA CO₂ emissions from fuel combustion Statistics (IEA, 2020a, b, c).⁷ Variable information, definitions, and data sources are summarized in Table 4.

A note on the export product diversification index is important. It is constructed by the United Nations Trade and Development Department and estimated for all the products exported. More specifically, it is computed by calculating the absolute deviation of country share from world structure. The range of diversification is from 0 to 1 and is weighted by the difference between the trade structure of the country and the world average. The high index value shows more diversification. As we know, China is currently a leading exporter and polluter worldwide. Taking this case, as an illustration, might allow researchers to draw new conclusions regarding whether export product diversification is a sustainability-enabler or environmental threat.

Theoretical EKC framework

This sub-section aims at presenting the standard theory laying under the EKC hypothesis, along with its commonly used econometric specification.

The environmental Kuznets curve (EKC) is a theory underlining that economic growth generates

⁵ Data on export product diversification are available at: <https://unctad.org/statistics>

⁶ Data on fossil and renewable energy use are available at: https://www.oecd-ilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en

⁷ Data on CO₂ emissions from fuel combustion (electricity and heating production) are available at: https://www.oecd-ilibrary.org/energy/data/iea-co2-emissions-from-fuel-combustion-statistics_co2-data-en

Table 4 Data specification

Indicator	Acronym	Measure	Source
CO ₂ emissions from fuel combustion	<i>E</i>	Thousand tons	IEA CO ₂ Emissions from Fuel Combustion Statistics (2020a)
Export product diversification	<i>EPD</i>	Index	UNCDAT Database (2020)
Fossil fuel consumption	<i>NRE</i>	Kilo tons of oil equivalent (ktoe)	OECD Environment Statistics (2020)
Renewable consumption	<i>RE</i>	Kilo tons of oil equivalent (ktoe)	OECD Environment Statistics (2020)
Per capita GDP	<i>Y</i>	PPP, constant 2017 international US dollar \$	World Development Indicators (WDI, 2020)
Foreign direct investments	<i>FDI</i>	Net inflows (BoP, current US\$)	World Development Indicators (WDI, 2020)

heterogeneous effects on environmental quality. Studies asserted that initially, the economic growth acts as a pioneer to the environmental degradation; however, economies, when reaching the threshold level of income or economic growth, tends to focus on the sustainability of environmental quality (see for instance: Kaika and Zervas (2013); Bimonte and Stabile (2017); Sarkodie and Strezov (2019); Adeel-Farooq et al. (2020); Dogan and Inglesi-Lotz (2020) that gives an inverted U-shaped pattern for different regions of the world).

The EKC assumption states that, in the earlier phases of the county's economic growth, when primary production takeovers due to limited economic activities, the natural resources are available in abundance, and wastes are abundantly generated, although their absolute amount is controlled. However, as industries grow, a substantial reduction of natural resource availability is observed and translates into critical levels of wastes, carbon emissions, and environmental degradation more generally. Throughout this period, the association between the per capita income or economic activity and environmental pollution is said to be positive and linear (Kaika & Zervas, 2013; Haseeb et al., 2018). However, after an identified turning point, further economic (and notably per capita income) improvements are accompanied by a depletion of environmental degradation. This results from the internalization of environmental externalities, energy efficiency measures, and renewable energy reforms, but also a global ecological awareness of consumers. According to Al-Mulali et al. (2015), the upper-middle- and high-income economies might be the most likely countries to follow the EKC strategy, whereas the low and lower-middle-income countries

seem far from this development pattern. This might be because of the technological factor's availability (which increases energy efficiency, energy-saving as well as enhances renewable energy). Indeed, due to high costs, it remains weakly accessible to low and lower-middle-income countries, although it could take a central role in turning them towards a greener path.

In Fig. 1, the graphical representation of the EKC is provided. The plotted inverted U-shaped structure indicates the association between per capita environmental deterioration and per capita income as projected by Kuznets (1955). The under-discussion of Fig. 1 further illustrates that economic activity and environmental degradation can be consistently de-linked once per capita income has reached a turning point. Under such conditions, further economic growth contributes to the establishment of a

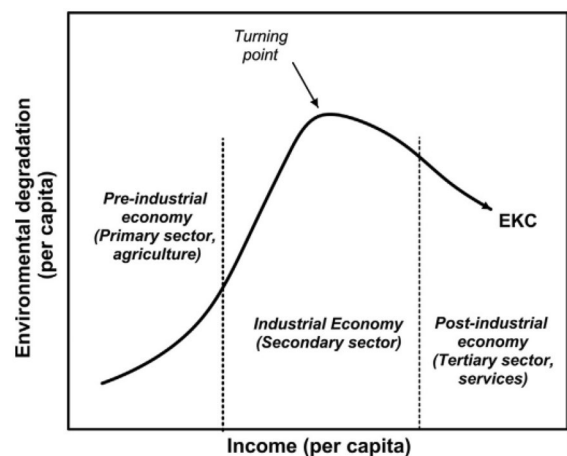


Fig. 1 An environmental Kuznets curve (EKC). Source: Kaika and Zervas (2013)

sustainable path. Inversely, this theory postulates that no comprehensive reforms can be achieved without a sufficient level of economic development.

Despite the various approaches used in assessing the EKC, almost all of them obey a common model specification. The connection regarding environmental pressure or level of emissions and per capita level is represented in a reduced form using a panel data series (see for instance Isik et al. (2019a, b) and Hasanov et al. (2019) who used such a conventional model to study the economic growth-CO₂ emissions nexus):

$$Y_{it} = \alpha_{it} + \beta_1 x_{it} + \beta_2 x_{it}^2 + \beta_3 x_{it}^3 + \beta_4 Z_{it} + \mu_{it} \quad (1)$$

where the dependent variable “y” represents environmental degradation, α represents intercept (constant), independent variables x , x^2 , and x^3 represent the level of income, squared and cubic level of income, respectively. The variable “Z” denotes other variables that influence environment degradation. Moreover, β_1 , β_2 , β_3 , and β_4 are the coefficient estimates of the discussed parameters, and μ is the error term throughout the cross-sections (i) and time (t). Based on Eq. (1), several empirical patterns can be delivered regarding the study of the economic growth-environmental degradation nexus. Figure 2 outlines the scope of possible income-pollution relationships.

- I. If $\beta_1 = \beta_2 = \beta_3 = 0$, (x and y have no association) (a)
- II. If $\beta_1 > 0, \beta_2 = \beta_3 = 0$, (x and y have positive monotonic relationship) (b)
- III. If $\beta_1 < 0, \beta_2 = \beta_3 = 0$, (x and y have negative monotonic relationship) (c)
- IV. If $\beta_1 > 0, \beta_2 < 0, \beta_3 = 0$, (x and y have inverted U-shaped structure) (d)
- V. If $\beta_1 < 0, \beta_2 > 0, \beta_3 = 0$, (x and y have U-shaped structure) (e)
- VI. If $\beta_1 > 0, \beta_2 < 0, \beta_3 > 0$, (x and y have N-shaped relation) (f)
- VII. If $\beta_1 < 0, \beta_2 > 0, \beta_3 < 0$, (x and y have inverted N-shaped relation) (g)

In the traditional EKC estimating method, the insertion of a non-linear variable in the regression model results in the test of a non-linear relationship. If the non-linear variable is negative and statistically significant along with the turning points in the data series, this can be an inverted U-shaped. Hence, if $\beta_1 > 0, \beta_2 < 0$, and $\beta_3 = 0$, the EKC-hypothesis is valid at a turning point estimated as, $x^* = (-0.5\beta_1)/\beta_2$, as shown earlier in Fig. 1.

Linking the EKC theory with trade is thought to be a fruitful research direction. As mentioned in Al-Mulali et al. (2015), trade can significantly contribute to environmental degradation through various

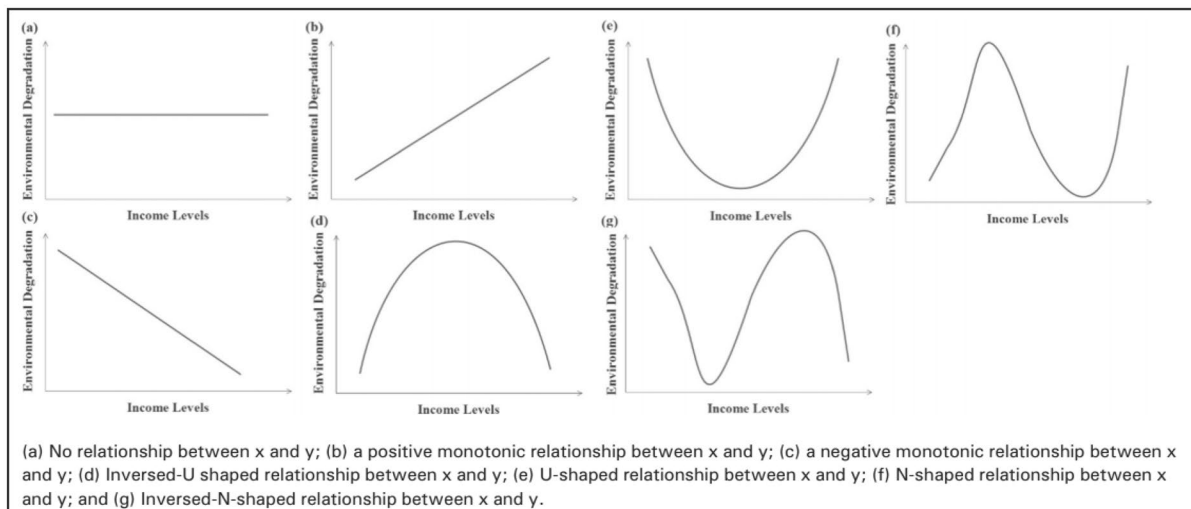


Fig. 2 Eq. (1)’s empirical specifications, several interpretations regarding income-environment nexus. Source: Sarkodie and Strezov (2019)

channels. One of them is the export diversification strategy. By expanding economic activities for export diversification, a serious threat to environmental sustainability may arise. Accordingly, at the initial stage of development, important energy needs (for industrial purposes notably) are met through the massive use of non-renewable resources, contributing thus to environmental degradation. However, as income grows and after achieving a threshold export diversification level, a shift towards the use of more innovative and environmental-friendly technologies is observed along the supply chain. Thus, efficiency gains results are thought to allow for the establishment of a low-carbon supply chain, which in turn, translates into fewer carbon emissions. Overall, this cycle takes the form of an inverted U-shaped pattern and follows the EKC theory accordingly.

Econometric framework

In this paper, we did not follow the common literature presented above but instead relied on a modified EKC version. Thus, we follow the seminal and recent studies on the relationship between export product diversification and environmental pollution (Apergis et al., 2018; Can et al., 2020; Gozgor & Can, 2016b; Liu et al., 2018, 2019; Mania, 2020) and design our econometric model accordingly. In what follows is outlined our empirical methodology and the corresponding econometric specifications.

Data presented in Table 4 were first collected at the annual level. Subsequently, we transformed and

converted annual data into quarterly data by using the Quadratic Match-Sum Method (QMSM). Being decomposed, a quarterly dataset allows for a consistent single-country analysis of the Chinese case and avoids data unavailability concerns. This strategy has been employed in recent literature (Shahbaz et al., 2020; Shahzad et al., 2021). The second transformation denotes the conversion of level-variables into their natural log forms. (see Table 5).

Following Can et al. (2020), we adapted our export diversification model to the standard EKC specification (as adopted in Arouri et al., 2012; Narayan & Narayan, 2010). In the present approach, GDP per capita, low-carbon energy, fossil energy, foreign direct investments, and export product diversification are considered a potential CO₂ emissions drivers. This modified EKC approach states that if the short-run value of export product diversification is larger than its long-run value, we may argue in favor of the validity of the EKC hypothesis. Following Narayan and Narayan (2010), this is a shred of evidence that CO₂ emissions are reduced in the long run, as the export diversification strategy is achieved (Can et al., 2020). To this end, we seek to test for the existence of the EKC model between export product diversification and CO₂ emissions in China, but also to assess the importance of the energy channel in explaining this relationship. Hence, we inspected how such a pattern is sensitive to the inclusion of low-carbon and polluting energy sources within our framework. Thus, the following two models are specified and estimated.

