RESEARCH ARTICLE

Consumption of energy from conventional sources a challenge to the green environment: evaluating the role of energy imports, and energy intensity in Australia

Yasir Khan[1] · Fang Liu[1]

Abstract

Conventional energy consumption such as coal, natural gas, and oil is a source of deteriorating environmental sustainability as well as a severe challenge to the green environment. The present paper explores the nexus between CO_2 emissions, energy imports, energy intensity, and power generation from renewable and non-renewable energies from 1990 to 2021 in Australia. Based on the ARDL model, the findings reveal that energy imports and power generation from non-renewable energy sources show an adverse effect on the green environment. A 1% increase in conventional energy imports leads to an 11% increase in CO_2 emissions. Similarly, a 1% increase in energy generation from conventional sources will increase CO_2 emissions by 45%. On the other hand, lower energy intensity and power generation from renewable sources reveal a positive effect on environmental quality. A 1% increase in energy intensity will decrease CO_2 emissions by 92% while energy generation from non-conventional sources by 15%. Most interestingly, energy intensity reveals the foremost position among all the selected variables to decarbonize and effectively transform conventional energy to clean and green energy production and utilization. The robustness test outcomes confirm the results of the empirical output. Furthermore, this study suggests that governments and policymakers should focus on the adaptation of lower energy intensity for the purpose to reduce CO_2 emissions and promote a clean and green environment. Finally, power generation from renewable energy sources plays an inevitable role which ultimately helps environmentally sustainability in Australia.

Keywords CO_2 emissions · Energy imports · Energy intensity · Electricity generation from renewable and non-renewable · Time-series analysis

Highlights

• The role of energy intensity and electricity generation from non-renewable energy sources is analyzed.
• Energy generation from renewable sources plays a vital role in environmental quality and sustainability.
• CO_2 emission degradation targets can be met by mitigating conventional energy imports and fossil fuels.
• A one-way causal association runs from conventional energy imports to CO_2 emissions.
• Energy intensity positively affects CO_2 emissions in Australia.

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Abbreviations

CO_2 emissions	Carbon dioxide emissions
ARDL	Autoregressive distributed lag
EI	Energy imports
ET	Energy intensity
EPR	Electricity production from renewables
EPNR	Electricity production from non-renewables
ZA	Zivot-Andrews
FMOLS	Fully-modified ordinary least squares
DOLS	Dynamic ordinary least squares

Introduction

The energy sector is the most important factor in the economic development of various countries; it is also a priority development sector in the economic development strategies of numerous economies in the world (Bacon and

Besant-Jones 2001; Mercure 2012; He et al. 2021). In 2018, the global power consumption was about 24.5 trillion kWh, an increase of 3.1% over the previous year, and the growth rate reached a new high point in the past 5 years (Ahmad and Zhang 2020). Meanwhile, due to the rising energy demand, carbon dioxide emissions from global energy consumption reached 33.1 billion tons in 2018 with a year-on-year increase of 1.7% (about 560 million tons). This was the highest growth rate since 2013 and 70% above the average growth rate since 2010. It is found that the global average surface temperature has increased by 1 °C above the pre-industrial level of which more than 0.3 °C is caused by carbon dioxide emission from coal burning (Saint Akadiri et al. 2020), making coal the largest single source of global temperature rise, as shown in Fig. 1. Commercial and public services are the top sector generating CO_2 emissions in Australia followed by agriculture, residential, electricity, manufacturing industry, transport, and other energy industries, respectively. Although global CO_2 has decreased by 7% since the COVID-19 pandemic, it is paltry compared with the efforts that governments and international organizations need to work together for abating global warming. According to the World Meteorological Organization (WMO), the concentrations of global greenhouse gas have reached a new high point in 2020, with concentrations of carbon dioxide, methane, and nitrous oxide 149%, 262%, and 123% higher than the pre-industrial levels, respectively. The rise in the frequency and intensity of extreme weather events is creating a "dangerous compound effect," combined with violent conflicts, economic recession, and the shock of the pandemic, undermining decades of progress in improving food security globally (Chavez et al. 2015; Weilnhammer et al. 2021). Recent study developed by Khan et al. (2019) found that due to climate change deterioration, agriculture

trade export in Pakistan was severely affected. The mismatch between social demands for action on mitigating climate warming and the actual pace of progress is growing and the world is on an unsustainable path of development.

Facing the severe climate change situation, the world's major economies such as Australia, China, India, the USA, and the UK have gradually formulated carbon reduction policies to deal with climate warming. In 1988, the European Union (EU) published the report "Energy Internal Market," which proposed to integrate the natural gas and electricity sectors, promote the substitution of natural gas for coal and oil, and improve the efficiency of energy utilization. In recent years, China has actively adjusted its energy structure, and the total installed capacity of wind power and photovoltaics has become the largest in the world. Bazán et al. (2018) investigated electricity production through the implementation of photovoltaic panels in rooftops in three cities in Peru and found that annual reductions in GHG emissions reach up to 523kton CO_2 emissions. In addition, substantial climate change mitigation could be accomplished via a low-carbon electricity system and green technological innovation (Khan et al. 2020; Hassan et al. 2022a, b). Further, the study by Safi et al. (2021a, b, c), examined that environmental taxes, environmental R&D, and exports significantly reduce carbon emissions, whereas GDP and imports significantly enhance carbon emissions. Abundant hydropower allows for a low-cost renewable power system. Along with the development and implication of green technology in the electricity sectors, the carbon intensity of the power energy sector has decreased by 20%. As shown in Fig. 2, Australia is a major contributor to the world's carbon emissions compared to China and India. The USA has the largest proportion of CO_2 emissions as the country extensively adopted non-renewable energy sources such as (coal, natural gas, and oil). However,

