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Research paper

Energy policy simulation in times of crisis: Revisiting the impact of renewable and non-renewable energy production on environmental quality in Germany

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ABSTRACT

In this paper, we examine for the first time in the literature the implications of energy policy alternatives for Germany considering the aftermath of coronavirus as well as Electricity and Gas energy supply shortages. Whilst several policy options are open to the government, the choice of investment in renewable energy generation versus disinvestment in non-renewable energy such as coal energy generation provides divergent impacts in the long term. We utilize data from British Petroleum and the World Bank Development Indicator database for Germany covering 1981 to 2020 to explore a Carbon function by applying a battery of Autoregressive distributed lag model (ARDL), dynamic ARDL and Kernel-Based Regularized Least squares approaches. The particular policy tested is the pledge by Germany to decrease emissions by ∼100% in 2050, and this was integrated through the estimation of dynamic ARDL estimation. The simulation result shows that a +61% shock in renewable energy production decreases carbon emissions unlike coal energy production which increases carbon emissions in the beginning but the carbon emissions decrease thereafter. The findings highlight the inevitability of cutting down on coal production, and recommends energy investment alternatives. Hence, Germany's energy policy should contemplate more thoroughly on these factors.

1. Introduction

Energy is an indispensable production factor that contributes to the economic development and welfare of nations. Yet, the energy also conveys negative aspects in terms of sustainability by creating deteriorations in the environment, water, and air, which is the main suspect for global warming. International initiatives force the countries to take action to control the negative impacts of global warming levels below 2 °C degrees and if the emission levels keep their pace in line with historical levels, global warming will reach 1.5 °C above the pre-industrial levels between 2030 and 2052 (IPCC, 2018, 4). These deteriorations necessitated the shift towards renewable energy to mitigate harmful pollution effects (Madaleno et al., 2022; Taskin et al., 2022) of non-renewable energy consumption.

Hydro, wind, solar, biomass and geothermal, which are renewable energy sources are required for controlling air pollution and climate change, as they are considered as having minimal levels of carbon emissions (Sohag et al., 2019). The production of renewable energy sources is associated with increased sustainable economic development, given the fact that these sources encompass fewer externalities in their production. Following the Kyoto Protocol and Paris Agreement, COP 26 in Glasgow directed strict requirements to phase out carbon emissions and eliminate coal consumption to reach to zero-carbon target.

The lockdown measures as a result of COVID-19 brought about improvements in environmental quality and gas emissions, yet, the reductions were smaller and temporary for some regions since the measures were not compelled for extended periods (Ram et al., 2022). Moreover, the lockdown measures and restrictions on international travel caused air transportation to

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Abbreviations: ARDL, Autoregressive distributed lag model; IPCC, Intergovernmental Panel on Climate Change; COP 26, Conference of Paris 26 Summit; IEA, International Energy Agency; EKC, Environmental Kuznets Curve; GDP, Gross Domestic Product; CO2, Carbon Emissions; SAARC, South Asian Association for Regional Cooperation; BRICS, Brazil, Russia, India, China, and South Africa; ASEAN, Association of Southeast Asian Nations; AIR, Air transport; COP, Coal Production; RNW, Renewable Energy production; ADF, Augmented Dickey-Fuller; PP, Philip Perron

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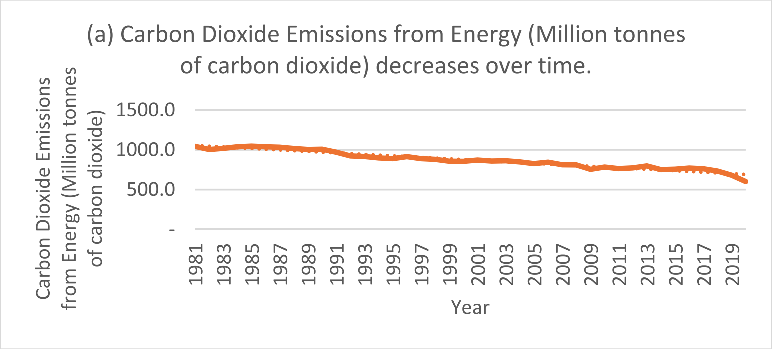
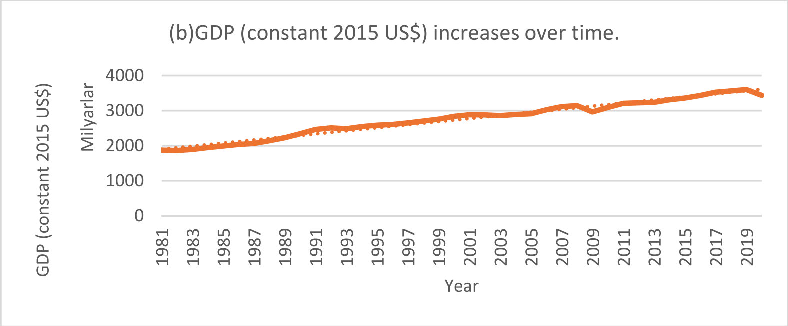




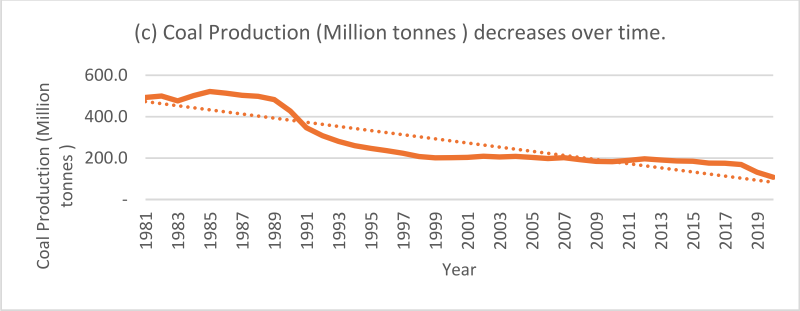


Fig. 1. The trend of carbon emissions, economic growth and dirty energy production in Germany over 40 years (1981–2020).

shrink. Aviation is one of the industries that are dependent on oil (Kandaramath et al., 2015). On the other hand, the allocation of public funds to the health industry during the pandemic caused investments in renewable energy technologies to shrink. Tiwari et al. (2022) noted the hit on the energy sector by the COVID-19 pandemic and Hosseini (2020) remarked on the confrontation faced by the renewable energy sector from the pandemic that is decelerating the developments in the sector.

Albeit the shrinkage of the investments during the pandemic, energy security issues provide a converse action related to renewable investments given the increased tensions between Ukraine and Russia. Russia recently uses energy supplies as leverage against Europe, which necessitates immense actions to shift to renewable energy issues for European countries (Mišík, 2022). Russia then interrupted its supplies of natural gas to Germany (Reuters, 2021). These chaotic developments are expected to increase the shift to renewable energy, which is also proclaimed by German authorities in March 2022 as full decarbonization of the electricity sector by 2035.