Table 5 Descriptive statistics

	E	Y	RE	NRE	FDI	EPD
Mean	0.004112	6314.643	0.000132	0.000380	87.62640	0.453307
Median	0.003659	4817.131	0.000136	0.000331	52.55658	0.456200
Maximum	0.006841	15,243.25	0.000177	0.000570	214.3309	0.477983
Minimum	0.001840	1423.702	8.18E-05	0.000217	3.071746	0.403262
Std. Dev	0.001867	4154.148	3.43E-05	0.000129	66.77084	0.016883
Skewness	0.271139	0.640016	-0.164452	0.199316	0.509105	-1.596047
Kurtosis	1.394743	2.076314	1.441137	1.346145	1.799518	4.826402
Jarque–Bera	13.51723	11.73164	11.95085	13.62660	11.66681	63.68121
Probability	0.001161	0.002835	0.002540	0.001099	0.002928	0.000000
Sum	0.464683	713,554.7	0.014959	0.042989	9901.783	51.22369
Sum Sq. Dev	0.000391	1.93E+09	1.32E-07	1.87E-06	499,334.7	0.031924
Observations	113	113	113	113	113	113

E shows the total carbon emissions, Y presents GDP per capita, RE shows renewable energy, NRE shows non-renewable energy, FDI shows Foreign direct investments and, EPD indicates export product diversification. Descriptive is reported for quarterly data before converting to the logarithm

Model-1 specification:

$$e_t = \beta_1 y_t + \beta_3 re_t + \beta_4 fdi_t + \beta_5 epd_t + \beta_2 epd_t^2 + \varepsilon_t \quad (2)$$

Model-2 specification:

$$e_t = \beta_1 y_t + \beta_3 nre_t + \beta_4 fdi_t + \beta_5 epd_t + \beta_2 epd_t^2 + \varepsilon_t \quad (3)$$

where e represents the total carbon emissions, y represents GDP per capita, re stands for renewable energy, nre for non-renewable energy (i.e., and operates as a proxy for fossil energy consumption), fdi represents foreign direct investments, epd indicates export product diversification, and epd^2 is export diversification squared. Moreover, t denotes the period and ε stands for the error term. Model-1 and Model-2 specifications include both epd and epd^2 , but the ARDL model specification presented below was a linear one and for that reason does not incorporate the quadratic term, as testing the EKC is not the explicit aim of the ARDL process. By opposition, it is the purpose of the FMOLS and DOLS methodologies, and for this reason, the econometric specifications presented below will already display the quadratic component.

While analyzing time series it is important to find meaningful cointegrated relationships to rule out misleading estimates. In the literature, both bi- and multivariate cointegration models identifying long-run relationships have been employed (Engle & Granger, 1987; Johansen, 1988, 1991; Johansen & Juselius, 1990). The multivariate model turns relevant but less straightforward to interpret when dealing with more than one cointegrating vector (Ang, 2009). However, mixed orders of integration will drive the inappropriateness of bivariate and multivariate models. An alternative emerges from the autoregressive distributed lag (ARDL) bounds test, developed by Pesaran and Pesaran (1997), Pesaran and Smith (1998), and Pesaran et al. (2001). Another important test to verify cointegration is the Johansen cointegration test, which was as well applied here, and results will be provided upon request. For the already identified problems, we simply relied upon the exposition of the ARDL results for cointegration analysis.

ARDL bounds test turns better than more traditional cointegration tests as it can be employed using singular lag lengths for each variable, exhibiting higher small-sample properties (Smyth & Narayan, 2015), with a lag-order correctly specified controls for serial correlation and minimizes the endogeneity

bias and finally, allows to obtain a dynamic unrestricted error correction model (ECM) by using a simple linear transformation to the ARDL specification. This transformed unrestricted ECM displays the advantageous feature of merging short-run dynamics and long-run equilibrium within a single framework without any information cost.

To model the above two model specifications, first, we inspected the stationary properties of the series using the Clemente–Montanes–Reyes (CMR) (1998) unit root test. The ARDL bounds test displays a more flexible assumption concerning the order of integration when compared with standard cointegration approaches. Also, we used the traditional ADF and DF-GLS unit root tests, although both failed to take into account possible structural breaks, unlike the CMR. This latter follows removes sudden changes in the mean of the variable following the additive outlier method.

To control for endogeneity in the causal relationship we want to verify in Model-1 and Model-2 specifications, we might apply ECM. In a second step, we explore short-run dynamics using the ARDL approach and the long-run relationships among variables in Model-1 and Model-2 specifications, using the ARDL approach. In a third step, we apply Granger causality analysis following the ECM model structure and in a fourth step to estimate Model-1 and Model-2, we used the dynamic ordinary least squares (DOLS) estimator as well as the fully modified ordinary least squares (FMOLS) method.⁸ It is important to mention here that the Kuznets curve of export product diversification is tested by FMOLS and DOLS estimators, while the long-run cointegrating relationship is checked through ARDL.

First, it is important to note that the ARDL cointegration technique appears more relevant when facing variables integrated of different orders — namely $I(0)$ and $I(1)$, or resulting from a combination of the both. It is also more robust with small sample sizes with $N < T$. The ARDL regression is applied with restricted constant and no trend, having the lag order been auto-selected by the Akaike information criterion (AIC). The forms of the panel ARDL of Model-1 and Model-2 specifications are described in Eqs. (4) and (5), respectively:

⁸ All estimations were performed using the Eviews and Stata software's.

$$e_t = \mu_{1t} \sum_{i=1}^p e_{t-i} + \alpha_{1i} \sum_{i=0}^{q_0} y_{t-i} + \alpha_{2i} \sum_{i=0}^{q_1} re_{t-i} + \alpha_{3i} \sum_{i=0}^{q_2} fdi_{t-i} + \alpha_{4i} \sum_{i=0}^{q_3} epd_{t-i} + \varepsilon_t \tag{4}$$

$$e_t = \mu_{1t} \sum_{i=1}^p e_{t-i} + \alpha_{1i} \sum_{i=0}^{q_0} y_{t-i} + \alpha_{2i} \sum_{i=0}^{q_1} nre_{t-i} + \alpha_{3i} \sum_{i=0}^{q_2} fdi_{t-i} + \alpha_{4i} \sum_{i=0}^{q_3} epd_{t-i} + \varepsilon_t \tag{5}$$

where $p, q_0, q_1, q_2,$ and q_3 denote the optimal lag(s) of dependent and independent variables. μ and α are the vectors of coefficients, and ε_t are the error terms. Following Eqs. (4) and (5), we specify the error correction equations, described by Eqs. (6) and (7), respectively, by:

$$\Delta e_t = \pi(e_{t-1} - \theta_1 y_t - \theta_2 re_t - \theta_3 fdi_t - \theta_4 epd_t) + \mu_{1t} \sum_{i=1}^{p-1} \Delta e_{t-i} + \alpha_{1i} \sum_{i=0}^{q_0-1} \Delta y_{t-i} + \alpha_{2i} \sum_{i=0}^{q_1-1} \Delta re_{t-i} + \alpha_{3i} \sum_{i=0}^{q_2-1} \Delta fdi_{t-i} + \alpha_{4i} \sum_{i=0}^{q_3-1} \Delta epd_{t-i} + \varepsilon_t \tag{6}$$

$$\Delta e_t = \pi(e_{t-1} - \theta_1 y_t - \theta_2 nre_t - \theta_3 fdi_t - \theta_4 epd_t) + \mu_{1t} \sum_{i=1}^{p-1} \Delta e_{t-i} + \alpha_{1i} \sum_{i=0}^{q_0-1} \Delta y_{t-i} + \alpha_{2i} \sum_{i=0}^{q_1-1} \Delta nre_{t-i} + \alpha_{3i} \sum_{i=0}^{q_2-1} \Delta fdi_{t-i} + \alpha_{4i} \sum_{i=0}^{q_3-1} \Delta epd_{t-i} + \varepsilon_t \tag{7}$$

where in the ARDL approach, the term $(e_{t-1} - \theta_1 y_t - \theta_2 nre_t - \theta_3 fdi_t - \theta_4 epd_t)$ represents the long-run relationship between total carbon emissions and the set of independent variables.

Followingly, the usual diagnostic testing for the ARDL model with renewable energy consumption and with non-renewable energy consumption is applied: the normality (Jarque Bera) test, the serial correlation

test (Breusch-Godfrey Serial Correlation LM), and the heteroscedasticity test (Breusch-Pagan-Godfrey). The F-statistic (Wald test) detects the long-run relationship of the underlying variables. First, we estimate the models by ordinary least squares (OLS), in the ARDL bounds approach. This allows testing the existence of a long-run relationship among the variables through the F-test for the joint significance of the coefficients of the lagged levels of the variables. In this view, the bounds test uses the joint F-statistic, whose asymptotic distribution is non-standard under the null of no cointegration. The null hypothesis of no cointegration is rejected (accepted) when the value of the test statistic exceeds (lowers) the upper (lower) critical bounds value, respectively. Otherwise, it becomes inconclusive.

The long-run coefficient stability is tested as follows. After the estimation of the ECM model given by Eqs. (6) and (7), the cumulative sum of recursive residuals (CUSUM) test is applied to assess the parameter stability (Pesaran & Pesaran, 1997).

Besides, we also conducted the Granger causality test. It is a statistical model able to infer whether changes in a time series can help predict the future variations of another. This Granger causality test is used to assess the nature and direction of causalities within the vector error correction model (VECM). If a set of variables is cointegrated, they should display an error correction representation and an error correction term (ECT) must be included in the model (Engle & Granger, 1987). Summing up, the advantage of the VECM is the reintroduction of the information lost while we are differencing time series, being an important step to analyze the short-run dynamics and the long-run equilibrium (Simionescu et al., 2022; Simionescu and Schneider, 2022). The short-run dynamic parameters are obtained through the estimation of the ECM related to the long-run estimates. Findings relative to the short-run Granger causality tests are reported, allowing us to infer as well the relationship between emissions and the variables of interest, in a pairwise way.

Finally, for robustness check testing the EKC hypothesis, we also used the fully modified ordinary least squares (FMOLS) method and the dynamic ordinary least squares (DOLS) estimator. Both DOLS and FMOLS present advantageous features when compared to the OLS. Even though OLS estimates are efficient, consistent, and unbiased, the t-statistic is calculated without prior testing for the order of

integration of variables, or else $I(0)$ terms are only approximately normal. Even though the OLS method is the best linear unbiased estimator (BLUE) when dealing with “a large finite sample bias,” convergence of OLS can be low in finite samples. OLS estimates may suffer from serial correlation, multicollinearity, and heteroscedasticity since the omitted dynamics are captured by the residual. Turning inference using the normal tables is not valid, even asymptotically, and the “ t ” statistics for the OLS estimates are thus useless. DOLS and FMOLS take care of endogeneity by adding leads and lags (DOLS), and white heteroskedastic standard errors are used through a non-parametric approach, both offering the consistency not provided through OLS. In the following, we need to consider that export diversification squared has been as well included in the specifications. This is so because China is currently the leading economy in exports with a range of diversification; hence China is better suited as a case study to check the linear and non-linear impacts. With the Pedroni cointegration model (Pedroni, 2001, 2004), we will test for the long-run association between the carbon emissions from fuel combustion and other independent variables. The model might be specified as in Eq. (8):

$$e_t = \delta + x_t\psi + \omega_t \tag{8}$$

$$x_t = x_t + \xi_t$$

where x is a vector of $5*1$ of independent variables (considering the Model-1 and Model-2 specifications, and epd squared), δ is the intercept, and both error terms, ω , and ξ are assumed to be $I(0)$. The ψ estimated by the FMOLS is expressed as in Eq. (9), where e stands for carbon emissions from fuel combustion.

$$\hat{\psi} = \left[\sum_{t=1}^T (x_t - \bar{x}_t) \times (x_t - \bar{x}_t)' \right] \times \left[\sum_{t=1}^T (x_t - \bar{x}_t) \times \hat{e}_t - T\widehat{\Delta}_{v\xi} \right]^{-1} \tag{9}$$

The DOLS estimator was first introduced in Kao and Chiang (2001) and takes the form of Eqs. (10) and (11), for Model-1 and Model-2, respectively:

$$e_t = \delta + x_t\psi + \sum_{i=-p}^p \mu_i e_{t-i} + \alpha_{1i} \sum_{i=-q_0}^{q_0} y_{t-i} + \alpha_{2i} \sum_{i=-q_1}^{q_1} re_{t-i} + \alpha_{3i} \sum_{i=-q_2}^{q_2} fdi_{t-i} + \alpha_{4i} \sum_{i=-q_3}^{q_3} epd_{t-i} + \alpha_{5i} \sum_{i=-q_4}^{q_4} epd_{t-i}^2 + \varepsilon_t \tag{10}$$

$$e_t = \delta + x_t\psi + \sum_{i=-p}^p \mu_i e_{t-i} + \alpha_{1i} \sum_{i=-q_0}^{q_0} y_{t-i} + \alpha_{2i} \sum_{i=-q_1}^{q_1} nre_{t-i} + \alpha_{3i} \sum_{i=-q_2}^{q_2} fdi_{t-i} + \alpha_{4i} \sum_{i=-q_3}^{q_3} epd_{t-i} + \alpha_{5i} \sum_{i=-q_4}^{q_4} epd_{t-i}^2 + \varepsilon_t \tag{11}$$

where p and q refer to the number of lags and leads of the dependent and independent variables, being chosen by the AIC criteria.