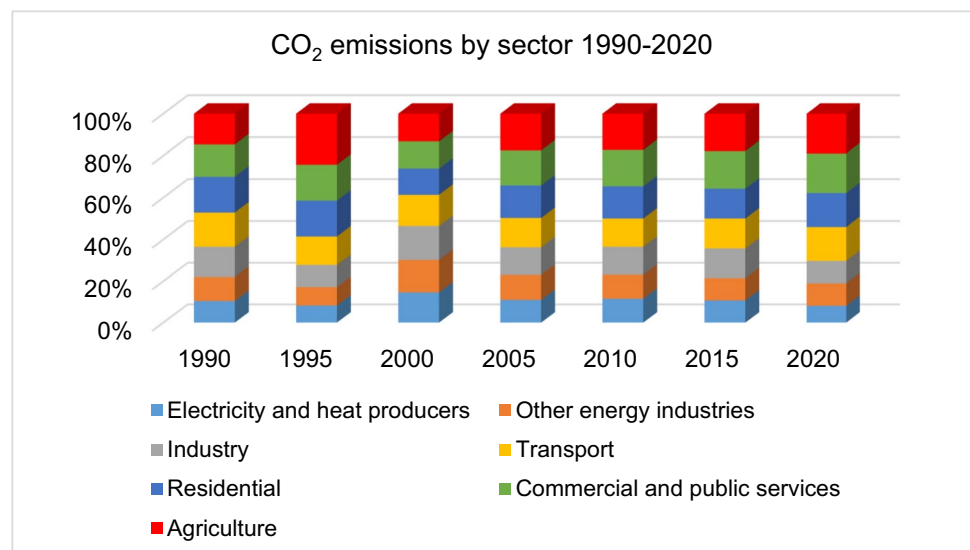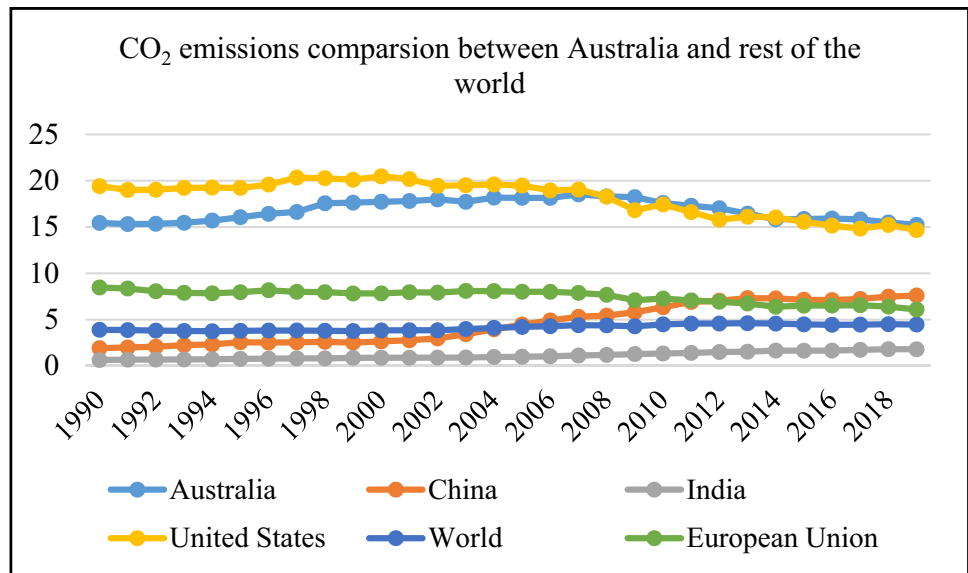**Fig. 1** The trend in CO_2 emissions by sector. Source: International Energy Agency (IEA)

Fig. 2 CO_2 emission comparison between Australia and the rest of the world from 1990 to 2020. Source: World Bank Indicator (WDI)


the country is still dependent on conventional energy sources due to the higher demand for energy utilization.

As a major energy consumption country, Austria has plenty of coal resources. Hence, coal power is an important source of electricity for Australia (Shafiullah et al. 2012). As shown in Fig. 3, energy generation from coal has the largest share of the total energy generation from conventional sources followed by natural gas and oil. On the other hand, energy generation from renewable sources has improved specifically between 2015 to 2020, indicating that the country is struggling to adopt more renewable energy sources under the Paris Agreement. However, its economic development still depends on huge oil imports. It is currently the

only net oil importer in the International Energy Agency (IEA). To meet the demands of decarbonisation in energy structure, Australia has also adopted a series of measures. In 2018, about 20% of Australia's electricity supply was provided by clean energy, of which hydropower, wind power, and distributed solar power were the main power types (Hamilton et al. 2019). Australia has the highest per capita share of small-scale photovoltaic power generation in the world. The high price of electricity sold with the relatively low cost of distributed photovoltaics form a large profit margin, which has prompted the rapid development of household distributed photovoltaics. Its largest power system is intended to securely operate with up to 75% of variable

Fig. 3 Share in power generation from 1990 to 2018. Source: World Energy Transition
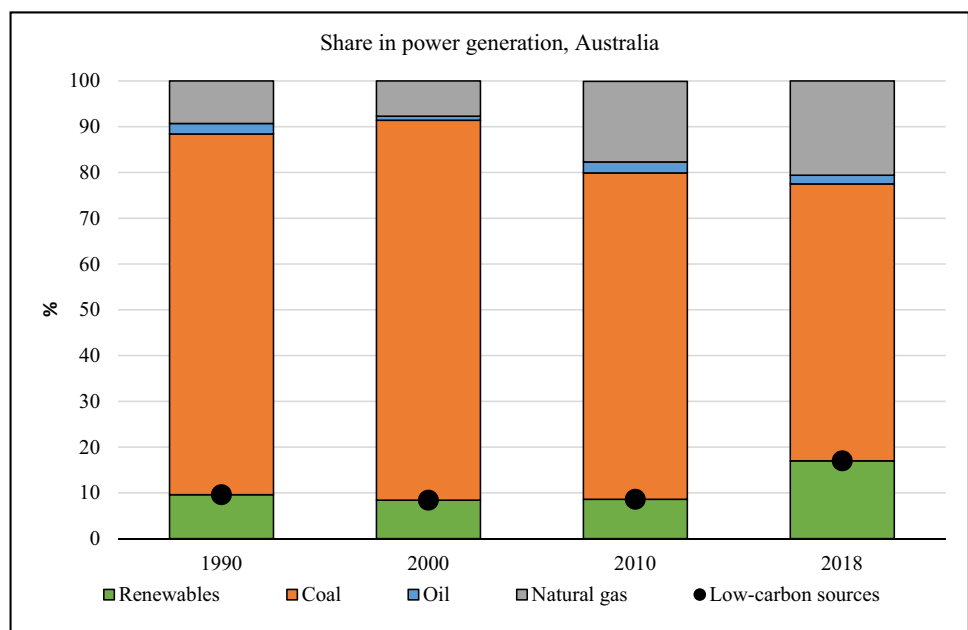
renewable generation by 2025 (Arraño-Vargas et al. 2022). However, the plan is too ideal while the reality is too harsh. How to use more new energy in the power generation field has become a key development direction of the government, since the carbon dioxide emission from the electricity sector accounts for 50% of the national total emissions (Sarkodie and Strezov 2018). In the context of frequent climate disasters and intensified energy market volatility, it is significant to further explore the relationship between CO_2 emissions, energy intensity, energy imports, and the development of renewable energy. The most recent study developed by Hassan, Khan et al. (2022a, b, c, d, e, f) examined the connection between environmental regulations, political risk, and corban-based CO_2 emission in the OECD economies. The findings revealed that effective environmental regulations and lower political risk can decrease CO_2 emissions. The latest study proposed by Wahab et al. (2021) found that energy productivity, exports, and technological innovation are inversely related to consumption-based carbon emission. Khan and Bin (2022) and Safi, Wang et al.'s (2022a, b) fiscal decentralization decreases carbon emissions and is essential for achieving the goals of net-zero carbon emissions. The results also show that the indirect effect is significantly positive in the economic-geographical weight matrix, and the spatial spillover effect of fiscal decentralization is not conducive to the environment of countries with economic exchanges.

The present study aims to explore the nexus between CO_2 emissions, energy imports (EI), and energy intensity (ET) of the primary energy and electricity generation from renewable and non-renewable sources in Australia considering two situations of renewable and non-renewable power generation during the period 1990–2021. This is to quantify the impact of energy import and energy intensity on environmental quality in Australia, by employing time-series analysis to assess changes in CO_2 emissions given the increase in corresponding variables over almost three decades. Therefore, the contribution of this paper to the literature is that it assumed that this research is the first study to investigate the reasons for CO_2 emissions growth or decrease arising from renewable and non-renewable power generation using the ARDL model in Australia. As shown in Fig. 4, an important insight has been displayed taking three decades in segments. Energy generation from fossil fuels substantially increased between 2010 and 2018; however, the consumption level of fossil fuels decreased between 2000 and 2018. Furthermore, Australia has extensively adopted energy efficiency by decreasing higher energy intensity from 2000 to 2018.