The last four decades witnessed the shift from a clear dominance of coal and oil in Germany's energy structure to a diversified system. Germany defines itself as one of the pioneer countries to tackle environmental issues and emission reduction, yet it is struggling to meet its near-term targets, in large part due to uneven progress across sectors, with notable challenges in transport and heating. Germany introduced its energy plan with the term "Energiewende" which combines the words energy and transformation requiring a phase-out of coal and nuclear energy and making renewable energy the centre of energy policy (Telli et al., 2021). Germany announced aims to reduce greenhouse gas emissions by at least 40% by 2020 70% by 2040 and 80%–95% by 2050, suggesting that the country anticipates being mostly GHG-neutral.

Despite, the clear explanations related to energy policy implications, Germany is still struggling to accomplish the climate goals and it is not very likely to meet short-term emission targets. The phase-out policy on coal has progressed and displays a significant reduction as of 2019, as can be followed in Fig. 1 Panel (a). Followed by the reduction in coal production, emissions decline but are aligned to the rate of decrease in coal production. Fig. 1 Panel (b) displays that the evolution of carbon dioxide emissions from energy in Germany is descending over time, yet this trend is not a prospective of net zero. The growth in electricity generation from renewables has lowered emissions, but the nuclear phase-out as well as higher electricity exports have offset some of the emissions benefits (IEA, 2020).

Fig. 1 presents the trend of the data demonstrating a mix of the downward trend of emissions, the upward trend of economic growth in Germany as well as a downward historical trend of coal production with fluctuations in certain periods, and a potential for a rising trend in light of recent global events such as the COVID19 pandemic, BREXIT as well as the war in Ukraine

Germany stands as the largest economy in Europe and the fourth largest in the world, continuing its phase (Fig. 1 Panel (c)). The strong economy, followed by broad financial savings, makes Germany an inevitable leader in terms of energy transition and carbon emissions mitigation in Europe and the world. Despite the irreplaceable position of Germany in energy policy adaptation to fight climate change and environmental degradation, the improvements in emissions are short of Germany's 2030 target of at least a 65% reduction below 1990 levels. As of 14 December 2020, Germany's ruling coalition arranged alterations to its energy law to form the legal basis for enduring the enlargement of renewable energy in the energy mix in the long term and ensure the goal of producing 65% of its electricity from clean sources from 2030.

Alongside all these motivations, Germany embraces a rich economic record in the air transport industry with unique characteristics. The aviation industry in Germany generated over 40 billion euros in 2019, quadrupling the size compared to the 1990s. Germany has many airports and offers various aviation services, which makes it one of the leading countries in Europe. Thus, the transportation industry benefits the German economy a great deal, yet transportation is the largest consumer of petroleum products and 20% of the total emissions belong to this sector (Haasz et al., 2018). Given the indispensable dependence on air transport for non-renewable energy, Germany has a tough choice between emissions and economic growth.

This paper aims to investigate the role of possible energy policy alternatives for Germany on carbon emission reductions by taking the choice of investment in renewable energy generation versus disinvestment in non-renewable energy into consideration. To fulfil this aim, the paper examines economic growth, renewable energy, non-renewable energy production and air transport as determinants of carbon dioxide emissions. The paper contributes to the literature in three ways. First, this paper examines Germany, which is considered one of the leading countries in terms of energy policies to reduce emissions and shift to renewable energy from non-renewable energy sources. Second, the world is at the edge of two significant events which have contradictory impacts on emissions, namely the COVID-19 pandemic, and Russia's tendency to limit natural gas supply to European countries. Thus, this paper evaluates the two sides of the coin and the possible impacts of each policy. Consequently, the paper proposes the outcomes of alternative scenarios for different policy adaptations for policymakers. Third, the paper adopts Kernel-based regularized least squares, which is a novel machine-learning methodology to evaluate and establish causal relationships among the variables. The paper proceeds as follows: The Second section presents the literature review, the third section introduces the data, model, and methods, the fourth section summarizes the results and discussion, the fifth section provides energy policy simulations and the last section concludes.

2. Literature review

Energy consumption has increased by many folds since the beginning of the twentieth century. The prior literature discussed the impact of energy consumption, energy production and energy policies on environmental degradation from various perspectives. Various analytical approaches are used to study these relationships. One familiar approach to studying economic growth and environmental degradation is Environmental Kuznets Curve (EKC) hypothesis. This theory states that environmental degradation initially fosters the prosperity of nations until a certain point, and after that point, it eventually decreases despite of further rise in prosperity. So, the EKC hypothesis articulates a certain association between economic growth and environmental quality (Pérez-Suárez and López-Menéndez, 2015; Arouri et al., 2012). Another group of researchers examined the association between economic growth, energy consumption and pollution emissions (Kraft and Kraft, 1978; Omri, 2013; Arouri et al., 2012; Magazzino et al., 2021; Mele et al., 2021; Kasman and Duman, 2015).

The findings of these studies differ based on institutional variations between countries, several model specifications and estimation methods used for data analysis. Another group of researchers examined the relationship between renewable energy consumption and economic growth (Sadorsky, 2012; Brady and Magazzino, 2018; Magazzino, 2017; Tugcu et al., 2012; Apergis et al., 2018). The other empirical literature investigated the influence of both renewable and non-renewable energy consumption on environmental degradation (Bélaïd and Ben Youssef, 2017). With the advancement of rapid development in renewable energy across various countries, another group of researchers examined how renewable energy consumption influences the quality of the environment at the global, regional and local levels. The study by Menyah and Wolde-Rufael (2010) examined the causality association between CO_2 emissions, nuclear energy, and renewable energy. Their finding underpins the theory that the production of non-renewable energy adversely influences the environment. They also found unidirectional causality between CO_2 emissions and renewable energy consumption. In the study of Shafiei and Salim (2014), the relationship between CO_2 emissions and renewable and non-renewable energy consumption has examined stochastic impacts by utilizing regression on Population, Affluence, and Technology model (STIPRAT model). The finding supports the theory that non-renewable energy enhances CO_2 emissions whereas renewable energy consumption decreases CO_2 emissions. This finding suggests that policymakers should focus on developing policies that promote renewable energy technologies.

Similarly, Bekhet and Othman (2018) found that renewable energy adversely influences CO_2 emissions in long run in Malaysia. The study by Mongo et al. (2021) implied that environmental innovations are inclined to reduce CO_2 emissions. Ricci (2007) contends that inefficient techniques used in making environmental policies and regulations restrict production possibilities for economies and adversely affect economic growth during the long term. Magazzino and Falcone (2022) opine that increase in CO_2 emissions is one of the main factors that increased global warming and climate change.