Empirical results

Table 1 reports the main descriptive statistics (means, maximum, minimum, standard deviation, skewness, kurtosis, Jarque–Bera, probability, sum, the sum of squared deviations, and observations) of our analysis variables. Based on these statistics, we notice that CO₂ emissions per capita present an upward trend during the selected period. The maximum value of emissions in China has reached 0.007 thousand tons in 2019, while the minimum value has attained 0.001 thousand tons in 1990. Regarding energy use in China, the highest level of renewable and non-renewable energy consumed was equal to 0.000177 kilo tons of oil equivalent (ktoe) (in 1990) and 0.00057 ktoe (in 2012), respectively. The main amount of real GDP per capita was equal to 6314.643 US dollars. The highest amount has been reached in 2018 (15,243.25 US dollars) while the lowest amount was in 1990 (1423.702 US dollars). The economic product diversification index is characterized by an average of 0.45. The biggest index was 0.47 (1995) while the smallest index was equal to 0.40 (2018).

Table 6 Clemente–Montanes–Reyes unit root findings

Variables	Innovative outlier method			Additive outlier method		
	t-statistic	Time break	Decision	t-statistic	Time break	Decision
e	-5.025***	1975q3, 1982q2	I(1)	-1.875*	1972q1, 1981q1	I(1)
y	-7.451***	1977q3, 1981q4	I(1)	-2.745***	1971q1, 1977q1	I(1)
re	-7.335***	1978q3, 1969q4	I(1)	-2.790***	1976q1, 1969q1	I(0)
nre	2.894***	1975q3, 1973q1	I(1)	4.054***	1972q1, 1969q1	I(1)
fdi	-8.125***	1975q2, 1963q4	I(1)	-1.948*	1974q1, 1963q1	I(1)
epd	-6.585***	1985q3, 1982q4	I(1)	-4.241***	1984q1, 1983q1	I(1)

e shows the total carbon emissions, y presents GDP per capita, re shows renewable energy, nre shows non-renewable energy, fdi shows Foreign direct investments, and, epd indicates export product diversification. ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively

We next shift to assess the integration order of each variable. To do so, unit root procedures accounting for structural breaks in the series (Clemente et al., 1998) have been performed. The outcomes of these tests are checked for the two established cases: the innovative outlier method and the additive outlier method. The null hypothesis assumes the existence of a unit root, while the alternative implies stationarity. All tests are computed in both levels and the first difference.

Unit root test outcomes are reported in Table 6 and indicate that all variables contain a unit root at level, but turn stationary after their first difference. Thus, variables are said to be integrated of order one, $I(1)$. Now, all series are stationary and the presence of a long-run association between the variables should be checked. The ARDL bounds test to cointegration developed by Pesaran et al. (2001) has been employed for both two models (with renewable and non-renewable energy). Based on the Fisher statistic

of the Wald test, the results of these statistics are reported in Tables 7 and 8.

According to these tests, the null of no cointegration can be rejected for both two models at the 1% significance level given that the computed Fisher statistics exceed the upper bound. Thus, there are long-run relationships among variables, regardless of the renewable or non-renewable energy specification.

Now, our two models underline the existence of long-run equilibrium. So, we can proceed with estimating the ARDL model for the short and long run. Table 9 reports the results of the estimation for the model with renewable energy consumption. All estimated coefficients are statistically significant at mixed levels. The outcomes revealed that the lagged error correction term (ECT) is statistically significant at the 1% level, confirming that there is a long-run interaction running from real GDP, renewable energy consumption, foreign direct investment, and economic production diversification to emissions

Table 7 F-bound test for ARDL model with renewable energy consumption

F-bounds test		Null hypothesis: no levels relationship		
Test statistic	Value	Significance	I(0)	I(1)
F-statistic	4.591632***	10%	2.2	3.09
k	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

***denotes significance level at 1% with upper and lower boundaries. F bound test is more than lower and upper bound values of 1% in both cases

Table 8 F-bound test for ARDL model with non-renewable energy consumption

F-bounds test		Null hypothesis: no levels relationship		
Test statistic	Value	Significance	I(0)	I(1)
F-statistic	5.207888***	10%	2.2	3.09
k	4	5%	2.56	3.49
		2.5%	2.88	3.87
		1%	3.29	4.37

***denotes significance level at 1% with upper and lower boundaries. F bound test is more than lower and upper bound values of 1% in both cases

Table 9 ARDL empirics with renewable energy consumption

Variable	Coefficient	Std. error	t-statistic	Prob
Short-run estimates				
D(E(-1))	0.7599***	0.0479	15.836	0.0000
D(Y)	0.8089***	0.1398	5.7824	0.0000
D(EPD)	0.9100***	0.1323	6.8738	0.0000
D(EPD(-1))	-0.7190***	0.1381	-5.2035	0.0000
CointEq(-1)*	-0.0421***	0.00784	-5.3771	0.0000
Long-run estimates				
Y	0.6588***	0.1801	3.6579	0.0004
RE	-0.6487**	0.2672	-2.4275	0.0170
FDI	-0.1050*	0.0575	-1.8257	0.0708
EPD	1.9510***	0.5044	3.8677	0.0002
C	-15.393***	1.2950	-11.886	0.0000

The dependent variable is total carbon emissions. ARDL regression is applied with restricted constant and no trend. Lags are auto-selected. ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively

of CO₂. In the long run, the estimation shows that real GDP and economic product diversification lead to increase CO₂ emissions levels, while renewable energy consumption and foreign direct investment

Table 10 ARDL empirics with non-renewable energy consumption

Variable	Coefficient	Std. error	t-statistic	Prob
Short-run estimates				
D(E(-1))	0.7095***	0.058347	12.16068	0.0000
D(Y)	0.7739***	0.160358	4.826519	0.0000
D(Y(-1))	-0.3046*	0.169663	-1.795578	0.0757
D(NRE)	0.4011***	0.030809	13.01928	0.0000
D(NRE(-1))	-0.2556***	0.037824	-6.758538	0.0000
D(FDI)	0.00513	0.004364	1.176936	0.2421
D(EPD)	0.48246***	0.092111	5.237840	0.0000
D(EPD(-1))	-0.2727***	0.097468	-2.798735	0.0062
CointEq(-1)*	-0.1193***	0.020820	-5.732191	0.0000
Long-run estimates				
Y	0.5529***	0.024496	22.57407	0.0000
NRE	0.4239***	0.020929	20.25525	0.0000
FDI	-0.0326***	0.010880	-3.004338	0.0034
EPD	0.5754***	0.116934	4.921272	0.0000
C	-6.4199***	0.293441	-21.87831	0.0000

The dependent variable is total carbon emissions. ARDL regression is applied with restricted constant and no trend. Lags are auto-selected. ***, **, * denote statistical significance at the 1%, 5%, and 10% levels, respectively

Table 11 Diagnostic testing for ARDL model with renewable energy consumption

Diagnostic tests	Statistic	Prob
Normality (Jarque Bera)	0.531528	0.7666
Serial correlation (Breusch-Godfrey Serial Correlation LM)	0.245911	0.7844
Heteroskedasticity test: Breusch-Pagan-Godfrey	1.552074	0.2104

Heteroscedasticity, serial correlation, normality, and homoscedasticity tests are also proved as normal, as the *p*-value of each is more than 5%

contribute to the mitigation of emissions levels in the long run. Thus, a 1% increase in real GDP per capita and economic product diversification increases pollution by 0.65% and 1.95%, respectively. However, a 1% increase in renewable energy consumption per capita and foreign direct investment decreases CO₂ emissions per capita by 0.64% and 0.10%, respectively.

The results of ARDL estimates for the model with non-renewable energy consumption are reported in Table 10. The outcomes show that all estimated parameters are statistically significant at mixed levels. In the short run, the lagged ECT is statistically significant at the 1% level. This indicates the presence of a long-run association running from all explanatory variables to the endogenous one (CO₂ emissions). (see Tables 11 and 12).

In the long run, ARDL estimates show that only foreign direct investment lowers carbon emissions, while economic growth, non-renewable energy use, and economic product diversification affect positively the growth of pollution. A 1% increase in real GDP per capita, non-renewable energy consumption per capita, and economic product diversification leads to an increase in

Table 12 Diagnostic testing for ARDL model with non-renewable energy consumption

Diagnostic tests	Statistic	Prob
Normality (Jarque Bera)	1.062536	0.5878
Serial correlation (Breusch-Godfrey Serial Correlation LM)	0.034163	0.9664
Heteroskedasticity test: Breusch-Pagan-Godfrey	0.746605	0.7131

Heteroscedasticity, serial correlation, normality, and homoscedasticity tests are also proved as normal, as the *p*-value of each is more than 5%

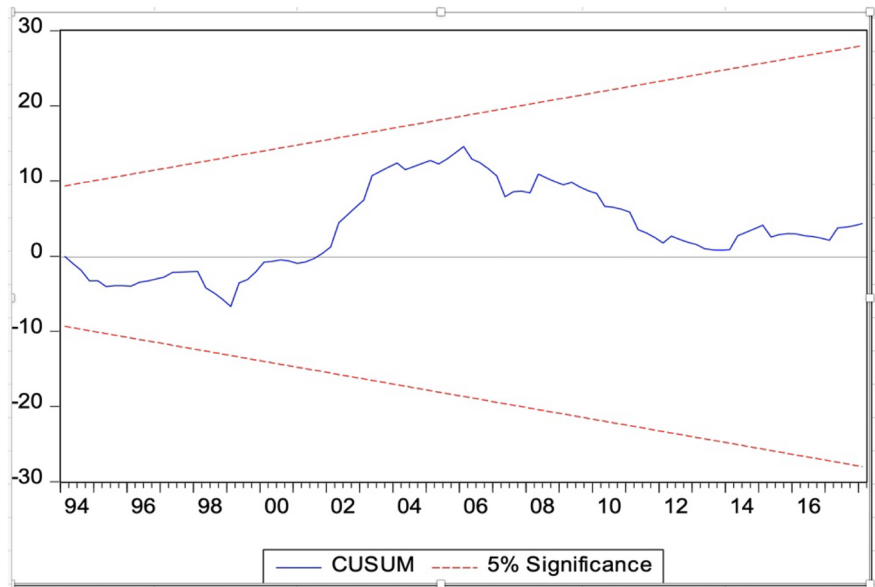
per capita CO₂ emissions by 0.55%, 0.42%, and 0.57%, respectively. However, a 1% increase in foreign direct investment mitigates CO₂ emissions per capita by 0.03%.

The diagnostic tests of the ARDL empirics should be checked to validate our empirical findings. To do that, the normality test (Jarque Bera), serial correlation test (Breusch-Godfrey serial correlation LM), and heteroskedasticity test (Breusch-Pagan-Godfrey)

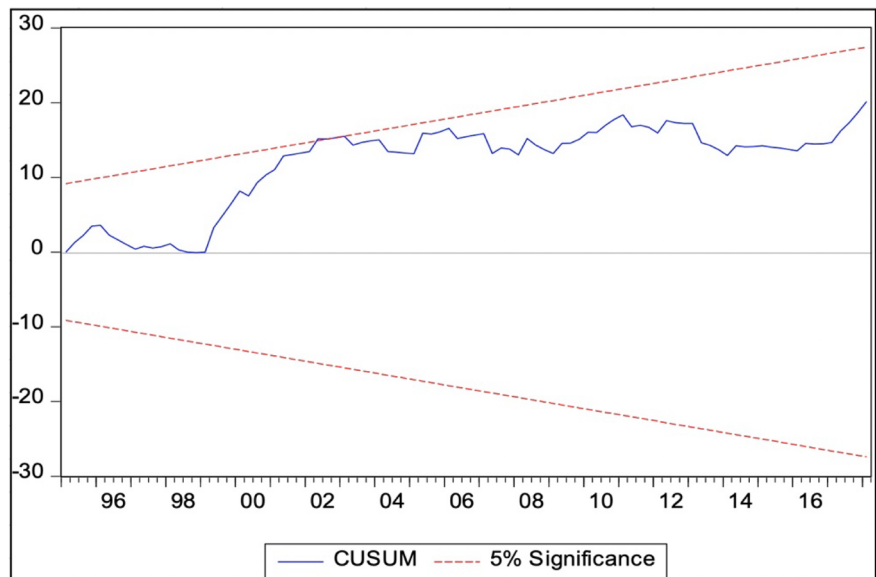
are applied for both two models. All diagnostic tests are calculated for a risk threshold of 5%.

Either for the model with renewable energy consumption or the model with non-renewable energy consumption, the consequences from these diagnostic tests reject the presence of non-normality, serial correlation, or heteroskedasticity. Thus, our empirical ARDL estimates are robust.