The reminding of the paper is arranged as follows: the study has considered the literature review on the linkage between CO_2 emissions, energy intensity (EI), energy imports (ET), electricity generation from a renewable source (EPNR), and electricity generation from conventional energy sources (EPR). The methodology section describes the model specification, data source, and econometric analysis. The results and discussions section highlights the empirical outcomes of the present study. Finally, the paper discusses the conclusion, policy recommendations, and limitations of the study.

Fig. 4 Annual average change from 1990 to 2018. Source: World Energy Transition
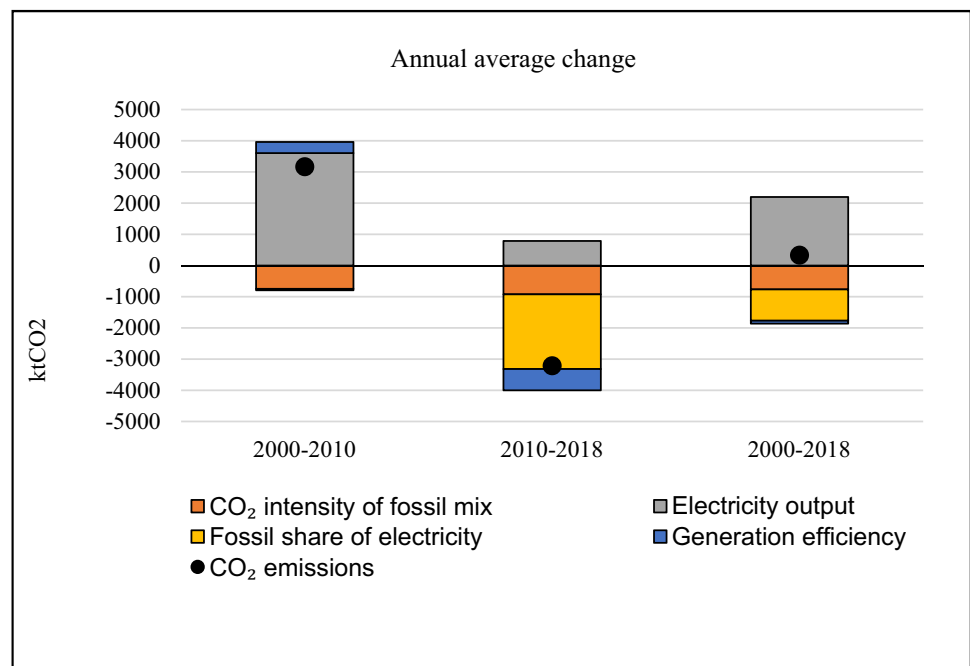
Literature review

The present study endeavors to examine the impacts of effects of energy intensity (ET), energy imports (EI), electricity production from renewable energy sources (EPR), and electricity production from non-renewable energy sources (EPNR) on CO_2 emissions from 1990 to 2021 and propose policy implications for utilizing the higher energy intensity in Australia. The current study divides the literature review section into four segments: First, the association between energy intensity and CO_2 emissions; Second, the relationship between energy imports and CO_2 emissions; Third, the impact of electricity production from renewable energy sources on CO_2 emissions; and Fourth, the connection between electricity production from non-renewable energy sources and CO_2 emissions.

The nexus between energy imports and CO_2 emissions

The majority of the world's economies rely heavily on the import of fossil fuels energy. The nexus between energy import, energy consumption, and CO_2 emissions have aroused many scholars' attention. Bouznit and Pablo-Romero (2016) analyze the relationship between CO_2 emissions and economic growth in Algeria, taking into account energy use, electricity consumption, and energy imports. They found that an increase in energy use and electricity consumption increase CO_2 emissions and that energy imports also affect CO_2 emissions positively. Anwar (2016) employed a long-term integrated energy system model to analyze the influence of reducing energy imports on primary energy supply, cost of imported fuels, energy security, and CO_2 emissions in the case of Pakistan. Similarly, Adewuyi and Awodumi (2021) and Khan et al. (2022a, b, c, d, e, f) stress that simultaneous achievement of energy efficiency, economic growth, and emissions reduction is a major challenge for developing countries and they found that CO_2 emission can only induce increased GDP per capita when the petroleum import is below the threshold level using the data of South Africa and Nigeria. The economic growth of emerging economies in Asia was even hampered by high fuel prices and the related high energy import bills. Dowling and Russ (2012) assessed the role of major Asian economies in the global effort to reduce CO_2 emissions and quantified the impact of reducing energy imports. Their results showed that the costs of reaching ambitious emission reduction targets are offset by reduced energy import bills. In addition, Li and Lin (2015) used the price-gap approach to analyze the impacts of subsidy removal on energy consumption

and CO_2 emissions of 22 Chinese departments during the period 2006–2020 and revealed that removing energy subsidies would reduce energy consumption and emissions. The win–win objective of decarbonization and independence on energy import is a big challenge for some developed countries. The European energy sector relies on gas resources to provide electricity and heating for industrial and domestic consumers. Therefore, the study by Pedersen et al. (2022) analyzed that gas imports from Russia may be discontinued due to Russia's invasion of Ukraine and this would challenge Europe's energy supply. Thus, the faster integration of different renewable energy is necessary to maintain climate governance targets. Similarly, Carfora et al. (2022) conducted an in-depth analysis of factors determining the energy import demand of EU countries by studying the role of renewable versus non-renewable energy sources and the impact of renewable energy policy on CO_2 emissions reduction targets. Safi et al. (2021a, b, c) found that in the short and long run, imports and economic growth enhance carbon emission, whereas financial instability, technological innovation, and exports significantly reduce consumption-based carbon emission. Further, the most recent study introduced by Safi et al. (2021a) explored that institutional quality, energy productivity, eco-innovation, and exports adversely affect CCO_2 emissions and improve environmental quality in the short and long run. In contrast, imports and GDP are positively linked with CCO_2 emissions and contribute to environmental degradation.