Energy use, energy policies and environmental degradation

The empirical literature provides mixed results on energy consumption usage and environmental degradation. Ang (2007) analysed the relationship between energy use, pollution emissions and economic growth in France. He found a unidirectional causality relationship between energy use and economic growth during the short run. Apergis and Payne (2011) examined the role of CO_2 emissions and energy consumption for six Central American nations by extending the work of Ang (2007). They found a unidirectional causality relationship between energy consumption and real GDP to CO_2 emissions discharge during the short run whereas found bidirectional causality during the long run. One group of researchers finds a positive relationship between CO_2 emissions and energy consumption (Apergis and Payne, 2011; Ang, 2007; Shahbaz et al., 2012; Ahmed and Shimada, 2019).

Shahbaz et al. (2012) observed a significant relationship between CO_2 emissions and energy consumption along with financial development and trade openness for Pakistan in the presence of EKC. They argue that energy consumption boosts

CO_2 emissions in both the short run and long run. Ahmed and Shimada (2019) also signified a cointegration association between economic growth and energy consumption in Pakistan. Akhmat et al. (2014) analysed the relationship between energy consumption and ecological pollutants in SAARC countries. They observed energy consumption is the main driver of ecological pollutants in SAARC economies except for Nepal where CO_2 emissions and energy consumption has a bidirectional causal relationship with one another. Loganathan et al. (2014) found an inverted U-shaped relationship between economic growth and CO_2 emission in Malaysia.

Mutingi et al. (2017) presented a taxonomic analysis of system dynamic approaches to energy policy modelling and simulation. They argued that system behaviour is affected by various dynamic uncertainties, time lags, nonlinear relationships between system variables, and interactive feedback loops that are inherited in the energy system due to the complex structure of the energy system. They provided a causal loop analysis of the generic structures of the identified energy formulation problems. Irfan and Shaw (2017) and Ali et al. (2017) contend that CO2 is positively associated with non-renewable energy sources whereas it is inversely related to renewable energy sources in the case of South Asian economies. Kisswani (2017) argued that energy consumption and GDP have a nonlinear relationship in the case of ASEAN countries. Liu et al. (2017) depicted renewable energy sources are inversely related to CO2 emissions whereas non-renewable energy is positively associated with CO2 emissions in the case of BRICS. Mbarek et al. (2018) found a bidirectional causality relationship between energy consumption and CO2 emissions in Tunisia. Shahbaz et al. (2018) explored that energy consumption is positively associated with CO2 emissions.

Arminen and Menegaki (2019) found bidirectional causality between energy use and economic growth. However, the study does not find any evidence of the existence of an environmental Kuznets curve in their study. Khan et al. (2019) used the data for China and found that an inverse relationship exists between CO2 omissions and environmental regulation. Moreover, they suggested China could reduce CO2 emissions through technological innovations. Munir and Riaz (2019) examined the data from South Asia and depicted that increase in the use of coal, gas, electricity, and oil fosters CO2 omissions. Rafindadi and Usman (2019) used data from South Africa and found the existence of unidirectional causality between energy consumption and environmental degradation. Toumi and Toumi (2019) observed the presence of a non-linear association between renewable energy and CO2 emissions while examining the data from Saudi Arabia. Malik et al. (2020) examined the data from Pakistan and showed that an inverse relationship exists between oil prices and CO2 omissions in long run. Munir and Riaz (2020) studied data from China, Australia and USA and found a non-linear relationship between energy use and environmental degradation. Ozcan et al. (2020) argued that an increase in energy consumption significantly contributes to environmental degradation in the case of 35 OECD economies. Raggad (2020) confirmed the existence of asymmetric cointegration between energy use and CO2 emissions in the case of Saudi Arabia. Muhammad et al. (2021) contend that an increase in FDI increases environmental degradation in the case of BRICS economies where as in the case of developed economies it reduces environmental degradation. They further argued that non-renewable and renewable energy sources lessen environmental degradation in the case of BRICS, global, developed and developing economies.

Filimonova et al. (2021) analysed the impact assessment of economic, environmental and institutional factors on the future consumption of renewable energy sources. Their findings confirmed that CO_2 emissions have an adverse effect on renewable energy sources. They also found a negative relationship between non-renewable energy resources and renewable energy sources. They further argued the increase in prices of non-renewable energy sources fosters the growth of renewable energy sources. Musibau et al. (2021) observed that increase in energy consumption reduces environmental quality in the case of Nigeria. Chang et al. (2022) examined the impact of renewable energy (wind energy) on the ecological footprint of European countries by applying Quantile on Quantile estimation technique. They observed that wind energy is a vital source to reduce the ecological footprint in selected countries. Therefore, policymakers should pay attention to spreading awareness about wind energy so that environmental sustainability can be achieved. Magazzino et al. (2022) observed that the usage of renewable energy has increased in Scandinavian countries. The empirical analysis found that renewable energy consumption is an effective technique to reduce CO_2 emissions.

Munir (2022) argued that there exists a positive relationship between coal, electricity and oil usage and CO2 emissions in long run in the case of European countries. As the usage of coal, oil, gas and electricity increases, it increases CO2 emissions. Likewise, when there is a decrease in the usage of coal, gas, electricity and oil, it reduces CO2 emissions. They suggested that new and efficient technologies should be developed to control environmental degradation. They further argued that traditional energy resources should be replaced with renewable energy sources to reduce CO2 emissions. Fareed and Pata (2022) investigated how renewable and non-renewable energy consumption affects economic growth in the top ten energy-consuming countries. They observed that in eight out of ten countries, non-renewable energy sources foster economic growth in the long run. However, renewable energy sources are positively associated with economic growth in France, the United Kingdom and Brazil only. They also observed that the energy-led growth hypothesis is valid in India, the United States, Spain and the United Kingdom for both renewable and non-renewable energy. However, the non-renewable energy-led growth hypothesis is valid for Italy only. They argued renewable energy is vital for economic growth but not as important as non-renewable energy.

In light of the above discussion, it can be concluded that both renewable energy consumption and non-renewable energy consumption are important sources to enhance economic growth. Renewable energy reduces carbon emissions and lowers environmental degradation. However, non-renewable energy consumption increases carbon emissions and causes environmental degradation.

The prior literature has examined the impact of renewable and non-renewable energy consumption on economic growth, CO2 emissions, ecological footprint, environmental degradation, population etc. The prior literature mostly focused on European countries. This is the first-ever study to investigate the role of possible energy policy alternatives for Germany on carbon emission reductions by taking the choice of investment in renewable energy generation versus disinvestment in non-renewable energy into consideration. Because Germany is considered one of the leading countries in terms of energy policies to reduce carbon emissions and shift to renewable energy from non-renewable energy sources. The previous literature used methodologies like causality analysis, ARDL, Asymmetric ARDL etc. While this study adopts Kernel-based regularized least squares, which is a novel methodology named machine learning to establish and evaluate causal relations among the variables.