Fig. 3 **A** CUSUM stability model with renewable energy. **B** CUSUM stability model with non-renewable energy



A: CUSUM stability model with Renewable energy



B: CUSUM stability model with non-Renewable energy

After establishing the ARDL short and long-run parameters, it is worth necessary to check for the stability of these estimated coefficients for both two models using the CUSUM test. The inference is based on a sequence of sums, or sums of squares, of recursive residuals (standardized one-step-ahead forecast errors), computed iteratively from nested subsamples of the data. Figure 3A and B display the results. For both renewable and non-renewable energy specifications, one observes that the statistics fall between the bounds displaying the 5% significance margin. Thus, all estimated coefficients contained within our multivariate autoregressive model are stable and consistent.

The results from FMOLS and DOLS are reported in Table 13 for both two models. Concerning the model with renewable energy consumption, the estimated coefficients are statistically significant at the 1% level, except for real GDP and foreign direct investment which were found to be insignificant. Indeed, only renewable energy consumption per capita mitigates per capita emissions in the long term. This consequence confirms the result of the ARDL long-run coefficient. For the economic product diversification, the hypothesis of EKC is not verified given that the coefficients of EPD and its square are still positive. (see Table 14).

For the model with non-renewable energy consumption, FMOLS and DOLS results revealed that all estimated coefficients are statically significant at the level of 1%, except for foreign direct investment which is insignificant. Indeed, all calculated coefficients are positive confirming the non-negative effect on CO₂ emissions level in the long run. Also, the hypothesis of EKC is not verified for the model with non-renewable energy consumption.

According to the test of pairwise Granger causality, the following insights emerged:

- Bidirectional causality between CO₂ emissions and real GDP;
- Unidirectional causality from CO₂ emissions to renewable energy consumption;
- Unidirectional causality from CO₂ emissions to non-renewable energy consumption;
- Unidirectional causality from CO₂ emissions to FDI;
- Unidirectional causality from CO₂ emissions to EPD;
- Unidirectional causality from real GDP to renewable energy consumption;
- Bidirectional causality between non-renewable energy consumption and real GDP;
- Bidirectional causality between FDI and real GDP;
- Unidirectional causality from real GDP to EPD;
- Unidirectional causality from renewable energy consumption to FDI;
- Unidirectional causality from renewable energy consumption to EPD;
- Unidirectional causality from non-renewable energy consumption to FDI.

Discussion of the results: what insights can we draw?

This section seeks to discuss our results in the light of the most recent and relevant literature. Starting with the most common EKC analyses, this discussion is enlarged to export diversification-related papers.

Proposing a modified version of the EKC accounting for the trade structure, this study incorporates export product diversification into an EKC framework with Chinese data. As a result, it does not provide evidence supporting the existence of an inverted-U-shaped

Table 13 FMOLS and DOLS estimates

Variables	Model with RE		Model with NRE	
	FMOLS	DOLS	FMOLS	DOLS
EPD	42.67986***	41.39243***	13.18445***	12.80627***
EPD2	25.43469***	24.61689***	7.740532***	7.470375***
Y	0.055536	0.138127	0.472951***	0.468814***
RE	-1.269288***	-1.144604***	-	-
NRE	-	-	0.503999***	0.515289***
FDI	0.085175	0.064760	-0.014145	-0.015191

“***” indicates statistical significance at the 1% level

Table 14 Pairwise Granger causality empirics

Null hypothesis:	Obs	F-statistic	Prob
Y does not Granger cause E	111	3.22141**	0.0438
E does not Granger cause Y		2.75916*	0.0679
RE does not Granger cause E	111	1.50677	0.2263
E does not Granger cause RE		3.93464**	0.0225
NRE does not Granger cause E	111	1.98336	0.1427
E does not Granger cause NRE		2.17342*	0.1088
FDI does not Granger cause E	111	0.04136	0.9595
E does not Granger cause FDI		7.29374**	0.0011
EPD does not Granger cause E	111	0.67399	0.5118
E does not Granger cause EPD		2.16436*	0.1099
RE does not Granger cause Y	111	0.16614	0.8472
Y does not Granger cause RE		5.72487**	0.0044
NRE does not Granger cause Y	111	2.34325*	0.1010
Y does not Granger cause NRE		3.72432**	0.0273
FDI does not Granger cause Y	111	3.77191**	0.0262
Y does not Granger cause FDI		7.32629**	0.0010
EPD does not Granger cause Y	111	0.24178	0.7857
Y does not Granger cause EPD		3.09120**	0.0496
NRE does not Granger cause RE	111	0.10459	0.9008
RE does not Granger cause NRE		2.13927	0.1228
FDI does not Granger cause RE	111	0.98127	0.3782
RE does not Granger cause FDI		4.78434**	0.0102
EPD does not Granger cause RE	111	0.30863	0.7351
RE does not Granger cause EPD		4.95694***	0.0088
FDI does not Granger cause NRE	111	0.93338	0.3964
NRE does not Granger cause FDI		3.51268**	0.0333
EPD does not Granger cause NRE	111	0.38512	0.6813
NRE does not Granger cause EPD		1.54362	0.2184
EPD does not Granger cause FDI	111	0.59123	0.5555
FDI does not Granger cause EPD		0.80794	0.4485

***, **, *denote statistical significance at the 1%, 5%, and 10% levels, respectively. Causality is tested with 2 lags

curve between export product diversification and environmental pollution in this economy. Therefore, no turning point can be estimated. Instead, this paper gives ample evidence of a one-way causality running from export product diversification to CO₂ emissions from fuel combustion. Drawn from a consistent econometric estimation procedure (structural breaks unit root test Clemente–Montanes–Reyes, autoregressive distributed lag (ARDL) cointegration, Granger causality, dynamic OLS (DOLS), and fully modified OLS (FMOLS) methods), our findings are congruent with

the export diversification-led-pollution hypothesis for China. Accordingly, they emphasized the dominance of the composition and scale effects by contrast to the technique effect.

When linked with the historical EKC literature, our results contrast with the panel findings from Grossman and Krueger (1991) for 42 countries; Shafik and Bandyopadhyay (1992) for 149 countries; Panayotou (1993) for 68 countries; Selden and Song (1994) for 30 countries; Stern and Common (2001) for 73 countries. However, the present outcome is in line with the conclusions drawn by Moomaw and Unruh (1997) for 16 transition economies; Agras and Chapman (1999) for 34 countries; Gangadharan and Valenzuela (2001) for 51 countries; Acaravci and Ozturk (2010) for 19 EU countries. Looking at the most recent EKC literature, our results confirm those of Narayan and Narayan (2010) for 43 developing countries; Arouri et al. (2012) for 12 MENA countries; Baek (2015a, b) for 12 nuclear energy-consuming countries and Arctic countries, Heidari et al. (2015) for 5 ASEAN countries; but also, the most accurate literature: Cai et al. (2018) for G-7 countries; Hu et al. (2018) for 25 developing countries; Moutinho et al. (2020) for 12 OPEC countries; Pata and Aydin (2020) for 6 hydropower consuming countries. Nonetheless, we must admit that our findings contrast with the panel outputs from York et al. (2003) for 142 countries; Apergis and Payne (2009) for 6 central American countries; Lean and Smyth (2010) for 5 ASEAN countries; Leitão (2010) for 94 countries; Jaunky (2011) for 36 high-income countries; Bilgili et al. (2016) for 17 OECD countries. Compared with the most recent multi-country EKC studies, the rejection of the EKC in this paper is not in line with Sarkodie (2018) for 17 African countries; Haseeb et al. (2018) for BRICS countries; Alshubiri and Elheddad (2019) for 32 OECD economies; Dogan and Inglesi-Lotz (2020) for 7 EU countries; Adeel-Farooq et al. (2020) for 6 ASEAN countries; Leal and Marques (2020) for 20 OECD countries. Comparing our results with those of the EKC literature which adopted a single-country approach to assessing the economic growth-environmental pollution nexus brings fruitful insights. While the present output contrasts with several studies (Soytas et al. (2007) and Işık et al. (2019a, b) for the USA; Fodha and Zaghoud (2010) and Shahbaz et al. (2014) for Tunisia; Iwata et al. (2010) for France; Baek and Kim (2013) for Korea; Saboori et al. (2016) for Malaysia;

Pata (2018) for Turkey; Rana and Sharma (2019) for India; Sarkodie and Ozturk (2020) for Kenya), they corroborate those of Fei et al. (2011), Wang et al. (2016), and Pata and Caglar (2021) who unanimously rejected the existence of an EKC curve for China.

Compared with the recent (and thus seminal) export diversification-environmental pollution literature, the rejection of the EKC hypothesis contradicts Gozgor and Can (2016b) who validated the presence of an inverted-U-shaped curve for Turkey. Besides, the present output is not in line with the large panel assessments of Apergis et al. (2018) and Can et al. (2020) conducted on 19 advanced countries and 84 developing economies, respectively. However, our findings corroborate those of Mania (2020) who rejected the existence of the EKC for a sample of 98 countries. Also, this study presents ample evidence in line with Liu et al. (2018) who failed to reject the existence of an inverted-U-shaped relationship between export diversification and environmental pollution in Japan and Korea, although the authors did not consider energy determinants. Finally, they did not support the EKC hypothesis for China which slightly contrasts with the present conclusions. Looking at more recent inputs, our results are in line with those of Khan et al. (2021) as they stressed that export diversification first boosts atmospheric pollution levels, before inhibiting them among the signatories of the Regional Comprehensive Economic Partnership (RCEP) agreement. Furthermore, those results contradict Magazzino et al. (2022a) who found that export diversification mitigates energy demand in the APEC region using artificial neural networks (ANNs) experiments and a decision tree (DT) model.

Exiting from the literature devoted to the non-linear pattern, the confirmation of a unidirectional causal link from export product diversification to environmental pollution contrasts with Shahzad et al. (2020) as their generalized method of moments (GMM) findings suggested negative impacts of product diversification on CO₂ emissions for 63 countries. Similarly, Wang, Chang, et al. (2020) concluded that export diversification drives CO₂ emissions for G-7 countries, but the negative reported impact of export diversification on the CO₂ emissions is revealed, even if weakened with increases in the degree of environmental innovation. We should tough notice that our methodologies partially differ as the authors relied

on a modified version of the ARDL model: the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) allowing for cross-sectional dependence among the series. Up to now, this is the first time that a significant and positive linear relationship is established between export product diversification and CO₂ emissions from fuel combustion.

Also, the non-validation of the EKC theory is weakly sensitive to the inclusion/exclusion of low-carbon energy use/fossil energy consumption data within our model. In other words, the magnitude of the impacts of export diversification on carbon emissions is much higher once fossil energy consumption is excluded from the framework. Reciprocally, controlling for non-renewable energy reduces the size of the coefficient of export diversification, although the significance of the coefficients of almost all variables remains merely stable across DOLS and FMOLS regressions. Similarly, looking at the ARDL results, export diversification coefficients (i.e., describing how deviations from short- to long-run equilibria are corrected from period t to $t + 1$) slightly change once fossil energy data are included in the model, while the average significance of variables does not. Another striking observation is that the income per capita coefficient becomes strongly significant once fossil energy consumption data are included within the DOLS and FMOLS estimations. This confirms that export diversification might affect environmental quality through the fossil energy channel, rather than the economic growth one. In a nutshell, above the well-known stage of development, an important determinant of the export diversification-environmental pollution link might be the level of fossil energy consumption. Thus, avoiding this non-negligible factor is thought to strongly overestimate the real impact of export diversification on carbon emissions levels.

These above-mentioned observations are also applicable to the coefficient of export diversification squared. In the literature, similar conclusions have been drawn by seminal papers that supported that any fluctuation in the trade may directly be transmitted back to the level of energy consumption in the country. For instance, Arif et al. (2017) confirmed that international trade increases energy demand while boosting economic activity in oil-importing Asian countries. Besides, Sadorsky (2011) estimated a 1% rise in exports triggers per capita energy use by 0.11% for the MENA area. As suggested by the authors, one

possible leverage to reduce this heavy dependence of trade on polluting energy resources stands in the energy price mechanisms.