Relationship between energy intensity and CO_2 emissions

Numerous studies examine the dynamic relationship between energy intensity and CO_2 emissions such as, Ulucak and Khan (2020) and Khan et al. (2022a, b, c, d, e, f) examined the role of economic policy uncertainty in energy intensity and CO_2 emissions nexus in the USA and East Asian countries during 1985–2017. The results show that America's economic policy uncertainty strengthens the detrimental effect of energy intensity on CO_2 emissions. Also, Shahbaz et al. (2015) employed VECM Granger causality to test the dynamic relationship between energy intensity and CO_2 emissions by incorporating economic growth based on the case of African countries, and their results reveal that energy intensity has a positive and statistically significant impact on CO_2 emissions. In addition, Khan and Bin (2020); Liu, Wahab et al. (2021); Wang et al. (2021); and Imran et al. (2022) used the dynamic spatial panel model to explore the influencing mechanism of FDI, trade on carbon emissions through energy intensity, and the moderating effects of the emissions trading system. Their results suggested that FDI can indirectly increase carbon emissions by

promoting energy intensity and the emission trading system has a significant negative impact on carbon emissions. The study of Khan et al. (2021) found a negative link between fossil fuels and renewable energy, while a positive connection between terrorism and fossil fuels in the case of Pakistan. Arroyo and Miguel (2019) pointed out that the energy intensity would be reduced to 54% and the production of CO_2 emissions would be cut to half in Ecuador by 2030, compared to the beginning of the simulation period, if industrialized country policies on the use of renewable energy and energy efficiency were applied. Shokoohi et al. (2022) investigated the effect of energy intensity and economic growth on CO_2 emissions in the Middle East countries, including Iran, Iraq, and Turkey; they found that energy intensity is one of the important sources of environmental degradation in all the studied countries and there was a significant positive relationship between energy intensity, CO_2 emissions, and ecological footprint. Wu et al. (2016) proposed a new DEA-based model to allocate CO_2 emissions and energy intensity reduction targets in China and they suggest that most of the 30 provincial industries to reduce energy intensity is required for the achievement of the CO_2 emissions reduction target. Rahman et al. (2022) found energy intensity and industrialization increase carbon intensity in the long run, while renewable energy use and urbanization decrease carbon intensity by studying the experience of large emerging economies. However, Wei et al. (2019) argued that energy intensity reduction would result in rebound effect on energy use and they further found that the key drivers behind the rebound effect are strong increases in resource inputs rather than technological changes.

The impact of renewable energy on CO_2 emissions

As an important part of the global energy system, renewable energy provides a new driving force for the social, political, and economic development of various countries, which plays a crucial role in ensuring energy security, improving environmental protection, and increasing employment in countries around the world in addition to reducing greenhouse gas emissions (Khan et al. 2022a, b, c, d, e, f; Khan et al. 2022a, b, c, d, e, f). Malmedal et al. (2007) pointed out that the US Energy Policy Act of 2005 has a positive impact on several types of renewable energy, the electricity market, and the national electrical grid. Okioga et al. (2018) employed the analytic hierarchy process to compute the benefit/cost ratio of selecting mandates versus incentives for the renewable electricity alternatives. Solorio and Bocquillon (2017) overviewed the history and evolution of EU renewable energy policy, and revealed that changes in the European governance structures to promote renewable energy sources are significant. Similarly, the study by Wahab (2021) and Khan et al. (2022a, b, c, d, e, f) found that investment in environmentally friendly technology can significantly mitigate CO_2 emission in Morocco. In

another study by Rahim et al. (2021); Safi et al. (2021a); and Khan et al. (2022a, b, c, d, e, f), they advocate that human capital and renewable energy are the key factors in the process of decarbonizing in the Belt and Road countries. Kilinc-Ata (2016) analyzed the renewable energy policy instruments for 27 EU countries and 50 US states based on panel data over 1990–2008 concluded that feed-in tariffs, tenders, and tax incentives are effective mechanisms for stimulating the deployment capacity of renewable energy sources for electricity, while the other commonly used policy instrument is not. Xu et al. (2020) uncovered the logic underlying the trade conflicts between the developed and emerging economies in the renewable energy transitions and argued that inequality acts restrict the optimization of energy use and effects global climate governance. In recent years, due to the impact of the international financial crisis and the sovereign debt crisis, as well as the advancement of wind power and photovoltaic technology, the cost of power generation has also been significantly reduced. Some countries have begun to reduce the on-grid electricity price of renewable energy or reduce financial subsidies. Taxes on energy equipment and electricity generation have increased. On the other hand, Wahab et al. (2022) examined that technological innovation, imports, financial stability, and economic growth contribute to consumption-based carbon emissions; in contrast, exports and renewable energy usage negatively affect consumption-based carbon emissions. Finally, further literature summary on the nexus between CO_2-energy association is presented in Table 1.

The above studies used various methods to examine energy consumption and CO_2 emissions problems based on data from different countries. However, none of them examined changes in Australia using the ARDL approach. Therefore, the contribution of this study to current literature on energy import and energy consumption policy and CO_2 emissions is through using the ARDL method to highlight the factors affecting CO_2 emissions in Australia. A recent time series method proposed by Jordan and Philips (2018) is employed to get robust and consistent estimation results in the study. This analysis will help policymakers to identify the impact of energy import, and energy consumption on environmental degradation and attach importance to the influence of energy consumption structure optimization on CO_2 reduction. They can then take steps toward raising energy efficiency by building an effective strategic plan for sustainable development.

Econometric methods, data source, and model specification

In this paper, we employed a series of econometric methods such as the conventional unit root test, Zovit-Andrew structural break unit root test, panel co-integration, ARDL model,

Table 1 Literature summary on the nexus between CO_2-green energy hypotheses

Authors	Region/Period	Method	Association between CO_2-innovation	Contribution
Khattak et al. (2020)	BRICS 1980–2016	CCEMG	Positive	Empirically confirmation of the linear linkage between innovation and CO_2 for the BRICS region
Cheng et al. (2021)	OECD 1996–2015	PQR	Negative	The study examines the impact of technological innovation on CO_2 emissions and the essential influencing factors in OECD countries
Mensah et al. (2019)	OECD 1990–2015	ARDL	Negative	The study examines the innovation-emission nexus to determine trademark's carbon mitigation in the climate change degradation fight
Weimin et al. (2021)	Developing countries 1990–2016	FMOLS	Negative	The authors investigate innovation shocks (both negative and positive) and estimate the influence of these shocks on pollution in developing countries
Rafique et al. (2020)	BRICS 1990–2017	AMG	Negative	The study included the current literature by visualizing the connection between technological innovation and CO_2
Ahmad et al. (2020) et al. (2020	OECD 1993–2014	Differenced GMM	Positive	Utilizing simultaneous equation modelling, the article displays the latest outlook in the resource economics and environmental literature by exploring FDI, innovation, and the energy-environment-growth connection
Zhao et al. (2021)	62 economies 2003–2018	MEM	Negative	The paper investigated the linkage between CO_2 emissions and financial risk by employing an extensive financial risk index
Álvarez-Herránz et al. (2017)	OECD 1990–2014	LDM	Negative	The paper contributes to the existing literature by investigating how technology advancements play a substantial role in processes of environmental quality
Khan et al. (2022a, b, c, d, e, f)	Morocco 1990–2020	Dynamic ARDL	Negative	The study found a negative association between CO_2 emissions and renewable energy usage
Hassan et al. (2022a, b)	OECD 1990–2020	CS-ARDL	Positive	The study revealed a positive influence on adopting energy efficiency to mitigate CO_2 emissions in the OECD economies

FMOLS, DOLS, CCR, and Granger causality tests. Figure 5 illustrates the econometric strategy of the present study.