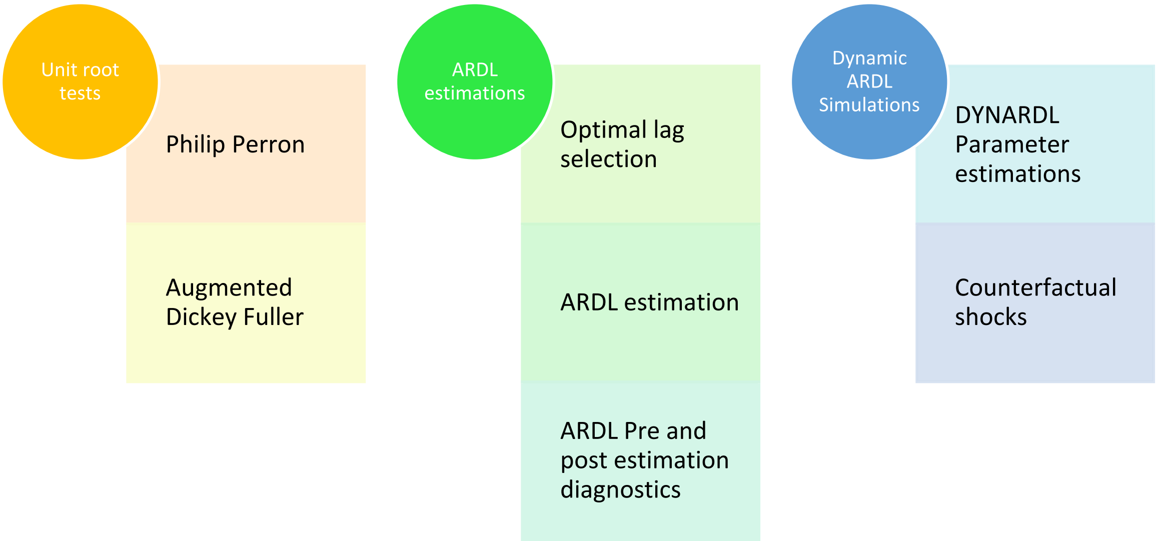


Fig. 2. Empirical scheme.

3. Data, model and methods

This study utilizes data on Carbon Emissions (CO_2), Real Gross Domestic Product (RGDP), Air transport (AIR), Coal Production (COP), and Renewable Energy production (RNW)for Germany covering a 40year period from 1981 to 2020. CO_2, COP and RNW data is collected from British Petroleum and RGDP, AIR data is retrieved from the World Bank Database. This data is applied to a carbon function as presented in Eq. (1), and its corresponding log-transformed expression is presented in Eq. (2). The use and inclusion of the variables utilized in these studies follow a significant body of literature on emissions and energy consumption (Adedoyin et al., 2021).

$$CO2_t = \beta_0 + \beta_1 RGDP_t + \beta_2 AIR_t + \beta_3 COP_t + \beta_4 RNW_t + \varepsilon_t \tag{1}$$

$$LCO2_t = \beta_0 + \beta_1 LRGDP_t + \beta_2 LAIR_t + \beta_3 LCOP_t + \beta_4 LRNW_t + \varepsilon_t \tag{2}$$

A dynamic simulation model is estimated in this paper as shown in the empirical scheme presented in Fig. 2 following Sarkodie and Owusu (2020) and Adedoyin et al. (2021). The empirical technique adopted is the autoregressive distributed lag model (ARDL) which first requires some pre-estimation checks to be carried out such as the unit root tests on the variables to ensure that stationarity aligns with the requirements, and this is followed by choosing the optimal lag as well as other post estimation diagnostics. The validity of the model was confirmed by the post-estimation diagnostics as well as the reliability of the estimates in making policy presentations and in interpreting the implications of the research findings. These diagnostics included in this study are the Pesaran, Shin, and Smith bounds testing; the LM test developed by Breusch–Godfrey for autocorrelation; the Cameron and Trivedi's decomposition of IM-test; as well as the tests of Skewness/Kurtosis for normality.

The dynamic ARDL simulation model derived from Eq. (2) is expressed as follows:

$$\begin{aligned} LCO2_t = {} & \beta_0 LCO2_{t-2} + \beta_1 LRGDP_t + \beta_2 LRGDP_{t-2} + \beta_3 LAIR_t \\ & + \beta_4 LAIR_{t-2} + \beta_5 LCOP_t + \\ & \beta_6 LCOP_{t-2} + \beta_7 LRNW_t + \beta_8 LRNW_{t-2} + \varepsilon_t \end{aligned} \tag{3}$$

In terms of process and relevance to the study, the Dynamic Autoregressive Distributed Lag (ARDL) simulation is a complex econometric method used to analyse the long-run relationships between variables and their short-term dynamics. It combines the strengths of both autoregressive (AR) and distributed lag (DL) models and is used in a wide range of fields, including macroeconomics, finance, and engineering. The first step in conducting a dynamic ARDL simulation is to define the model as presented in Eq. (3). This involves specifying the variables to be included in the model, the lag structure, and the functional form. It is important to have a clear understanding of the economic relationships being modelled and the relevant data sources. Additionally, the cleaning of data, dealing with missing values, and transforming the data if necessary is carried out. As shown in the data discussion, the data used in this study is in a time-series format and have enough observations to support the model.

The next step is to estimate the ARDL model using econometric software, such as Stata in the case of this study. The estimation process involves estimating the coefficients ($\beta_0 \ldots \beta_8$) of the model and testing for their significance. The model should be estimated using a suitable estimation method, such as maximum likelihood or Generalized Method of Moments. After estimating the model, the next step is to select the best ARDL model. This involves comparing the results of different models and choosing the one that best fits the data. The choice of model is based on criteria such as goodness of fit, stability, and parsimony. The next step is to conduct model diagnostics. This includes checking the residuals for normality and independence, checking for autocorrelation and heteroscedasticity, and testing for structural breaks. The results of the model diagnostics should be used to modify the model if necessary.

For the dynamic simulation, once the ARDL model has been selected and the model diagnostics have been completed, the next step is to conduct the dynamic simulation. This involves simulating the model for different values of the exogenous variables and calculating the dynamic response of the endogenous variables. It is vital to accurately interpret the results of the simulation. This involves analysing the dynamic relationships between the variables, understanding the short-term and long-term effects of changes in the exogenous variables, and making inferences about the underlying economic relationships.