Going one step further, Topcu and Payne (2018) argued that the trade-energy consumption relationship may exhibit a non-linear pattern in high-income countries, displaying the form of an inverted-U-shaped curve. Finally, it corroborates Zhao et al. (2018) who underlined that energy intensity and production structure substantially offset energy consumption changes. Also, accurate papers reported evidence of the dominance of the composition and scale effects (see Gozgor and Can (2016b) for Turkey over the long run; Liu et al. (2019) and Mania (2020) for the sub-samples of low-income countries). However, while lowering carbon emissions by using the trade costs leverage might be a solution, associated outcomes may be limited (Copeland & Taylor, 1994; Rieber & Tran, 2009). Thus, Mania (2020) defended that, to reach the highest effectiveness, promoting export diversification as a means to deploy a long-run economic growth should be complemented by early environmental policies. Yet, it is admitted that the most energy-intensive industries should commit to relying on cleaner energy sources along the supply chain (Shahzad et al., 2020). Inversely, other studies suggested that increasing trade openness might be an effective policy to reduce pollution, especially for high-income countries (Akin, 2014). Indeed, in the absence of strong environmental rules, the exports of products from the most polluting sectors increase and threaten the sustainability path of a given economy (Mutascu, 2018). For this reason, trade-related environmental policies are thought to attenuate carbon emissions (Mutascu & Sokic, 2020). This latter observation corroborates Gozgor and Can (2016b) while arguing that the product diversification of exports can benefit both economic and environmental objectives. Also, this is in line with Shahzad et al. (2020) who claimed that sustainable development policies should not omit to set export diversification targets and accompany them with adequate trade relations and the promotion of low-carbon products. All in all, Rieber and Tran (2009) reconciled these two trade-related pieces of literature as they emphasized that transferring cleaner technology towards developing countries might be effectively promising. Hence, the carbon content of trade (i.e., the pollution endowment of exported goods) should be rather regulated

than the absolute volume of export flows, which can be traced back to the original assertion of Suri and Chapman (1998).

As stressed in Sinha and Sengupta (2019), Asia-Pacific Economic Cooperation (APEC) nations are committed to reaching a set of Sustainable and Development Goals (SDGs) by 2030 and 2050. At the global scale, a contrasting picture emerges about the progression of SDGs targets. On the one hand, there has been a significant decline (35%) in the maternal mortality rate in Sub-Saharan Africa, and accessibility to electricity has become twofold in less developed countries. On the other hand, 2.3 billion people lack basic sanitation; over 1 billion live in areas without connection to an electricity grid; and 9 out of 10 people living in urban settlements inhale air charged with harmful pollutants (Sinha et al., 2020). Looking at SDG-13, climate mitigation turns out to be a long-run concern that remains overlooked by short-run mandated regulators. Besides, emissions projections modeled that amount of carbon released from the industrial sector may attain 37.1 billion tons, an all-time high, in 2018; while 2017 has been recorded by *Sustainable Development Goals Report 2018* as the hottest year in the history with a temperature of 1.1 °C above that of the pre-industrial period. Asian countries and in particular China, are, in general, far from being spared from this growing concern (UN, 2018).

Conclusions and policy recommendations

The environmental Kuznets curve (EKC) hypothesis has been abundantly studied in the literature, leading sometimes to conflicting results. In this study, we provided a state-of-the-art review of the topic and analytically compared the main features characterizing past assessments. Then, we highlighted the key methodological challenges that previous studies attempted to address so far. Given that China is experiencing profound structural changes in the content of its trade structure along with environmental reforms, we considered this illustrative case and investigated whether the EKC hypothesis holds among export product diversification and environmental pollution. Quarterly data are collected over the most available and recent period (i.e., 1990Q1-2018Q4) and obtained by applying the quadratic match-sum method on the annual

series. Besides, per capita income, foreign direct investments, fossil fuel energy, and renewable energy demand are included as additional factors to the baseline model specifications. To the best we know, this paper is the first to inspect this nexus for the single case of China and under the context of the EKC.

Our empirical analysis, conducted through the Clemente–Montanes–Reyes unit root test with structural break and additive outlier, the autoregressive distributed lag (ARDL) bounds testing approach to cointegration, the Granger causality test, and dynamic OLS (DOLS), and fully modified OLS (FMOLS) estimators revealed insightful outcomes. Empirically, the EKC hypothesis failed to be supported between export diversification and environmental pollution in China. Besides, renewable and fossil energy coefficients are negative and positive, respectively, which is in line with the main literature. Also, the parameter related to income is significant only for the specification excluding fossil fuel energy use. Furthermore, we noticed that those short-conclusions are weakly sensitive to the inclusion/exclusion of renewable energy consumption/non-renewable energy consumption data within our model. In other words, while for both specifications and estimators, the EKC hypothesis is rejected, the magnitude of the impacts of export diversification on carbon emissions tends to be much higher once fossil energy consumption is excluded from the framework. Reciprocally, controlling for non-renewable energy reduces the size of the estimated coefficient of export diversification, although the significance of the coefficients of almost all variables remains merely stable across DOLS and FMOLS regressions. Low-carbon and fossil energy use display expected negative and positive significant impacts on pollution (respectively), shedding light on potential interaction effects. Besides, a strong positive linear pattern between export product diversification and CO₂ emissions is revealed. However, this outcome is inconsistent with the pair-wise Granger causality procedure as no causality inferences are supported among the above-mentioned indicators. Furthermore, our multivariate causality analysis drew evidence of a one-way link running from fossil energy use to economic growth, as well as the existence of bidirectional causality between renewable energy consumption and real GDP. As early defined in Dagher and Yacoubian (2012), and extended in Magazzino and Schneider (2020), this corroborates the “conservation” and

“feedback” conventional hypotheses, respectively. All in all, renewable energy consumption causes export product diversification but not vice versa.

With several novelty aspects, this research strives to enlarge our knowledge of the EKC and bring far-reaching policy implications. Above all, since our results do not offer evidence of an inverted-U-shaped pattern between export diversification and carbon dioxide emissions (there was only evidence for a positive and linear association among indicators), conducting a trade diversification strategy seems adversely impacting environmental quality in China. Therefore, the higher the country’s degree of export diversification is, the larger would be the associated emissions levels (Liu et al., 2018). Second, the magnitude of this impact might be highly sensitive to the nature of the energy source considered in the specification: fossil fuels energy (lower) or renewable energy sources (much intense and stronger). Practically, this calls for higher efforts in environmental policies effectiveness as, over the period analyzed, these do not seem to have induced the necessary and expected improvements. This can notably be achieved through careful fossil energy conservation policies or energy-efficiency measures. Third, China is now a leading exporter and the largest pollution emitter in the world. Its booming manufacturing production cannot be disconnected from its export-led growth strategy, as pointed out in the literature survey, whereas associated externalities should be internalized within future environmental planning. In this view, regulatory instruments (carbon tax) should start high, grow fast, and cover all provinces, to make the long-run extraction and consumption of fossil fuels unprofitable within the industrialization process. Since our estimated findings underline how incorporating renewable energy consumption increases the effective impact of export diversification on emission levels, this may incentivize the ongoing use of fossil energy resources (more energy-intensive per unit of output produced) along the Chinese supply chains. But, in doing so, China might simply shift the carbon problem and postpone its effective resolution. On the one hand, an export product concentration policy is thought to consistently mitigate environmental pollution but threatens future income growth rates. Hence, maintaining a high diversification strategy is decidedly linked to triggering environmental

concerns and cannot without considering the nature and the way energy is consumed by the most intensive sectors. On the other hand, achieving sustainable, safe, and low-carbon development may, under reasonable conditions, operate as an explicit contributing factor to growth. It has been shown that the higher the income countries are, the more persistent and significant the feedback relationship between those variables is (Al-Mulali et al., 2013). These findings display generalizable features with South Asian and emerging countries displaying slightly related characteristics: a fast-growing economy, a substantial carbon content embedded within manufactured goods, and a progressive export diversification process oriented towards the production and exports of low-carbon energy technologies, for domestic and trade purposes (Magazzino et al., 2021a).

Notwithstanding, such topic becomes critical in the current environmental context, as the COP 26 which took place between 31st October and 12th November 2021 in Glasgow failed to endorse a rapid phase-out from coal-based power and heating plants and a decisive shift from fossil-fuelled towards low-carbon driven automobiles. It is true that the standard approach to global warming, which mainly consists in alleviating the constraints on economic growth while enabling a continuous technological development thought suitable to compensate environmental damages, may be critical. Deploying wind turbines, solar photovoltaic panels, lithium batteries, hydrogen, and carbon capture and storage technologies cannot go without a massive supply of resources and mineral components. It involves the development of competitive industrial sectors with adequate trade agreements and export promotion policies to ensure low-carbon technologies transfer across countries and sustain economic growth. In this paper, we showed that carbon emissions grow linearly with the degree of structural diversification of exports. Whether this corresponds to a short-run cost induced by a low-carbon industrial restructuring, an additional economic externality following the mitigation of a previous one, and induced by the pattern of unconstrained sectoral value-added accumulation is a question that the next COP 27 will have to tackle.

In sum, to curb pollution levels, China may have to do it at the expense of slower growth. Since the

results presented here clearly point out a highly expensive trade-off decision to be made in this country, policymakers would have to effectively balance two antagonist objectives: hindering growth to maintain environmental quality or supporting income at the expense of carbon mitigation. In answering this question, estimating the social cost of carbon matters to identify whether income losses might be compensated by pollution savings is relevant. Future studies should extend the present work by pointing out which would be the least expensive solution. Based on adequate measures, this would help orientating the Chinese economy towards a long-run sustainable development. Additionally, this paper presents novel results based on a recently explored modified EKC version. Operating a break with the common nexus between environmental degradation and economic activity, the econometric study of the export diversification-environmental pollution link follows seminal literature that is believed to further extend the standard EKC theory. Thus, impact estimation findings are concentrated around the trade channel which enables us to draw important environmental insights for the case of an export-oriented economy like China. Further research should bring sector-specific results and identify which energy-intensive industries should be the subject of comprehensive reforms if data availability allows that. All in all, the utilization of machine learning (ML) methodologies derived from artificial intelligence (AI), still incipient on this topic, has demonstrated a powerful potential on neighboring research questions related to COVID-19, nuclear phase-out, and solid waste generation (Magazzino et al., 2020a, b, c, 2021a, b, c, 2022b; Mele et al., 2021). Employing advanced empirical procedures may overcome the statistical limits associated with standard time-series econometrics models. This would not only enlarge our current knowledge of the EKC but also highlight shift the examination of this extensively discussed topic towards more multi-disciplinary approaches bridging applied economics, multivariate statistical analysis, and environmental research.

Nomenclature 2SLS: 2 Stages least squares; AMG: Augmented mean group; ANNs: Artificial neural networks; ARDL: Autoregressive distributed lag bounds; AI: Artificial intelligence; CCE: Common correlated effects; COP: Conference of parties; CO₂: Carbon dioxide; CS-ARDL: Cross-sectionally augmented autoregressive distributed lag; DHC:

Dumitrescu-Hurlin causality test; DKSE: Driscoll-Kraay standard errors; DOLS: Dynamic ordinary least squares; DT: Decision tree; ECM: Error correction model; EIA: Energy information administration; EKC: Environmental Kuznets curve; FDI: Foreign direct investments; FE: Fixed effects; FMOLS: Fully modified ordinary least squares; GC: Granger causality test; GHG: Greenhouse gas; GMM: Generalized method of moments; IEA: International Energy Agency; IRF: Impulse response function; KTOE: Kilo ton of oil equivalent; MG: Mean group; ML: Machine learning; OLS: Ordinary least squares; PCSR: Panel corrected standard errors; PMG: Pooled mean group; POEU: Public Office of the European Union; PPC: Pedroni panel cointegration; PSTR: Panel smooth transition regression; PQRQPR: Panel quantile panel regression; QMS: Quadratic match sum method; RE: Random effects; RWGC: Rolling window Granger causality; SD: Sustainable development; STIRPAT: Stochastic regression on population, affluence, and technology; TYC: Toda-Yamamoto causality test; UNCDAT: United Nations Conference on Trade and Development; VAR: Vector auto-regressive; VECM: Vector error correction model; WC: Westerlund cointegration; WCED: World Commission on Environment and Development

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Declarations

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References

Acaravci, A., & Ozturk, I. (2010). On the relationship between energy consumption, CO2 emissions and economic growth in Europe. *Energy*, 35(12), 5412–5420.

Adeel-Farooq, R. M., Raji, J. O., & Adeleye, B. N. (2020). Economic growth and methane emission: Testing the EKC hypothesis in ASEAN economies. *Management of Environmental Quality: An International Journal*, 32(2), 277–289.

Agosin, M. R., Alvarez, R., & Bravo-Ortega, C. (2012). Determinants of export diversification around the world: 1962–2000. *The World Economy*, 35(3), 295–315.

Agras, J., & Chapman, D. (1999). A dynamic approach to the environmental Kuznets curve hypothesis. *Ecological Economics*, 28(2), 267–277.

Ahmad, A., Zhao, Y., Shahbaz, M., Bano, S., Zhang, Z., Wang, S., & Liu, Y. (2016). Carbon emissions, energy consumption and economic growth: An aggregate and disaggregate analysis of the Indian economy. *Energy Policy*, 96, 131–143.