Model specification

$$CO_{2t} = f(EI_t, ET_t, EPR_t, EPNR_t) \qquad (1)$$

In Eq. 1, CO_2 defines carbon emissions, EI represents energy imports, ET describes energy intensity, EPR is the electricity production from renewable sources, and EPNR represents electricity production from non-renewable sources, respectively. The present study empirically probes the multivariate time series method. First, the data series is changed into a natural logarithmic form for the purpose to overcome the issue of heteroscedasticity. Second, the autoregressive distributed lag (ARDL) estimation is used which is a common approach in time-series data. The study of Khan et al. (2022a,

Fig. 5 Econometric strategy
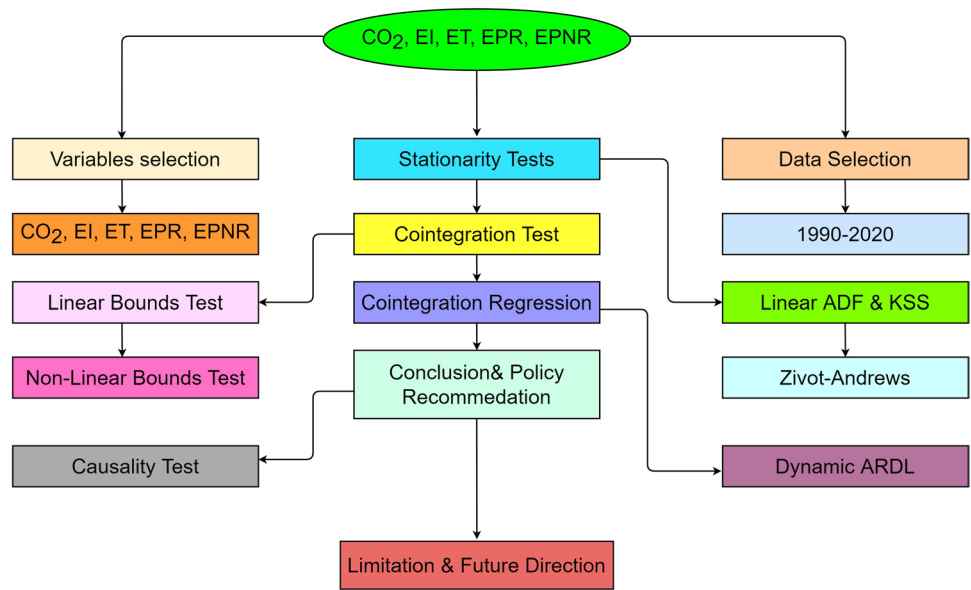
b, c, d, e, f) suggested such techniques could assess numerous potentially coherent theories in case the response variable is explored at level 1(0) or first difference 1(1).

Data source

The data for this study were obtained from the World Bank Indicator (WDI) database from 1990 to 2021. CO_2 represents carbon dioxide emission (metric tons per capita), EI defines energy imports, net (% of energy use), ET represents energy intensity level of primary energy (MJ/\$2017 PPP GDP), and EPCR is the electricity production from renewable sources, excluding hydroelectric (% of total), EPCNR denotes electricity production from coal sources (% of total). In addition, we presented the selected variables' description, source, time period, and expected sign in Table 2.

Unit root tests

The main objective of the unit root test is to differentiate the selected response and explanatory variables to be stationary at the level or first difference. All the selected variables were

joined at the standard unit order of 1(0) and 1(1) illustrating that is uniform with the sufficiency of the ARDL bounds estimation is specifically best fitted for our study. Further, all the selected variable connections were examined before utilizing the ARDL bounds model (Dickey and Fuller 1979; Phillips and Perron 1988) utilizing the following equation.

$$\sum_{i=1}^{r} \beta_1 \Delta CO2_{t-1} + \sum_{i=1}^{r} \beta_2 \Delta EI_{t-1} + \sum_{i=1}^{r} \beta_3 \Delta ET_{t-1} + \sum_{i=1}^{r} \beta_4 \Delta EPR_{t-1} + \sum_{i=1}^{r} \beta_5 \Delta EPNR_{t-1} + \mu_t$$

(2)

where CO_2 defines carbon emissions, EI represents energy imports, ET describes energy intensity, EPCR is the electricity production from renewable sources, and EPCNR represents electricity production from non-renewable sources respectively. Δ represents the variation in the response variable. Time is represented by t, and ε represents the error term. In addition, β_1, β_2, β_3, β_4, and β_5 are the coefficients of the explanatory variables. Finally, μ_t is the error term.

Co-integration tests

To examine the long-run association between CO_2 emissions, energy intensity, energy imports, and energy generation from

Table 2 Variable definitions

Variable	Description	Source	Period	Expected sign
CO_2	CO_2 emissions (metric tons per capita)	WDI	1990–2021	_____
EI	Energy imports, net (% of energy use)	WDI	1990–2021	Positive
ET	The energy intensity level of primary energy (MJ/\$2017 PPP GDP)	WDI	1990–2021	Negative
EPR	Electricity production from renewable sources, excluding hydroelectric (% of total)	WDI	1990–2021	Negative
EPNR	Electricity production from coal sources (% of total)	WDI	1990–2021	Positive

renewable and non-renewable energy sources, we employ the Johansen co-integration tests introduced by Johansen and Juselius (1990) for all the selected variables. In addition, to confirm the co-integration among the study variables, we used the Johansen co-integration technique of the three different estimations such as (1) the unit root test proposed by Pedroni (1999) and Pedroni (2004), an advanced estimation that is distinguished as the Padroni co-integration method; (2) another co-integration method developed by Kao (1999), the Kao co-integration technique; (3) an error correction based co-integration method, which is an appropriate estimation in the co-integration evaluation Westerlund (2007).

$$\Delta CO2_t = \alpha + \sum_{i=1}^{p_1} \alpha_{1i} \Delta CO2_{t-1} + \sum_{i=1}^{p_2} \alpha_{2i} \Delta EI_{t-1} + \sum_{i=1}^{p_3} \alpha_{3i} ET_{t-i}$$
$$+ \sum_{i=1}^{p_4} \alpha_{4i} EPR_{t-1} + \sum_{i=1}^{p_5} \alpha_{5i} EPNR_{t-1} + \varepsilon_{1t} \quad (3)$$

where CO_2 defines carbon dioxide emissions, EI represents energy imports, ET describes energy intensity, EPR denotes electricity production from renewable sources, and EPNR represents electricity production from non-renewable sources respectively. Δ represents the variation in the response variable. Time is represented by t, and ε represents the error term.

Granger causality tests

To explore the Granger causality association, this paper employs the Granger causality tests taking CO_2 emissions, energy imports (EI), energy intensity (ET), electricity production from renewable sources (EPR), and electricity production from non-renewable energy (EPNR).

$$\Delta CO2_t = \varphi_1 + \sum_{i=1}^{p} \varphi_{11i} \Delta EI_{t-1} + \sum_{i=1}^{p} \varphi_{12i} \Delta ET_{t-1} + \sum_{i=1}^{p} \varphi_{13i} EPR_{t-i}$$
$$+ \sum_{i=1}^{p} \varphi_{14i} EPNR_{t-1} + \tau_1 ECT_{t-1} \quad (4)$$

where CO_2 defines carbon dioxide emissions, EI represents energy imports, ET describes energy intensity, EPR denotes electricity production from renewable sources, and EPNR represents electricity production from non-renewable sources respectively. Δ represents the variation in the response variable. Time is represented by t, and ε represents the error term.