4. Results and discussion

The estimation analysis commenced with preliminary examinations of the dataset by displaying descriptive statistics for demonstrating the spread of the dataset as shown in Fig. 3. The

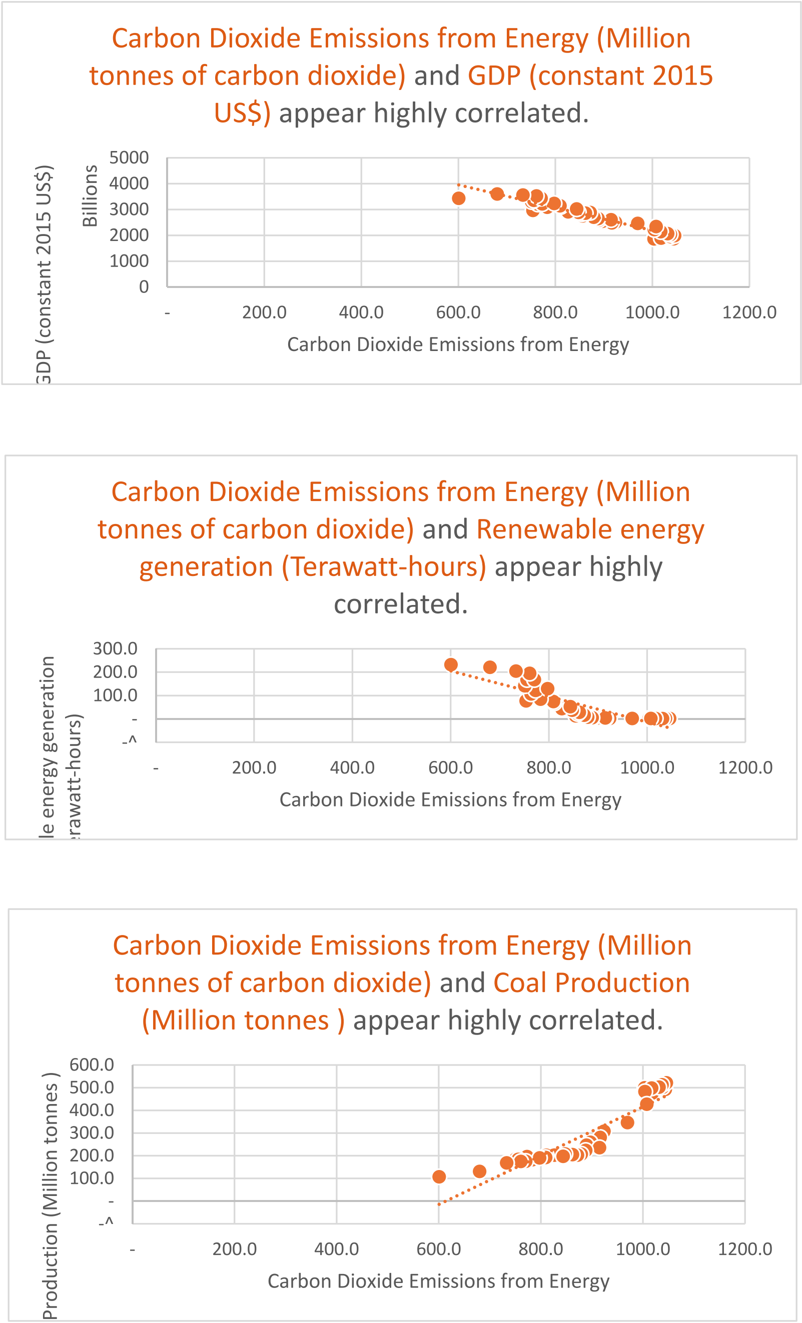


Fig. 3. Trend of variables.

figure visualizes the positive association of CO_2 with COP and the negative relationship with RDGP and RNW. Moreover, the figure dictates a non-monotonous relationship between CO_2 -RNW and CO_2-COP.

The descriptive statistics of our variables employed in this research are reported in Table 1. As shown, the mean value of CO_2 is 6.762 which is between 6.398 and 6.952 with a standard deviation of 0.131. The standard deviation for carbon emission is quite dispersed around the mean. This implies that there is resilient variation in the dataset. The mean average of real GDP per capita is 28.625 with a dispersion of 0.197 and falls between 28.253 and 28.912 suggesting that original data and its mean are less dispersed. On average, the passengers transported during the study period are around 17 ranging between maximum and minimum values of 18 and 16 respectively and a variability score of 0.798 demonstrating less variation from its mean. In the same line, on average, the mean of coal production is 5.529 with a variability score of 0.434 and ranging between the minimum and maximum values of 4.676, and 6.256 respectively. Finally, during the study period, the average value of renewable energy production is 2.693 and ranges between 0.370 and 5.446 with an average score of 1.913.

Additionally, correlations of the series also were investigated to test any potential connections between CO_2 emission and real GDP per capita, coal production, Air transport and renewable energy production. Table 2 presents the correlations matrix. As shown in the table, among the independent variables, coal production shows the highest correlation with the emission of CO_2 which is consistent with the theory. The correlation demonstrates that there is a negative relationship between CO_2 emission and real GDP per capita, air transport and renewable energy production.

Table 1
Descriptive statistics.

Variable	Unit of measurement	Obs.	Mean	Std. Dev.	Min	Max
CO2 emission	Carbon emission (kt)	40	6.762	0.131	6.398	6.952
Real GDP per capita	GDP (constant 2015 US$)	40	28.625	0.197	28.253	28.912
Air transport	Passengers carried	40	17.667	0.798	16.361	18.579
Coal production	Million tones	40	5.529	0.434	4.676	6.256
Renewable energy production	% of total final energy consumption	40	2.693	1.913	0.370	5.446

Table 2
Correlations.

	LCO2	LRGDP	LAIR	LCOP	LRNW
LCO2	1				
LRGDP	-0.9295^{*} 0.000	1			
LAIR	-0.7920^{*} 0.000	0.9249^{*} 0.000	1		
LCOP	0.9430^{*} 0.000	-0.9499^{*} 0.000	-0.8574^{*} 0.000	1	
LRNW	-0.9293^{*} 0.000	0.9279^{*} 0.000	0.8927^{*} 0.000	-0.8766^{*} 0.000	1

Table 3
Stationary test.

Variable	Level. PP	Δ. PP	Level. ADF	Δ. ADF
LCO2	1.180	-4.898^{***}	1.256	-4.733^{***}
LRGDP	−2.085	-4.327^{***}	−1.940	-4.501^{***}
LAIR	−1.547	-3.432^{***}	−1.520	-3.410^{**}
LCOP	−0.145	-2.987^{**}	0.332	-3.010^{**}
LRNW	0.385	-3.475^{***}	0.883	-3.554^{***}

Level. PP is the level of the PP unit root, Δ. PP is the first-difference value; Level. ADF level of ADF, Δ. ADF is the first difference; $*\ **$, $**$, $*$ significance at 10%, 5%, and 1% respectively. Legend: CO2 represents Carbon emissions; RGDP represents Real GDP per capita; RNW represents renewable energy generation; AIR represent Air Transport; COP represent Coal Energy Production.