Akadiri, S. S., Alola, A. A., & Usman, O. (2021). Energy mix outlook and the EKC hypothesis in BRICS countries: A perspective of economic freedom vs. economic growth. *Environmental Science and Pollution Research*, 28(7), 8922–8926.

Akbostanci, E., Tunc, G. I., & Türüt-Aşik, S. (2007). Pollution haven hypothesis and the role of dirty industries in Turkey’s exports. *Environment and Development Economics*, 12(2), 297–322.

Akin, C. S. (2014). The impact of foreign trade, energy consumption and income on CO2 emissions. *International Journal of Energy Economics and Policy*, 4(3), 465–475.

Alam, M. J., Begum, I. A., Buysse, J., Rahman, S., & Van Huynenbroeck, G. (2011). Dynamic modeling of causal relationship between energy consumption, CO2 emissions and economic growth in India. *Renewable and Sustainable Energy Reviews*, 15(6), 3243–3251.

Ali, R., Alwang, J. R., & Siegel, P. B. (1991). *Is export diversification the best way to achieve export growth and stability?: A look at three African countries* (Vol. 729). World Bank Publications.

Ali, S., Can, M., Shah, M. I., Jiang, J., Ahmed, Z., & Murshed, M. (2022). Exploring the linkage between export diversification and ecological footprint: evidence from advanced time series estimation techniques. *Environmental Science and Pollution Research*, 1–15.

Al-Mulali, U., Fereidouni, H. G., Lee, J. Y., & Sab, C. N. B. C. (2013). Examining the bi-directional long run relationship between renewable energy consumption and GDP growth. *Renewable and Sustainable Energy Reviews*, 22, 209–222.

Al-Mulali, U., Weng-Wai, C., Sheau-Ting, L., & Mohammed, A. H. (2015). Investigating the environmental Kuznets curve (EKC) hypothesis by utilizing the ecological footprint as an indicator of environmental degradation. *Ecological Indicators*, 48, 315–323.

Alshubiri, F., & Elheddad, M. (2019). Foreign finance, economic growth and CO2 emissions Nexus in OECD countries. *International Journal of Climate Change Strategies and Management*.

Ang, J. B. (2009). CO2 emissions, research and technology transfer in China. *Ecological Economics*, 68(10), 2658–2665.

Antonakakis, N., Chatziantoniou, I., & Filis, G. (2017). Energy consumption, CO2 emissions, and economic growth: An ethical dilemma. *Renewable and Sustainable Energy Reviews*, 68, 808–824.

Apergis, N., Can, M., Gozgor, G., & Lau, C. K. M. (2018). Effects of export concentration on CO2 emissions in developed countries: An empirical analysis. *Environmental Science and Pollution Research*, 25(14), 14106–14116.

Apergis, N., & Payne, J. E. (2009). CO2 emissions, energy usage, and output in Central America. *Energy Policy*, 37(8), 3282–3286.

- Arif, I., Kazmi, S. W., & Khan, L. (2017). Relationship between trade openness and energy consumption in oil importing Asian countries. *Journal of Finance & Economics Research*, 2(1), 37–53.
- Arouri, M. E. H., Youssef, A. B., & M'henni, H., & Rault, C. (2012). Energy consumption, economic growth and CO2 emissions in Middle East and North African countries. *Energy Policy*, 45, 342–349.
- Awan, U., Khattak, A., Rabbani, S., & Dhir, A. (2020). Buyer-driven knowledge transfer activities to enhance organizational sustainability of suppliers. *Sustainability*, 12(7), 2993.
- Aye, G.C., Edoja, P.E., (2017). Effect of economic growth on CO2 emission in developing countries: Evidence from a dynamic panel threshold model. *Cogent Economics & Finance*. Accessed at: <https://doi.org/10.1080/23322039.2017.1379239>
- Baek, J. (2015a). A panel cointegration analysis of CO2 emissions, nuclear energy and income in major nuclear generating countries. *Applied Energy*, 145, 133–138.
- Baek, J. (2015b). Environmental Kuznets curve for CO2 emissions: The case of Arctic countries. *Energy Economics*, 50, 13–17.
- Baek, J., & Kim, H. S. (2013). Is economic growth good or bad for the environment? Empirical evidence from Korea. *Energy Economics*, 36, 744–749.
- Balibey, M. (2015). Relationships among CO2 emissions, economic growth and foreign direct investment and the environmental Kuznets curve hypothesis in Turkey. *International Journal of Energy Economics and Policy*, 5(4), 1042–1049.
- Barro, R. J. (1997). *Determinants of economic growth: A cross-country empirical study*” mit press. Cambridge, MA.
- Beckerman, W. (1992). Economic growth and the environment: Whose growth? Whose environment? *World Development*, 20(4), 481–496.
- Ben Jebli, M., Ben Youssef, S., & Ozturk, I. (2013). The environmental Kuznets curve: The role of renewable and non-renewable energy consumption and trade openness.
- Bilgili, F., Koçak, E., & Bulut, Ü. (2016). The dynamic impact of renewable energy consumption on CO2 emissions: A revisited environmental Kuznets curve approach. *Renewable and Sustainable Energy Reviews*, 54, 838–845.
- Bimonte, S., & Stabile, A. (2017). Land consumption and income in Italy: A case of inverted EKC. *Ecological Economics*, 131, 36–43.
- Cadot, O., Carrère, C., & Strauss-Kahn, V. (2011). Export diversification: What's behind the hump? *Review of Economics and Statistics*, 93(2), 590–605.
- Cadot, O., Carrere, C., & Strauss-Kahn, V. (2013). Trade diversification, income, and growth: What do we know? *Journal of Economic Surveys*, 27(4), 790–812.
- Cai, Y., Sam, C. Y., & Chang, T. (2018). Nexus between clean energy consumption, economic growth and CO2 emissions. *Journal of Cleaner Production*, 182, 1001–1011.
- Can, M., Dogan, B., & Saboori, B. (2020). Does trade matter for environmental degradation in developing countries? New evidence in the context of export product diversification. *Environmental Science and Pollution Research*, 27(13), 14702–14710.
- Castiglione, C., Infante, D., & Smirnova, J. (2012). Rule of law and the environmental Kuznets curve: Evidence for carbon emissions. *International Journal of Sustainable Economy*, 4(3), 254–269.
- Chauhan, C., Dhir, A., Akram, M. U., & Salo, J. (2021). Food loss and waste in food supply chains. A systematic literature review and framework development approach. *Journal of Cleaner Production*, 295, 126438.
- Clemente, J., Montañés, A., & Reyes, M. (1998). Testing for a unit root in variables with a double change in the mean. *Economics Letters*, 59(2), 175–182.
- Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: Examining the linkages. *Ecological Economics*, 48(1), 71–81.
- Copeland, B. R., & Taylor, M. S. (1994). North-South trade and the environment. *The Quarterly Journal of Economics*, 109(3), 755–787.
- Copeland, B. R., & Taylor, M. S. (1995a). Trade and the environment: A partial synthesis. *American Journal of Agricultural Economics*, 77(3), 765–771.
- Copeland, B. R., & Taylor, M. S. (1995b). Trade and transboundary pollution. *The American Economic Review*, 716–737.
- Dagher, L., & Yacoubian, T. (2012). The causal relationship between energy consumption and economic growth in Lebanon. *Energy Policy*, 50, 795–801.
- Dhir, A., Talwar, S., Kaur, P., & Malibari, A. (2020). Food waste in hospitality and food services: A systematic literature review and framework development approach. *Journal of Cleaner Production*, 270, 122861.
- Dhir, A., Talwar, S., Sadiq, M., Sakashita, M., & Kaur, P. (2021). Green apparel buying behaviour: A Stimulus–Organism–Behaviour–Consequence (SOBC) perspective on sustainability-oriented consumption in Japan. *Business Strategy and the Environment*, 30(8), 3589–3605.
- Dijkgraaf, E., & Vollebergh, H. R. (2005). A test for parameter homogeneity in CO2Panel EKC estimations. *Environmental and Resource Economics*, 32(2), 229–239.
- Dinda, S., Coondoo, D., & Pal, M. (2000). Air quality and economic growth: An empirical study. *Ecological Economics*, 34(3), 409–423.
- Dogan, E., & Inglesi-Lotz, R. (2020). The impact of economic structure to the environmental Kuznets curve (EKC) hypothesis: Evidence from European countries. *Environmental Science and Pollution Research*, 27(11), 12717–12724.
- Dong, K., Sun, R., & Hochman, G. (2017). Do natural gas and renewable energy consumption lead to less CO2 emission? Empirical evidence from a panel of BRICS countries. *Energy*, 141, 1466–1478.
- Engle, R. F., & Granger, C. W. (1987). Co-integration and error correction: representation, estimation, and testing. *Econometrica: Journal of the Econometric Society*, 251–276.
- Fei, L., Dong, S., Xue, L., Liang, Q., & Yang, W. (2011). Energy consumption-economic growth relationship and carbon dioxide emissions in China. *Energy Policy*, 39(2), 568–574.
- Fodha, M., & Zaghoud, O. (2010). Economic growth and pollutant emissions in Tunisia: An empirical analysis of the environmental Kuznets curve. *Energy Policy*, 38(2), 1150–1156.

- Gangadharan, L., & Valenzuela, M. R. (2001). Interrelationships between income, health and the environment: Extending the environmental Kuznets curve hypothesis. *Ecological Economics*, 36(3), 513–531.
- Gozgor, G. (2017). Does trade matter for carbon emissions in OECD countries? Evidence from a new trade openness measure. *Environmental Science and Pollution Research*, 24(36), 27813–27821.
- Gozgor, G., & Can, M. (2016a). Effects of the product diversification of exports on income at different stages of economic development. *Eurasian Business Review*, 6(2), 215–235.
- Gozgor, G., & Can, M. (2016b). Export product diversification and the environmental Kuznets curve: Evidence from Turkey. *Environmental Science and Pollution Research*, 23(21), 21594–21603.
- Grossman, G. M., & Krueger, A. B. (1991). Environmental impacts of a North American free trade agreement. *National Bureau of Economic Research (NBER) Working Paper*, No. w3914.
- Haddad, M., Lim, J. J., & Saborowski, C. (2010). Managing openness and volatility: The role of export diversification. The World Bank Poverty Reduction and Economic Management Network, Economic Premise, No.6
- Hajar, H. A. A., Tweissi, A., Hajar, Y. A. A., Al-Weshah, R., Shatanawi, K. M., Imam, R., ... & Hajer, M. A. A. (2020). Assessment of the municipal solid waste management sector development in Jordan towards green growth by sustainability window analysis. *Journal of Cleaner Production*, 258, 120539.
- Hasanov, F. J., Mikayilov, J. I., Mukhtarov, S., & Suleymanov, E. (2019). Does CO2 emissions–economic growth relationship reveal EKC in developing countries? Evidence from Kazakhstan. *Environmental Science and Pollution Research*, 26(29), 30229–30241.
- Haseeb, A., Xia, E., Baloch, M. A., & Abbas, K. (2018). Financial development, globalization, and CO2 emission in the presence of EKC: Evidence from BRICS countries. *Environmental Science and Pollution Research*, 25(31), 31283–31296.
- Heidari, H., Katircioğlu, S. T., & Saeidpour, L. (2015). Economic growth, CO2 emissions, and energy consumption in the five ASEAN countries. *International Journal of Electrical Power & Energy Systems*, 64, 785–791.
- Holtz-Eakin, D., & Selden, T. M. (1995). Stoking the fires? CO2 emissions and economic growth. *Journal of Public Economics*, 57(1), 85–101.
- Hu, H., Xie, N., Fang, D., & Zhang, X. (2018). The role of renewable energy consumption and commercial services trade in carbon dioxide reduction: Evidence from 25 developing countries. *Applied Energy*, 211, 1229–1244.
- Hummels, D., & Klenow, P. J. (2005). The variety and quality of a nation’s exports. *American Economic Review*, 95(3), 704–723.
- Imbs, J., & Wacziarg, R. (2003). Stages of diversification. *American Economic Review*, 93(1), 63–86.
- Intergovernmental Panel on Climate Change (IPCC). (2007). In O. R. D. B. Metz, P. R. Bosch, & L. A. Meyer Cambridge (Eds.), *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*. Cambridge University Press, United Kingdom.
- Intergovernmental Panel on Climate Change (IPCC). (2011). *Special report on renewable energy sources and climate change mitigation*. Cambridge University Press, United Kingdom.
- Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: synthesis report (Geneva: IPCC), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, United Kingdom.
- International Energy Agency (IEA). (2020a). Fuels & technologies – Fuel report - Renewables 2019. Available at. <https://www.iea.org/reports/renewables-2019>. Accessed 2 January 2021.
- International Energy Agency (IEA). (2020b). *IEA CO2 emissions from fuel combustion statistics (database)*. Available at. https://www.oecd-ilibrary.org/energy/data/iea-co2emissions-from-fuel-combustion-statistics/co2-emissions-by-product-and-flow_data-00430-en. Accessed 2 January 2021.
- International Energy Agency (IEA). (2020c). *World energy balances, 2020 IEA World Energy Statistics and Balances (database)*. Available at. https://www.oecdilibrary.org/energy/data/iea-world-energy-statistics-and-balances_enestats-data-en. Accessed 2 January 2021.
- Isik, C., Ongan, S., & Özdemir, D. (2019a). The economic growth/development and environmental degradation: Evidence from the US state-level EKC hypothesis. *Environmental Science and Pollution Research*, 26(30), 30772–30781.
- Işık, C., Ongan, S., & Özdemir, D. (2019b). Testing the EKC hypothesis for ten US states: An application of heterogeneous panel estimation method. *Environmental Science and Pollution Research*, 26(11), 10846–10853.
- Iskandar, A. (2019). Economic growth and CO2 emissions in Indonesia: Investigating the environmental Kuznets curve hypothesis existence. *Jurnal BPPK*, 20.
- Iwata, H., Okada, K., & Samreth, S. (2010). Empirical study on the environmental Kuznets curve for CO2 in France: The role of nuclear energy. *Energy Policy*, 38(8), 4057–4063.
- Iwata, H., Okada, K., & Samreth, S. (2012). Empirical study on the determinants of CO2 emissions: Evidence from OECD countries. *Applied Economics*, 44(27), 3513–3519.
- Jalil, A., & Mahmud, S. F. (2009). Environment Kuznets curve for CO2 emissions: A cointegration analysis for China. *Energy Policy*, 37(12), 5167–5172.
- Jaunky, V. C. (2011). The CO2 emissions-income nexus: Evidence from rich countries. *Energy Policy*, 39(3), 1228–1240.
- Jiang, G., Alvarado, R., Murshed, M., Tillaguango, B., Toledo, E., Méndez, P., & Isik, C. (2022). Effect of agricultural employment and export diversification index on environmental pollution: Building the agenda towards sustainability. *Sustainability*, 14(2), 677.
- Johansen, S. (1988). Statistical analysis of cointegration vectors. *Journal of Economic Dynamics and Control*, 12(2–3), 231–254.
- Johansen, S. (1991). Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. *Econometrica: Journal of the Econometric Society*, 1551–1580.