Autoregressive distributed lag model

The ARDL technique was first proposed by Pesaran et al. (1999) and Pesaran et al. (2001). It is important to understand that the ARDL method has numerous advantages, in contrast to other co-integration methods. Further, the ARDL co-integration method can be employed with a lag

length of response and explanatory variables, whereas the other co-integration techniques require identical lag lengths (Engle and Granger 1987; Johansen and Juselius 1990). Additionally, ARDL co-integration method can use in the case of data series stationarity level of 1(0) or 1(1). The present study designs the following ARDL equations:

$$\Delta CO2_t = \alpha_0 + \sum_{i=1}^{r} \sigma_1 \Delta CO2_{t-i} + \sum_{i=1}^{r} \sigma_2 \Delta EI_{t-i} + \sum_{i=1}^{r} \sigma_3 ET_{t-i}$$
$$+ \sum_{i=1}^{r} \sigma_4 EPR_{t-i} + \sum_{i=1}^{p} \sigma_5 \Delta EPNR_{t-i} + u_t \quad (5)$$

In the above equation, $\sigma_1 to \sigma_5$ represents the long-run variance of explanatory variables. CO_2 is carbon dioxide emission, EI is energy imports, ET represents energy intensity, EPR denotes energy production from renewable sources, and EPNR is electricity production from non-renewable sources. The Akaike information criteria (AIC) were employed to examine the appropriate lag length. Moreover, for the ARDL short-run model, the following ECM model was adopted.

$$\Delta CO2_t = \alpha_0 + \sum_{i=1}^{r} \beta_1 \Delta CO2_{t-i} + \sum_{i=1}^{r} \beta_2 \Delta EI_{t-i} + \sum_{i=1}^{r} \beta_3 ET_{t-i}$$
$$+ \sum_{i=1}^{r} \beta_4 EPR_{t-i} + \sum_{i=1}^{p} \beta_5 \Delta EPNR_{t-i} + \emptyset ECT_{t-i} + u_t \quad (6)$$

Based on the above equation, β represents the short-run coefficients of the study variables. The ECT defines the short-run variance that estimates the variation acceleration from fluctuations. In addition, the term ranges of standard error correction if from -1 to 0.

The output of the descriptive summary are presented in Table 3. The mean value of CO_2 emissions is reported at 1.22, and the standard deviation is 0.02. The energy import mean value is 11.85, and the standard deviation is 0.26. The energy intensity mean value is 0.72, while the standard deviation is 0.05. The mean value of EPNR means the value is reported as 1.86, and its standard deviation is 0.05. In last, the mean value of EPR is 0.28, while the value of the standard deviation is 0.51. The Jerque-Bera statistic shows the data is equally distributed. The total number of observations in this study accounted for 33.

Moreover, the output of the correlation matrix are presented in Table 3. A positive correlation was found between CO_2 emissions, energy imports, and electricity generation from non-renewable energy sources, indicating that energy imports and non-renewable energy sources adversely affect CO_2 emissions in Australia. In contrast, a negative and significant correlation was found between CO_2 emissions, energy intensity, and renewable energy sources, indicating that lower energy intensity and consumption of electricity from renewable energy sources play a crucial role in abating CO_2 emissions.

Table 3 The output of summary statistics correlation matrix

Statistics	LCO_2	LEI	LET	LEPNR	LEPR
Mean	1.221	11.85	0.728	1.864	0.281
Median	1.215	11.87	0.742	1.887	0.390
Max	1.267	12.19	0.789	1.924	0.921
Min	1.182	11.49	0.633	1.786	−0.386
Std. Dev	0.029	0.269	0.054	0.051	0.513
Skewness	0.113	−0.060	−0.579	−0.445	−0.008
Kurtosis	1.373	1.297	1.784	1.492	1.351
J-B	3.707	4.007	3.879	4.217	3.737
Prob	0.156	0.134	0.143	0.121	0.154
Obs	33	33	33	33	33
LCO_2	1.000				
LEI	−0.105	1.000			
	0.559	——			
LET	0.416	−0.899	1.000		
	0.015	0.000	——		
LEPNR	0.463	−0.893	0.965	1.000	
	0.006	0.000	0.000	——	
LEPR	−−0.163	0.977	−0.945	−0.926	1.000
	0.364	0.000	0.000	0.000	——

CO2MT is carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, and EPR represents electric power generation from renewable energy

Results and discussions

The output of the unit root test are tabulated in Table 4. To verify whether the time series is stationary or not by employing the unit root test which has a substantial effect on the empirical outcomes of time series when utilizing approximation parameters and econometric techniques, we believe that if their time series has no unit root function, consequently, the data fall or rise in the long-run across a fixed observation. It indicates that the time-series value of the constant does not affect over time. On the other hand, in the stochastic approach, the likelihood function of non-stationary time series has state-dependent characteristics. Particularly, the effects of exogenous shocks in the long-term on the study variables do not regress over time to the central position of equilibrium as well as to the condition of random walk. For instance, the econometric method induces prediction pseudo-regression straightforwardly or partially employing non-stationarity time-series; therefore, the data's validity and reliability need to be verified. Moreover, the unit root technique is developed to examine the study variables stationery which is the basics of numerous critical statistical approaches and theories.

The results of the Zivot-Andrews structure unit-root test with a single break year are presented in Table 5. The present study examines all the variables' stationarity at both level and first difference by using the Zivot-Andrews structural unit root test. The variables are verified by adding the following factors such as intercept, trend and interest, and single trend at the level and first difference. At the intercept level, the CO_2 emission structural break year was 2008 (energy imports), 2006 (energy intensity), 2010 (electricity generation from renewable sources), 2008, and (electricity generation from non-renewable energy) 2003. As it can be seen from Table 6, CO_2 emissions, energy imports, energy intensity, electricity generation from renewable energy, and electricity generation from non-renewable energy are stationary at the first difference, indicating that the overall series has an identical integration order of significance (1). Over the past decade, Australia has implemented several energy policies, such as energy efficiency, an adaptation of renewable energy sources, and energy security over the selected sample period. Moreover, the structure break unit-root method showed non-linearity in the data series. Thus, after examining structural breaks and evaluating the integration order, estimations were overseen to choose the optimal lag order for further estimations.

The presence of long-term connections among the study variables is validated through Johansen co-integration method presented in Table 6. The purpose of employing the co-integration test is to examine the different levels of co-integration among the study variables as well as provide more robust and precise results. Therefore, the Westerlund

Table 4 The output of unit root tests

Variable	ADF		PP		KPSS	
	Level	1st difference	Level	1st difference	Level	1st difference
CO_2	−0.749	−3.666***	−1.220	−3.765***	0.202	0.384*
LEI	−0.807	−4.360***	−0.827	−4.360***	0.614	0.148***
LET	0.948	−5.258***	0.608	−5.370***	0.608	0.298**
LEPNR	0.005	−5.148***	−0.128	−5.164***	0.569	0.225*
LEPR	−0.237	−4.301***	−0.355	−4.368***	0.624	0.163***

CO2MT is the carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, EPR represents electric power generation from renewable energy. Note: *, **, *** represent 10%, 5%, 1% respectively