Table 4
ARDL (1,0,0,1,0,1) regression.

Variables	(1)	(2)
ECT	-0.710^{***} (0.141)	-0.249^{**} (0.119)
Long-Run		
L. LRGDP	0.191^{***} (0.0150)	0.374^{***} (0.0777)
L.LAIR	0.0366^{**} (0.0177)	-0.234^{**} (0.0882)
L.LCOP	0.151^{***} (0.0304)	0.0330 (0.124)
L.LRNW	-0.0676^{***} (0.00679)	
Short-Run		
Δ LRGDP	0.136^{***} (0.0304)	0.0930^{**} (0.0401)
Δ LAIR	0.0259^{**} (0.0122)	0.0659^{***} (0.0196)
Δ LCOP	0.269^{***} (0.0644)	0.247^{***} (0.0714)
Lagged Δ LCOP	0.274^{***} (0.0811)	0.153^{*} (0.0876)
Δ LRNW	-0.0480^{***} (0.00846)	
Lagged Δ LCO2		-0.425^{***} (0.149)
Observations	38	38
R-squared	0.767	0.767

Standard errors are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$ represents statistical significance at 1%, 5% and 10% respectively. Legend: CO2 represents Carbon emissions; RGDP represents Real GDP per capita; RNW represents renewable energy generation; AIR represent Air Transport; COP represent Coal Energy Production.

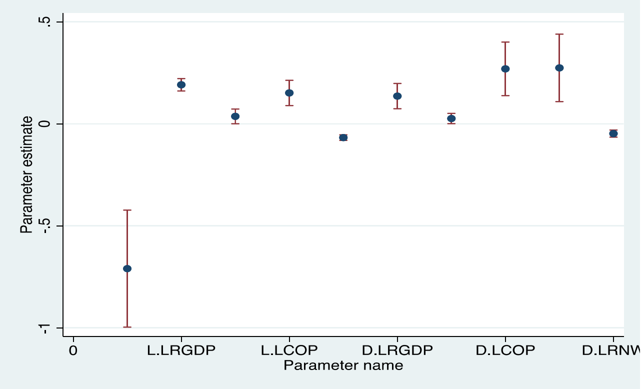


Fig. 4. The ARDL parameter estimates. Notes: blue (●) is the estimate in a log–log model, olive teal long-dash 3-dots is the reference line, and red-spike denotes the upper 95% and lower 95% confidence limit. Legend: CO2 refers to s carbon emissions; RGDP refers to real GDP per capita, COP represents coal production; RNW represents renewable energy production. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3 reports the outcomes of the unit root tests based on the Augmented Dickey–Fuller (ADF) and Philip Perron (PP). As shown in the table, all variables employed in this research are not stationary at their levels since the critical values are higher than their absolute t-values. But, at the first difference of both tests (PP&ADF) the non-stationarity null hypothesis is rejected which indicates that the data is stationary at integrated order one or I(1). Thus, the finding fulfils the ARDL bound test criterion. In addition, to estimate the ARDL model the number of optimal lags should be determined. Fig. 4 shows the generating parameters based on the lag ARDL (1,0,0,1,0,1) and the empirical findings are displayed in Table 4.

4.1. Results of ARDL estimation

Table 4 reports the empirical outcomes based on ARDL estimation where the short-run and long-run estimations include two models. Model (1) represents the full model; including both renewable and coal production, where Model (2) represents the model excluding renewable energy. As shown in Table 4, in Model (1) all variables, namely, real GDP per capita, coal production, air transport and renewable energy produce statically significant determinants of carbon emission in both the short-run and long-run. For example, carbon dioxide is negatively related to renewable energy variables. Results suggest that a one percentage point increase in renewable energy, on average, causes the CO_2 emissions to diminish by 0.0676 in the long run. However, RGDP, air transport and coal production impact carbon emissions positively which is consistent with the theory. In Model (2) by excluding renewable energy from the original model, the results indicate that all variables, namely, real GDP per capita, air transport and coal production are statically significant in the short run. But, in the long-run, only air transport and RGDP (passengers carried) are found to impact significantly the carbon emission whereas coal production is not significant in the long run. Moreover, it can be seen that in both models, the value

Table 5
Diagnostics tests.

a. Pesaran, Shin, and Smith bounds testing

	K	10%		5%		1%		*p-value*	
		I (0)	I (1)	I (0)	I (1)	I (0)	I (1)	I (0)	I (1)
F	7.633	2.08	3.297	2.567	3.947	3.741	5.485	0.000	0.001
t	−5.049	−1.612	−3.247	−1.972	−3.653	−2.691	−4.467	0.000	0.003

I (0) is the lower bound critical value; I(1) is the upper bound critical value; ** indicate the significance of KS critical values at the 0.01 significance level.

b. Breusch–Godfrey LM test

lags(p)	F	df.	Prob > F
1	1.905	(1, 34)	0.1766
2	1.194	(2, 33)	0.3158
3	0.809	(3, 32)	0.4984
4	0.608	(4, 31)	0.6602

H0: no serial correlation

Cameron & Trivedi's decomposition of IM-test.

Source	chi2	df.	*p-value*
Heteroskedasticity	11.81	14	0.6212
Skewness	1.48	4	0.8303
Kurtosis	0.98	1	0.3221
Total	14.27	19	0.7675

d. Skewness/Kurtosis tests

Variable	Obs.	Pr. (skewness)	Pr. (kurtosis)	Joint adj. $\text{chi}^2(2)$	Prob > chi2
Residuals	39	0.9704	0.6996	0.15	0.9276

of R-square (0.767) is the same. This suggests that 76.7% of the variability in carbon dioxide can be explained by the independent variables.

Several diagnostic tests were performed in this study as shown in Table 5. Using a bound test of Pesaran, Shin, and Smith (PSS) along with the critical value of Kripfganz & Schneider (KS), the long-run cointegration association with the coefficients of the short-run was computed. As reported in Table 5a the absolute value of t is (−5.049) and the value of the F-statistic of the independent variables (short-run coefficients) is (7.633) that is higher than I(1), the upper bound at a different level of significance (5% & 10%). Furthermore, the results are validated since the p-value of KS is lower than (0.01) which means the null hypothesis of no-cointegration is rejected. This implies that the long-run cointegration relationship exists.