- Johansen, S., & Juselius, K. (1990). Maximum likelihood estimation and inference on cointegration—With applications to the demand for money. *Oxford Bulletin of Economics and Statistics*, 52(2), 169–210.
- Kaika, D., & Zervas, E. (2013). The environmental Kuznets curve (EKC) theory—Part A: Concept, causes and the CO₂ emissions case. *Energy Policy*, 62, 1392–1402.
- Kais, S., & Sami, H. (2016). An econometric study of the impact of economic growth and energy use on carbon emissions: Panel data evidence from fifty eight countries. *Renewable and Sustainable Energy Reviews*, 59, 1101–1110.
- Kao, C., & Chiang, M. H. (2001). On the estimation and inference of a cointegrated regression in panel data. In *Non-stationary panels, panel cointegration, and dynamic panels*. Emerald Group Publishing Limited.
- Katz, D. (2015). Water use and economic growth: Reconsidering the environmental Kuznets curve relationship. *Journal of Cleaner Production*, 88, 205–213.
- Khan, Z., Murshed, M., Dong, K., & Yang, S. (2021). The roles of export diversification and composite country risks in carbon emissions abatement: Evidence from the signatories of the Regional Comprehensive Economic Partnership agreement. *Applied Economics*, 53(41), 4769–4787.
- Khanra, S., Dhir, A., Islam, A. N., & Mäntymäki, M. (2020). Big data analytics in healthcare: A systematic literature review. *Enterprise Information Systems*, 14(7), 878–912.
- Klinger, B., & Lederman, D. (2004). *Discovery and development: an empirical exploration of “new” products* (Vol. 3450). World Bank Publications.
- Klinger, B., Lederman, D., (2006). Diversification, Innovation, and Imitation Inside the Global Technological Frontier. World Bank eLibrary. Accessed at: <https://doi.org/10.1596/1813-9450-3872>
- Koc, S., & Bulus, G. C. (2020). Testing validity of the EKC hypothesis in South Korea: Role of renewable energy and trade openness. *Environmental Science and Pollution Research*, 27(23), 29043–29054.
- Kong, Y., & Khan, R. (2019). To examine environmental pollution by economic growth and their impact in an environmental Kuznets curve (EKC) among developed and developing countries. *PloS One*, 14(3), e0209532.
- Krugman, P. (1991). Increasing returns and economic geography. *Journal of Political Economy*, 99(3), 483–499.
- Kushwah, S., Dhir, A., Sagar, M., & Gupta, B. (2019). Determinants of organic food consumption. A systematic literature review on motives and barriers. *Appetite*, 143, 104402.
- Kuznets, S. (1955). Economic growth and income inequality. *The American Economic Review*, 45(1), 1–28.
- Kuznets, S. (1967). Population and economic growth. *Proceedings of the American Philosophical Society*, 111(3), 170–193.
- Le, D. N. (2019). Environmental degradation and economic growth in ASEAN-10: The perspective of EKC hypothesis. *Malaysian Journal of Economic Studies*, 56(1), 43–62.
- Leal, P. H., & Marques, A. C. (2020). Rediscovering the EKC hypothesis for the 20 highest CO₂ emitters among OECD countries by level of globalization. *International Economics*, 164, 36–47.
- Lean, H. H., & Smyth, R. (2010). CO₂ emissions, electricity consumption and output in ASEAN. *Applied Energy*, 87(6), 1858–1864.
- Lederman, D., & Maloney, W. F. (2007). Trade structure and growth. *Natural resources: Neither curse nor destiny*, 15–39.
- Lee, C. C., Chiu, Y. B., & Sun, C. H. (2010). The environmental Kuznets curve hypothesis for water pollution: Do regions matter? *Energy Policy*, 38(1), 12–23.
- Leitão, A. (2010). Corruption and the environmental Kuznets curve: Empirical evidence for sulfur. *Ecological Economics*, 69(11), 2191–2201.
- Li, M., Ahmad, M., Fareed, Z., Hassan, T., & Kirikkaleli, D. (2021). Role of trade openness, export diversification, and renewable electricity output in realizing carbon neutrality dream of China. *Journal of Environmental Management*, 297, 113419.
- Lin, B., Omoju, O. E., Nwajeze, N. M., Okonkwo, J. U., & Megbowon, E. T. (2016). Is the environmental Kuznets curve hypothesis a sound basis for environmental policy in Africa? *Journal of Cleaner Production*, 133, 712–724.
- Liu, H., Kim, H., & Choe, J. (2019). Export diversification, CO₂ emissions and EKC: Panel data analysis of 125 countries. *Asia-Pacific Journal of Regional Science*, 3(2), 361–393.
- Liu, H., Kim, H., Liang, S., & Kwon, O. S. (2018). Export diversification and ecological footprint: A comparative study on EKC theory among Korea, Japan, and China. *Sustainability*, 10(10), 3657.
- Lütkepohl, H. (1982). Non-causality due to omitted variables. *Journal of Econometrics*, 19(2–3), 367–378.
- Luzzati, T., & Orsini, M. (2009). Investigating the energy-environmental Kuznets curve. *Energy*, 34(3), 291–300.
- Madanaguli, A., Srivastava, S., Ferraris, A., & Dhir, A. (2021). Corporate social responsibility and sustainability in the tourism sector: A systematic literature review and future outlook. *Sustainable Development*. <https://doi.org/10.1002/sd.2258>
- Magazzino, C., Mele, M., & Schneider, N. (2020a). The relationship between municipal solid waste and greenhouse gas emissions: Evidence from Switzerland. *Waste Management*, 113, 508–520.
- Magazzino, C., Mele, M., & Schneider, N. (2020b). The relationship between air pollution and COVID-19-related deaths: An application to three French cities. *Applied Energy*, 279, 115835.
- Magazzino, C., Mele, M., Schneider, N., & Vallet, G. (2020c). The relationship between nuclear energy consumption and economic growth: Evidence from Switzerland. *Environmental Research Letters*, 15(9), 0940a5.
- Magazzino, C., Mele, M., & Schneider, N. (2021a). A machine learning approach on the relationship among solar and wind energy production, coal consumption, GDP, and CO₂ emissions. *Renewable Energy*, 167, 99–115.
- Magazzino, C., Mele, M., & Schneider, N. (2021b). A D2C algorithm on the natural gas consumption and economic growth: challenges faced by Germany and Japan. *Energy*, 219, 119586.
- Magazzino, C., Mele, M., Schneider, N., & Sarkodie, S. A. (2021c). Waste generation, wealth and GHG emissions from the waste sector: Is Denmark on the path towards circular economy?. *Science of the Total Environment*, 755, 142510.
- Magazzino, C., Mele, M., Schneider, N., & Shahzad, U. (2022a). Does export product diversification spur energy

- demand in the APEC region? Application of a new neural networks experiment and a decision tree model. *Energy and Buildings*, 258, 111820.
- Magazzino, C., Mele, M., & Schneider, N. (2022b). Assessing a fossil fuels externality with a new neural networks and image optimisation algorithm: The case of atmospheric pollutants as confounders to COVID-19 lethality. *Epidemiology & Infection*, 150.
- Magazzino, C., & Schneider, N. (2020). The causal relationship between primary energy consumption and economic growth in Israel: A multivariate approach. *International Review of Environmental and Resource Economics*, 14(4), 417–491.
- Mania, E. (2020). Export diversification and CO2 emissions: An augmented environmental Kuznets curve. *Journal of International Development*, 32(2), 168–185.
- Mehmood, U., & Tariq, S. (2020). Globalization and CO2 emissions nexus: Evidence from the EKC hypothesis in South Asian countries. *Environmental Science and Pollution Research*, 27(29), 37044–37056.
- Mele, M., Magazzino, C., Schneider, N., & Strezov, V. (2021). NO2 levels as a contributing factor to COVID-19 deaths: The first empirical estimate of threshold values. *Environmental Research*, 194, 110663.
- Melitz, M. J. (2003). The impact of trade on intra-industry reallocations and aggregate industry productivity. *Econometrica*, 71(6), 1695–1725.
- Mikayilov, J. I., Galeotti, M., & Hasanov, F. J. (2018). The impact of economic growth on CO2 emissions in Azerbaijan. *Journal of Cleaner Production*, 197, 1558–1572.
- Minlah, M. K., & Zhang, X. (2021). Testing for the existence of the environmental Kuznets curve (EKC) for CO2 emissions in Ghana: Evidence from the bootstrap rolling window Granger causality test. *Environmental Science and Pollution Research*, 28(2), 2119–2131.
- Moomaw, W. R., & Unruh, G. C. (1997). Are environmental Kuznets curves misleading us? The case of CO2 emissions. *Environment and Development Economics*, 2(4), 451–463.
- Moutinho, V., Madaleno, M., & Elheddad, M. (2020). Determinants of the environmental Kuznets curve considering economic activity sector diversification in the OPEC countries. *Journal of Cleaner Production*, 271, 122642.
- Murshed, M., Ali, S. R., & Banerjee, S. (2021). Consumption of liquefied petroleum gas and the EKC hypothesis in South Asia: Evidence from cross-sectionally dependent heterogeneous panel data with structural breaks. *Energy, Ecology and Environment*, 6(4), 353–377.
- Mutascu, M. (2018). A time-frequency analysis of trade openness and CO2 emissions in France. *Energy Policy*, 115, 443–455.
- Mutascu, M., & Sokic, A. (2020). Trade openness-CO2 emissions nexus: A wavelet evidence from EU. *Environmental Modeling & Assessment*, 25(3), 411–428.
- Narayan, P. K., & Narayan, S. (2010). Carbon dioxide emissions and economic growth: Panel data evidence from developing countries. *Energy Policy*, 38(1), 661–666.
- Naudé, W., & Rossouw, R. (2011). Export diversification and economic performance: Evidence from Brazil, China, India and South Africa. *Economic Change and Restructuring*, 44(1), 99–134.
- Neary, J. P. (2001). Of hype and hyperbolas: Introducing the new economic geography. *Journal of Economic Literature*, 39(2), 536–561.
- OECD Environment Statistics database, (2020). Environment. Accessed at: <https://data.oecd.org/environment.html>
- Ongan, S., Isik, C., & Ozdemir, D. (2021). Economic growth and environmental degradation: Evidence from the US case environmental Kuznets curve hypothesis with application of decomposition. *Journal of Environmental Economics and Policy*, 10(1), 14–21.
- Özokcu, S., & Özdemir, Ö. (2017). Economic growth, energy, and environmental Kuznets curve. *Renewable and Sustainable Energy Reviews*, 72, 639–647.
- Ozturk, I., Al-Mulali, U., & Saboori, B. (2016). Investigating the environmental Kuznets curve hypothesis: The role of tourism and ecological footprint. *Environmental Science and Pollution Research*, 23(2), 1916–1928.
- Panayotou, T. (1993). *Empirical tests and policy analysis of environmental degradation at different stages of economic development* (No. 992927783402676). International Labour Organization.
- Paramati, S. R., Ummalla, M., & Apergis, N. (2016). The effect of foreign direct investment and stock market growth on clean energy use across a panel of emerging market economies. *Energy Economics*, 56, 29–41.
- Parteka, A., & Tamberi, M. (2013). What determines export diversification in the development process? *Empirical Assessment. the World Economy*, 36(6), 807–826.
- Pata, U. K. (2018). Renewable energy consumption, urbanization, financial development, income and CO2 emissions in Turkey: Testing EKC hypothesis with structural breaks. *Journal of Cleaner Production*, 187, 770–779.
- Pata, U. K., & Aydin, M. (2020). Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. *Journal of Cleaner Production*, 264, 121699.
- Pata, U. K., & Caglar, A. E. (2021). Investigating the EKC hypothesis with renewable energy consumption, human capital, globalization and trade openness for China: Evidence from augmented ARDL approach with a structural break. *Energy*, 216, 119220.
- Pedroni, P. (2001). Fully modified OLS for heterogeneous cointegrated panels. In *Nonstationary panels, panel cointegration, and dynamic panels*. Emerald Group Publishing Limited.
- Pedroni, P. (2004). Panel cointegration: Asymptotic and finite sample properties of pooled time series tests with an application to the PPP hypothesis. *Econometric Theory*, 20(3), 597–625.
- Pesaran, M. H., & Pesaran, B. (1997). *Working with Microfit 4.0: Econometric analysis*. Oxford University Press.
- Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, 16(3), 289–326.
- Pesaran, M. H., & Smith, R. P. (1998). Structural analysis of cointegrating VARs. *Journal of Economic Surveys*, 12(5), 471–505.
- Pollitt, H. (2020). Analysis: Going carbon neutral by 2060 ‘will make China richer’. CarbonBrief. Available at: <https://www.carbonbrief.org/analysis-going-carbon-neutral-by-2060-will-make-china-richer>. Accessed 2 January 2021.