Table 5 The output of Z-A structural break unit root test

	Variables	Level	BDS	1st difference	BDS	Integration
	LCO_2	−2.815	2008	−5.534***	2013	1(1)
	LEI	−4.452	2016	−5.511***	2012	1(1)
Intercept	LET	−3.860	2010	−8.104***	2018	1(1)
	LEPNR	−4.205	2008	−6.983***	2013	1(1)
	LEPR	−4.175	2003	−5.463***	2014	1(1)
	LCO_2	−5.638	2007	−5.952***	2008	1(1)
	LEI	−4.059	2016	−5.345**	2002	1(1)
Trend and intercept	LET	−4.609	2006	−8.151***	2010	1(0)
	LEPNR	−5.588	2003	−6.885***	2013	1(1)
	LEPR	−2.870	2016	−6.410***	2003	1(1)
	LCO_2	−5.626	2008	−5.404***	2014	1(1)
	LEI	−2.627	2016	−4.945***	2005	1(1)
Trend	LET	−5.063	2008	−7.791***	2016	1(1)
	LEPNR	−2.285	1996	−6.241***	2013	1(1)
	LEPR	−3.118	2014	−5.463***	2014	1(1)

CO2MT is the carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, and EPR represents electric power generation from renewable energy. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Note: *, **, *** represent 10%, 5%, and 1% respectively

Table 6 The output of the co-integration test

F-bounds test			Null hypothesis: no levels of relationship	
Test statistic	Value	Signif	I(0)	I(1)
			Asymptotic: $n = 1000$	
F-statistic	5.185	10%	2.45	3.52
k	4	5%	2.86	4.01
		2.50%	3.25	4.49
		1%	3.74	5.06
Actual sample size	29		Finite sample: $n = 35$	
		10%	2.696	3.898
		5%	3.276	4.63
		1%	4.59	6.368
			Finite sample: $n = 30$	
		10%	2.752	3.994
		5%	3.354	4.774
		1%	4.768	6.67

co-integration test allows large N (number of observations) and T (number of time periods) to investigate the co-integration association among CO_2 emissions, energy imports (EI), energy intensity (EI), electricity generation from renewable sources, and electricity generation from non-renewable sources over the period 1990 to 2020.

The results of the ARDL model are tabulated in Table 7. The coefficient regression between CO_2 emissions and conventional energy imports is positive and significant at a 5% level of significance; a 1% increase in energy imports will lead to CO_2 emissions by 0.11%. The coefficient regression

of energy intensity and CO_2 emissions is negative and significant at a 5% level of significance, indicating a 1% increase in energy intensity will help to mitigate CO_2 emissions by −0.92%. These findings are in line with the most latest study proposed by Liu, Khan et al. (2022a, b, c, d, e, f) On the other hand, a 1% increase in non-renewable energy sources will raise the level of CO_2 emissions by 0.45% at a 5% level of significance. A negative and significant relationship is found between electricity generation from renewable energy sources at a 5% level of significance, indicating that a 1% increase in electricity generation from renewable energy sources will decrease CO_2 emissions by −0.15%. The value of the constant is reported at −1.72 indicating that the ARDL model is best fitted for analysis.

The results of the Granger causality test are tabulated in Table 8. A one-way casual connection running from energy imports to CO_2 emissions indicates that the imports of conventional energy such as oil, gas, and coal increase the level of CO_2 emissions in Australia. In contrast, there is no causal linkage running from CO_2 emissions to conventional energy imports. Furthermore, a two-way causal association was found between energy intensity and CO_2 emissions, indicating that lower energy intensity will abate CO_2 emissions, while higher energy intensity will raise the level of CO_2 emissions in Australia. Similarly, a two-way causality runs from electricity production from non-renewable sources (i.e., coal, oil, natural gas) EPNR to CO_2 emission and from electricity production from renewable sources (i.e., solar, wind, hydroelectric) EPR to CO_2 emissions. These findings are in line with the latest study proposed by Khan et al. (2022a, b, c, d, e, f).

Table 7 The output of the ARDL model

Variable	Coefficient	Std. error	t-statistic	Prob.*
$\Delta \ln EI_t$	−0.006	0.029	−0.231	0.822
$\Delta \ln LEI_{t-1}$	0.116	0.055	2.089	0.066
ΔLET_t	0.491	0.270	1.816	0.102
ΔLET_{t-1}	−0.920	0.322	−2.859	0.018
$\Delta LEPNR_t$	0.099	0.158	0.628	0.545
$\Delta LEPNR_{t-1}$	0.451	0.227	1.985	0.078
$\Delta LEPR_t$	−0.155	0.056	−2.765	0.021
$\Delta LEPR_{t-1}$	−0.070	0.023	−3.034	0.014
Constant	−1.724	0.741	−2.327	0.044
R-squared	0.98			
Adjusted R-squared	0.96			
S.E. of regression	0.005			
Schwarz criterion	−6.570			
Akaike info criterion	−7.513			
F-statistic	45.86			
Prob(F-statistic)	0.000			
Durbin-Watson stat	2.741			

CO2MT is the carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, and EPR represents electric power generation from renewable energy

The results of diagnostic tests are reported in Table 9. The outcomes indicate that there is no issue of serial correlation between CO_2 emissions, LEI, LET, LEPNR, and LEPR; the value of the Breusch-Godfrey Serial Correlation LM test reported 1.61, while the probability is 0.232, respectively. The Breusch-Pagan-Godfrey F-statistics value is reported at 0.368, and the probability value is 0.963. In addition, to verify no heteroscedasticity issue, we run that the Ramasy F-statistics (2.743) probability value is (0.117), the Harvey F-statistics value is (0.938), the probability value is (0.538), the Glejsar F-statistics value is (0.945), while the probability value is (0.897), the ARCH F-statistics value is (0.458),

Table 8 The output of the Granger casualty test

Null hypothesis:	Observations	F-statistic	Prob	Causality
LEI→LCO$_2$	31	4.946	0.015	One-way
LCO$_2$≠LEI		1.843	0.178	
LET↔LCO$_2$	31	3.536	0.043	Two-way
LCO$_2$↔LET		2.682	0.087	
LEPNR↔LCO$_2$	31	5.958	0.007	Two-way
LCO$_2$↔LEPNR		3.097	0.062	
LEPR↔LCO$_2$	31	4.166	0.026	Two-way
LCO$_2$↔LEPR		3.310	0.052	

CO2MT is the carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, and EPR represents electric power generation from renewable energy

and the probability value is (0.503). Lastly, the CUSUM and CUSUM squares confirmed the stability of the model in Fig. 6.

The outcomes of robustness tests are presented in Table 10. We employ fully modified (OLS), dynamic (OLS), and canonical cointegrating regression (CCR) regression estimations. The outcomes from the three methods validated that energy intensity has a positive and significant connection with CO_2 emissions, and energy productivity has a negative and significant linkage with CO_2 emissions, indicating that energy efficiency can play a substantial role in abating CO_2 emissions in Australia. The relationship between natural resource rents and CO_2 emission is positive and significant, suggesting that the extensive use of natural resources will increase the level of CO_2 emissions. Finally, renewable energy is negatively associated with CO_2 emissions which means the adaptation of renewable energies will consequently decrease the level of environmental pollution. Moreover, these results are persistent and robust with the obtained outcomes of the ARDL model.