Additionally, to avoid serial correlation, heteroscedasticity, auto-correlation, structural break and violation of normality assumption several tests were computed as part of the dynamic autoregressive model assumption. For serial correlation, utilizing the Breusch–Godfrey LM test, it can be seen in Table 5, panel b that at a 5% significance level, the null hypothesis of no serial correlation is rejected among the variables and the lagged value (p-value is less than 0.05). Therefore, the estimated ARDL residuals (1,0,0,1,0,1) are freed from autocorrelation.

Furthermore, in this study, Cameron & Trivedi's decomposition of the IM-test was employed for checking whether the residuals are heteroscedastic in nature or not. Table 5, panel c reports the results of this test. White's test for homoskedasticity, with a null hypothesis (Ho) of homoskedasticity, is tested against an alternative hypothesis (Ha) of unrestricted heteroskedasticity. According to Table 5, panel c, we accept the null hypothesis (H0) at a 5% significance level because the p-value is greater than 5%. This implies that the residuals are not heteroscedastic.

Moreover, Table 5 panel displays the results of the skewness and kurtosis test that was performed for the normality assumption of residual independence. The outcome from this test demonstrates that within the mean, there is a normal distribution for our residuals. This is because, at a 5% significance level, H(0) is rejected suggesting that the residuals are normally distributed.

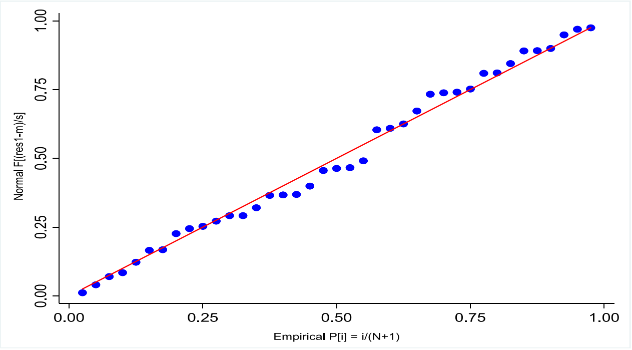


Fig. 5. Standardized normal probability plot.

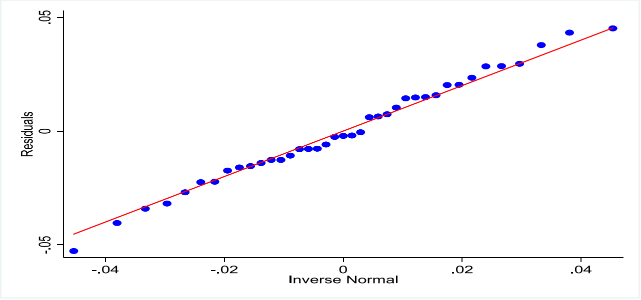


Fig. 6. Quantiles of residuals against quantiles of normal distribution.

4.2. Regression of ARDL: Post-estimation diagnostics

To shed additional light on the normality assumption, Fig. 5 demonstrates the standardized normal probability plot and Fig. 6 shows residual quantiles against normal distribution quantiles. Based on ARDL (1,0,0,1,0,1) the residuals are validated by both plots and they are normally distributed. Lastly, for the stability of parameters, we employed the cumulative sum test, potential

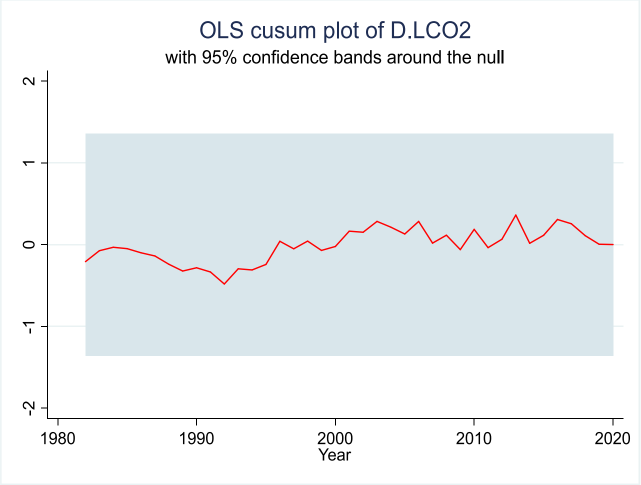


Fig. 7. Cumulative sum test.

structural breaks are examined and the findings are displayed in Fig. 7. The estimated coefficients stability is confirmed over time since the t-statistic is within a 95% confidence interval.

5. Simulation of energy policy

5.1. Simulations of dynamic ARDL

Following many papers in the literature (Sarkodie and Owusu, 2020; Shabbir et al., 2020), this paper adopts dynamic ARDL simulations to capture the impact of future shocks in renewable energy production and coal production. Table 6 reports the outcomes of the simulations considering the shocks to renewable energy production and coal production.

The results of the dynamic model that considers the shocks to renewable energy production suggest the statistically significantly diminishing impact of renewable energy on carbon dioxide emissions in the long-run.

This findings is consistent with the findings of (Adedoyin et al., 2021; Sharif et al., 2019a,b), that elaborated the negative relationship between renewable energy and carbon emission which will lead to an improvement in environmental conditions. The results contradict the findings of (Apergis et al., Azlina and Mustapha, 2012), who claimed that CO_2 emissions are not significantly reduced by renewable energy. Considering this finding and its leading position of Germany in terms of environmental issues, Germany must accelerate the deployment of renewable energy. Thus, the authorities should seek ways to promote renewable energy production through subsidies or penalties to increase this shift. Regarding other variables included in this model, coal production produces a statically significant coefficient in the short- and long-run but the air transport variable is significant only in the short run. Coal production remains to impact the carbon dioxide emissions even in the case of a shock to the renewable energy production. This result also clearly dictates the necessity to diminish coal (or non-renewable energy, in general) in the energy mix, which suggests the promotion of non-renewable energy producing firms and sectors. Furthermore, the policies should be directed at designing systems to inhibit coal production.

On the other side, results related to the dynamic model with shock to coal energy generation show that coal production does not produce significant results with CO_2 emission. This finding suggest that following a shock to the coal production will create insignificant impacts of coal on carbon dioxide emissions. This suggests that the policy changes of Germany related to coal production is likely to reach the aims related to carbon mitigation. Moreover, RGDP variable appears to be significant in the long run only, whereas air transport is found to have a positive significant impact in the short run. The significance of air transport is also crucial for Germany because of its high share in European and global traffic both in terms of air travellers and air freight.

Table 6
The dynamic ARDL model.