- Publication Office of the European Union (POEU). (2018). Fossil CO₂ emissions of all world countries – 2018 report. Available at. <https://ec.europa.eu/jrc/en/publication/fossil-co2-emissions-all-world-countries-2018-report>. Accessed 2 January 2021.
- Rana, R., & Sharma, M. (2019). Dynamic causality testing for EKC hypothesis, pollution haven hypothesis and international trade in India. *The Journal of International Trade & Economic Development*, 28(3), 348–364.
- Rieber, A., & Tran, T. A. D. (2009). The effects of unilateral environmental regulations in a world with capital mobility and trading costs. *Asia-Pacific Journal of Accounting & Economics*, 16(3), 317–338.
- Rees, W. E. (2021). COP-26: Stopping climate change and other illusions. *Buildings and Cities*.
- Saboori, B., Sulaiman, J., & Mohd, S. (2016). Environmental Kuznets curve and energy consumption in Malaysia: A cointegration approach. *Energy Sources, Part B: Economics, Planning, and Policy*, 11(9), 861–867.
- Sadorsky, P. (2011). Trade and energy consumption in the Middle East. *Energy Economics*, 33(5), 739–749.
- Sahu, A. K., Padhy, R. K., & Dhir, A. (2020). Envisioning the future of behavioral decision-making: A systematic literature review of behavioral reasoning theory. *Australasian Marketing Journal (AMJ)*, 28(4), 145–159.
- Sarkodie, S. A. (2018). The invisible hand and EKC hypothesis: What are the drivers of environmental degradation and pollution in Africa? *Environmental Science and Pollution Research*, 25(22), 21993–22022.
- Sarkodie, S. A., Adams, S., Owusu, P. A., Leirvik, T., & Ozturk, I. (2020). Mitigating degradation and emissions in China: The role of environmental sustainability, human capital and renewable energy. *Science of the Total Environment*, 719, 137530.
- Sarkodie, S. A., & Ozturk, I. (2020). Investigating the environmental Kuznets curve hypothesis in Kenya: A multivariate analysis. *Renewable and Sustainable Energy Reviews*, 117, 109481.
- Sarkodie, S. A., & Strezov, V. (2019). A review on environmental Kuznets curve hypothesis using bibliometric and meta-analysis. *Science of the Total Environment*, 649, 128–145.
- Sauvé, S., Bernard, S., & Sloan, P. (2016). Environmental sciences, sustainable development and circular economy: Alternative concepts for trans-disciplinary research. *Environmental Development*, 17, 48–56.
- Schneider, N. (2020). Renewable energy, energy efficiency, and CO₂ emissions in developing countries: Evidence from the Pesaran (2006) common correlated effects model. *SSRN Electronic Journal*, No. 3720674, 1–48.
- Schneider, N. (2022). Thoughts after COP26. *International Journal of Environmental Studies*, 1–2.
- Schneider, N., & Sprout, E. (2021). Scorched earth: Environmental warfare as a crime against humanity and nature: By Emmanuel Kreike, Princeton & Oxford, Princeton. (pp. 521). University Press. \$39.95, £ 34.00 (hc), ISBN 978-0-691-1374-21; eISBN 978-0-691-1890-17.
- Selden, T. M., & Song, D. (1994). Environmental quality and development: Is there a Kuznets curve for air pollution emissions? *Journal of Environmental Economics and Management*, 27(2), 147–162.
- Shafik, N., & Bandyopadhyay, S. (1992). *Economic growth and environmental quality: time-series and cross-country evidence* (vol. 904). World Bank Publications.
- Shahbaz, M., Gozgor, G., & Hammoudeh, S. (2019). Human capital and export diversification as new determinants of energy demand in the United States. *Energy Economics*, 78, 335–349.
- Shahbaz, M., Khraief, N., Uddin, G. S., & Ozturk, I. (2014). Environmental Kuznets curve in an open economy: A bounds testing and causality analysis for Tunisia. *Renewable and Sustainable Energy Reviews*, 34, 325–336.
- Shahbaz, M., Mutascu, M., & Azim, P. (2013). Environmental Kuznets curve in Romania and the role of energy consumption. *Renewable and Sustainable Energy Reviews*, 18, 165–173.
- Shahbaz, M., Raghutla, C., Song, M., Zameer, H., & Jiao, Z. (2020). Public-private partnerships investment in energy as new determinant of CO₂ emissions: The role of technological innovations in China. *Energy Economics*, 86, 104664.
- Shahzad, U., Fareed, Z., Shahzad, F., & Shahzad, K. (2021). Investigating the nexus between economic complexity, energy consumption and ecological footprint for the United States: New insights from quantile methods. *Journal of Cleaner Production*, 279, 123806.
- Shahzad, U., Ferraz, D., Doğan, B., & do Nascimento Rebelatto, D. A. (2020). Export product diversification and CO₂ emissions: Contextual evidences from developing and developed economies. *Journal of Cleaner Production*, 276, 124146.
- Shikwambana, L., Mhangara, P., & Kganyago, M. (2021). Assessing the relationship between economic growth and emissions levels in South Africa between 1994 and 2019. *Sustainability*, 13(5), 2645.
- Simionescu, M., & Schneider, N. (2022). Revisiting the nuclear energy-income nexus in Europe: An application of the JKS panel causality test with cross-sectional dependence and heterogeneity. *International Journal of Energy Research*. <https://doi.org/10.1002/er.7731>
- Simionescu, M., Schneider, N., & Gavurova, B. (2022). Decarbonized energies and the wealth of three European nations: A comparative nexus study using Granger and Toda-Yamamoto approaches. *Frontiers in Environmental Science*, 693.
- Sinha, A., & Sengupta, T. (2019). Impact of energy mix on nitrous oxide emissions: An environmental Kuznets curve approach for APEC countries. *Environmental Science and Pollution Research*, 26(3), 2613–2622.
- Sinha, A., Sengupta, T., & Saha, T. (2020). Technology policy and environmental quality at crossroads: Designing SDG policies for select Asia Pacific countries. *Technological Forecasting and Social Change*, 161, 120317.
- Smith, P., Beaumont, L., Bernacchi, C. J., Byrne, M., Cheung, W., Conant, R. T., ..., & Long, S. P. (2021). Essential outcomes for COP26. *Global Change Biology*, 28(1), 1–3. <https://doi.org/10.1111/gcb.15926>
- Smyth, R., & Narayan, P. K. (2015). Applied econometrics and implications for energy economics research. *Energy Economics*, 50, 351–358.
- Soytas, U., Sari, R., & Ewing, B. T. (2007). Energy consumption, income, and carbon emissions in the United States. *Ecological Economics*, 62(3–4), 482–489.

- Spratt, S., Dong, W., Krishna, C., Sagar, A., & Ye, Q. (2014). *What drives wind and solar energy investment in India and China?* (No. IDS Evidence Report; 87). IDS.
- Stern, D. I., & Common, M. S. (2001). Is there an environmental Kuznets curve for sulfur? *Journal of Environmental Economics and Management*, 41(2), 162–178.
- Sun, Y., Li, M., Zhang, M., Khan, H. S. U. D., Li, J., Li, Z., ..., & Anaba, O. A. (2021). A study on China's economic growth, green energy technology, and carbon emissions based on the Kuznets curve (EKC). *Environmental Science and Pollution Research*, 28(6), 7200–7211.
- Suri, V., & Chapman, D. (1998). Economic growth, trade and energy: Implications for the environmental Kuznets curve. *Ecological Economics*, 25(2), 195–208.
- Tandon, A., Dhir, A., Islam, A. N., & Mäntymäki, M. (2020). Blockchain in healthcare: A systematic literature review, synthesizing framework and future research agenda. *Computers in Industry*, 122, 103290.
- Topcu, M., & Payne, J. E. (2018). Further evidence on the trade-energy consumption nexus in OECD countries. *Energy Policy*, 117, 160–165.
- Ulucak, R., & Bilgili, F. (2018). A reinvestigation of EKC model by ecological footprint measurement for high, middle and low income countries. *Journal of Cleaner Production*, 188, 144–157.
- United Nations (UN). (2018). The Sustainable Development Goals Report 2018. Available at <https://unstats.un.org/sdgs/report/2018>. Accessed 2 January 2021.
- United Nations Conference on Trade and Development (UNCTAD). (2020). International Trade statistics. Available at <https://unctad.org/statistics>. Accessed 2 January 2021.
- Wang, L., Chang, H. L., Rizvi, S. K. A., & Sari, A. (2020b). Are eco-innovation and export diversification mutually exclusive to control carbon emissions in G-7 countries?. *Journal of Environmental Management*, 270, 110829.
- Wang, S., Gao, S., Li, S., & Feng, K. (2020a). Strategizing the relation between urbanization and air pollution: Empirical evidence from global countries. *Journal of Cleaner Production*, 243, 118615.
- Wang, S., Li, Q., Fang, C., & Zhou, C. (2016). The relationship between economic growth, energy consumption, and CO2 emissions: Empirical evidence from China. *Science of the Total Environment*, 542, 360–371.
- Wei, H., & Wang, S. (2019). Analysis of and theoretical reflections on China's "Excessive De-Industrialization" phenomenon. *Chinese Journal of Urban and Environmental Studies*, 7(04), 1950017.
- World Bank (WB). (2020). *World Development Indicators (WDI) database*. Available at <http://data.worldbank.org>. Accessed 2 January 2021.
- Yang, Z., & Zhao, Y. (2014). Energy consumption, carbon emissions, and economic growth in India: Evidence from directed acyclic graphs. *Economic Modelling*, 38, 533–540.
- York, R., Rosa, E. A., & Dietz, T. (2003). Footprints on the earth: The environmental consequences of modernity. *American Sociological Review*, 279–300.
- Zaman, K., & Abd-el Moemen, M. (2017). Energy consumption, carbon dioxide emissions and economic development: Evaluating alternative and plausible environmental hypothesis for sustainable growth. *Renewable and Sustainable Energy Reviews*, 74, 1119–1130.
- Zhang, X. P., Cheng, X. M., Yuan, J. H., & Gao, X. J. (2011). Total-factor energy efficiency in developing countries. *Energy Policy*, 39(2), 644–650.
- Zhao, N., Xu, L., Malik, A., Song, X., & Wang, Y. (2018). Inter-provincial trade driving energy consumption in China. *Resources, Conservation and Recycling*, 134, 329–335.

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