Conclusions and policy recommendations

Due to the severity of climate change, it is essential to explore conventional and non-conventional energy consumption, conventional energy imports, energy intensity, and CO_2 emissions from 1990 to 2021 by employing time-series data for Australia. The present study adopted more robust econometric methods which were used to investigate the study variables' connection; all the selected variables were integrated with first difference 1(1) and showed long-term co-integration association among variables. We used the Zivot-Andrews structural break unit root test to examine the break year of all the variables at both level 1(0) and first difference 1(1) with three different steps (i.e., intercept, trend, intercept, and trend). The ARDL model was adopted to explore the elastic effects of the predictors on the dependent variable, and from the findings,

Table 9 The output of diagnostic tests

Diagnostic tests	F-statistics	Probability
Breusch-Godfrey Serial Correlation LM Test:	1.610	0.232
Breusch-Pagan-Godfrey	0.368	0.963
Ramsey	2.743	0.117
Harvey	0.938	0.538
Glejsar	0.495	0.897
ARCH	0.458	0.503
CUSUM	Stable	
SUSUM2	Stable	
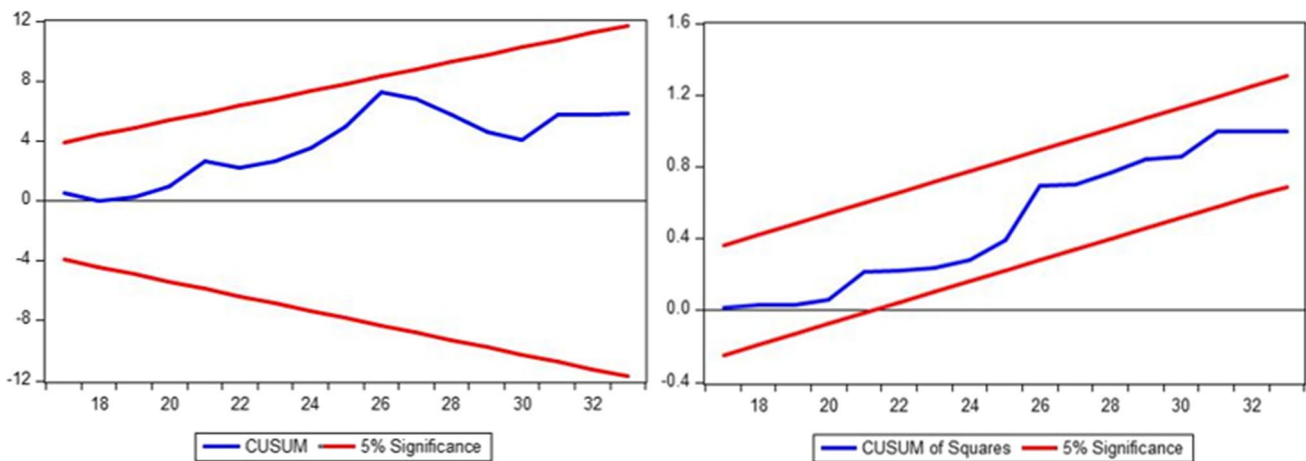
Fig. 6 CUSUM and CUSUM squares

Table 10 The output of robustness tests

Variable	FMOLS		DOLS		CCR	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
LEI	0.002*	0.097	0.066*	1.406	0.003*	0.064
LET	−0.627***	−5.188	−0.818**	−2.685	−0.430*	−1.555
LEPNR	0.921***	8.569	2.196***	8.107	1.142***	4.793
LEPR	−0.140***	−7.720	−0.059**	−1.875	−0.139***	−3.660
C	−1.023***	−2.897	−3.093***	−4.061	−1.307**	−1.846
R-squared	0.79		0.96		0.76	
Adjusted R-squared	0.76		0.92		0.72	

CO2MT is the carbon emissions metric per ton, EI represents energy imports, ET is energy intensity, EPNR is electric power generation from non-renewable energy, and EPR represents electric power generation from renewable energy. Note: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

energy imports and energy utilization from conventional sources significantly deteriorate environmental quality and sustainability in Australia. Additionally, dependence on non-renewable energy imports and utilization will consequently adversely affect environmental quality. However, lower energy intensity and energy generation from renewable sources improved environmental quality. Based on the causality test, we found a one-way causal linkage between energy imports and CO_2 emissions, indicating that energy imports will increase the level of CO_2 emissions. A two-way Granger causality runs from CO_2 emissions to energy intensity, renewable, and non-renewable electricity generation.

Moreover, the findings revealed a negative and significant connection between lower energy intensity and environmental pollution in Australia. This suggests that the adaptation of lower energy intensity supports Australia's transition to a decarbonized economy by mitigating the effusions of CO_2 emissions. Energy intensity is described as a measure of the energy inefficiency of an economy. It is estimated as units of energy per unit of GDP. In addition, a higher energy intensity shows a higher cost of converting energy into GDP, while a lower energy intensity indicates a lower cost of converting into GDP. For governments and policy-makers, energy generation from renewable sources should be adopted to the respective energy mixes of the country to assist its marginal rate of green energy utilization. Increasing the level of green energy consumption will likely reduce the country's dependency on fossil fuels. Furthermore, boosting energy generation from renewable sources is an effective and inevitable strategy that could enhance environmental quality in Australia. Additionally, decreasing conventional energy imports by implementing duties and tariffs can also assist to improve environmental sustainability in Australia. In line with the findings of Sarkodie and Strezov (2018) found that dependence on energy imports will resultantly increase the level of CO_2 emissions.

Moreover, some substantial policy implications can be designed from the empirical outcomes. The study suggests that energy intensity is consistently a significant element to fulfill

fundamental needs and achieve sustainable development objectives. The most interesting finding in the present study is that low energy intensity plays an important role in decarbonization in Australia. In this respect, the study by Danish and Khan (2020) found that higher energy intensity contributes to pollution in the USA. Innovation in environmentally friendly technology helps to decline to decarbonize the energy sector and energy intensity and hence decreases CO_2 emissions. Therefore, governments and policy-makers should encourage innovation to enhance environmental quality and energy efficiency. In addition, the role of investment in energy generation from renewable sources such as solar, hydropower, and wind is inevitable. Thus, policy-makers must attract more green finance and capital to invest in clean and green energy sources. Given the significance of reducing conventional energy imports and lower energy intensity, considering those countries utilizing advanced and environmentally friendly technology can tackle environmental pollution. Moreover, it is important to take substantial measures weighing innovation in technology policy instruments including government subsidies, discouraging conventional energy imports, and promoting investment in clean and green energy.

The present study has the following limitations that can help researchers to fill this gap in future studies. First, due to the lack of data, the time period estimation had to be restricted from 1990 to 2020. Similarly, the lack of data also limited our motivation for control and instrumental variables. In addition, this study can also be extended by evaluating the asymmetric effects of negative and positive shocks to energy imports, energy intensity, and energy generation from renewable and non-renewable sources on CO_2 emissions in Australia. Further, the causal connection between the study variables can also be inspected. Additionally, for more consolidated and inclusive policy designing purposes, the environmental effects of various kinds of renewable energy such as wind, hydro, solar, and energy efficiency can be further investigated in the case of Australia.

Data availability The datasets analyzed for this study can be found in the World Bank Database; here is the website reference https://databank.worldbank.org/reports.aspx?source=world-development-indicators

Declarations

Ethics approval We acknowledged that this paper has not been published elsewhere and is not under consideration by another journal. Ethical approval and informed consent do not apply to this study.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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