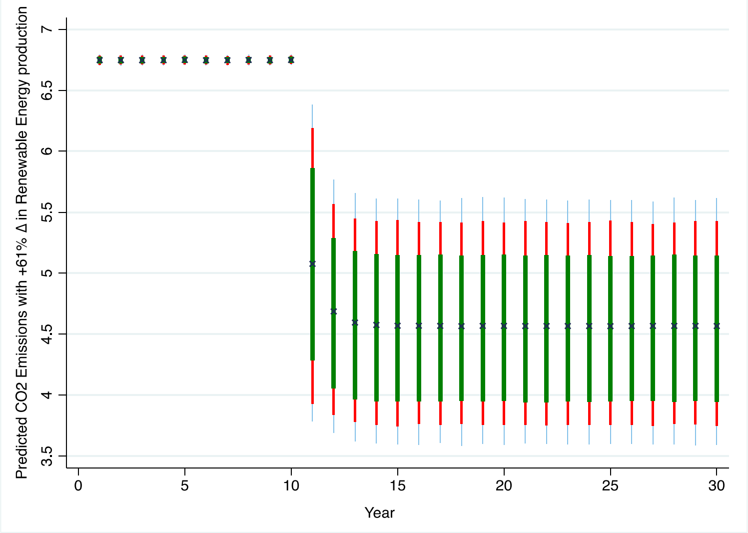
Variables	A dynamic model with shock to renewable energy generation ΔLCO2	The dynamic model with shock to coal energy generation ΔLCO2
$LCO2_{t-2}$	-0.774^{***}	-0.661^{***}
	-0.176	-0.208
$LRNW_{t-2}$	-0.0278^{**}	-0.0174
	-0.0107	-0.0118
$LRGDP_{t-2}$	-0.151	-0.361^{***}
	-0.114	-0.105
$LAIR_{t-2}$	0.0362	0.0511
	-0.0369	-0.042
$LCOP_{t-2}$	0.0963^{**}	0.0364
	-0.0468	-0.0625
Δ LRGDP	0.218	0.221
	-0.193	-0.228
Δ LAIR	0.0677^{***}	0.0862^{***}
	-0.0215	-0.0237
Δ LCOP	0.228^{***}	
	-0.0742	
Δ LRNW		-0.00898
		-0.0567
Δ LRNW		-0.00898
		-0.0567
Constant	8.438^{**}	13.74^{***}
	-3.397	-3.348
Observations	39	39
R-squared	0.687	0.589

Notes: Standard errors are in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$ represents statistical significance at 1%, 5% and 10% respectively. Legend: CO2 represents Carbon emissions; RGDP represents Real GDP per capita; RNW represents renewable energy generation; AIR represent Air Transport; COP represent Coal Energy Production.

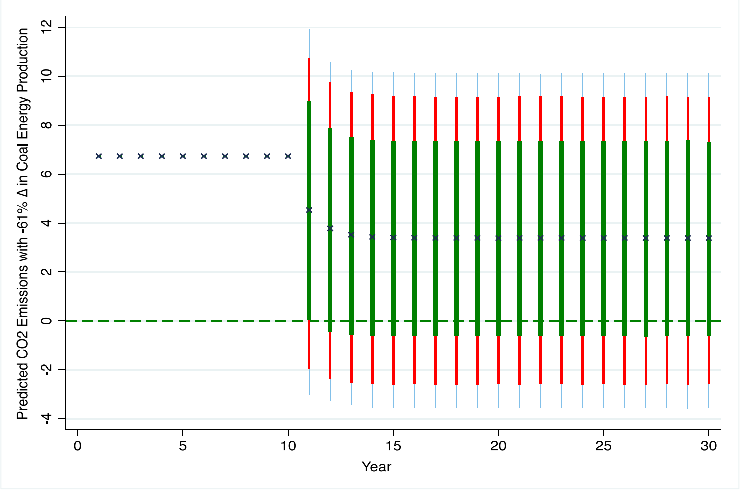
5.2. Policy shocks

To comprehend the energy policy options for Germany, policy simulations are carried out. The simulation checks are used to test for the impacts of reducing marginal returns of coal energy production and the production of renewable energy on carbon dioxide. The particular policy tested is the pledge by Germany to decrease emissions by ∼100% in 2050, and this was integrated through the estimation of dynARDL estimation. In particular, as of 2018, the goal was at 31% and considering that the period 2018 to 2050 is 32 years ($t = 32$), a boost of 69% is needed to arrive at the 2050 target of 100% renewable or non-greenhouse gas emissions.

The outcome of these policy shocks is demonstrated via the use of counterfactual shocks to the historical data. Particularly, counterfactual shock in forecasted renewable energy production refers to the deviation from the expected outcome of renewable energy production due to unexpected events or changes in the external environment or policy diagnostics. It is a phenomenon that has become increasingly relevant in recent years as the world shifts towards a greener energy mix and renewable energy sources become a more significant part of the energy mix. It is also vital to examine and shock this variable because renewable energy sources such as wind, solar, and hydro power have been growing in popularity as a cleaner and more sustainable alternative to traditional fossil fuels. They offer many benefits including lower emissions, greater energy security, and a reduction in the



Panel (a) Counterfactual shock in forecasted renewable energy production



Panel (b) Counterfactual shock in forecasted coal energy production

Fig. 8. Counterfactual shock in forecasted coal and renewable energy production.

dependence on foreign energy sources. However, the deployment of renewable energy sources is not without its challenges, and one of the most significant challenges is the unpredictability of renewable energy production.

Renewable energy sources are dependent on weather patterns and other environmental factors, which can cause fluctuations in energy production. For example, a sudden drop in wind speed can significantly reduce wind power generation, while a cloudy day can reduce solar power generation. These fluctuations can create uncertainty in the energy market and pose a challenge for energy planners who need to predict energy demand and supply. To mitigate these risks, energy planners often make use of forecasting models that predict the expected production of renewable energy sources based on historical data and current weather patterns. These forecasts are then used to inform energy market participants of the expected supply and demand dynamics, allowing them to make informed decisions.

However, these forecasts can be subject to counterfactual shocks that can significantly impact the expected outcome. For example, a natural disaster such as a hurricane can destroy wind turbines, reducing wind power generation and creating a supply shock or a major political investment and target as in the case of Germany which is expected to influence climate change outcomes and goals. A political crisis in a major oil-producing country can cause a sudden increase in oil prices, reducing the demand for renewable energy and creating a demand shock. These counterfactual shocks can have significant implications for the energy market and the transition to a greener energy mix. They can cause energy prices to fluctuate, disrupt the energy market, and reduce investment in renewable energy. They can also impact the overall energy mix, as energy planners may need to switch to non-renewable energy sources to meet energy demand.

To mitigate the impact of counterfactual shocks, energy planners need to have a robust contingency plan in place. This can include diversifying the energy mix to reduce dependence on a single energy source, investing in energy storage technologies to smooth out fluctuations in energy production, and developing flexible energy systems that can quickly respond to changes in energy demand and supply. Additionally, energy planners need to continuously monitor and update their forecasting models to account for changing weather patterns and other environmental factors that may impact renewable energy production. They also

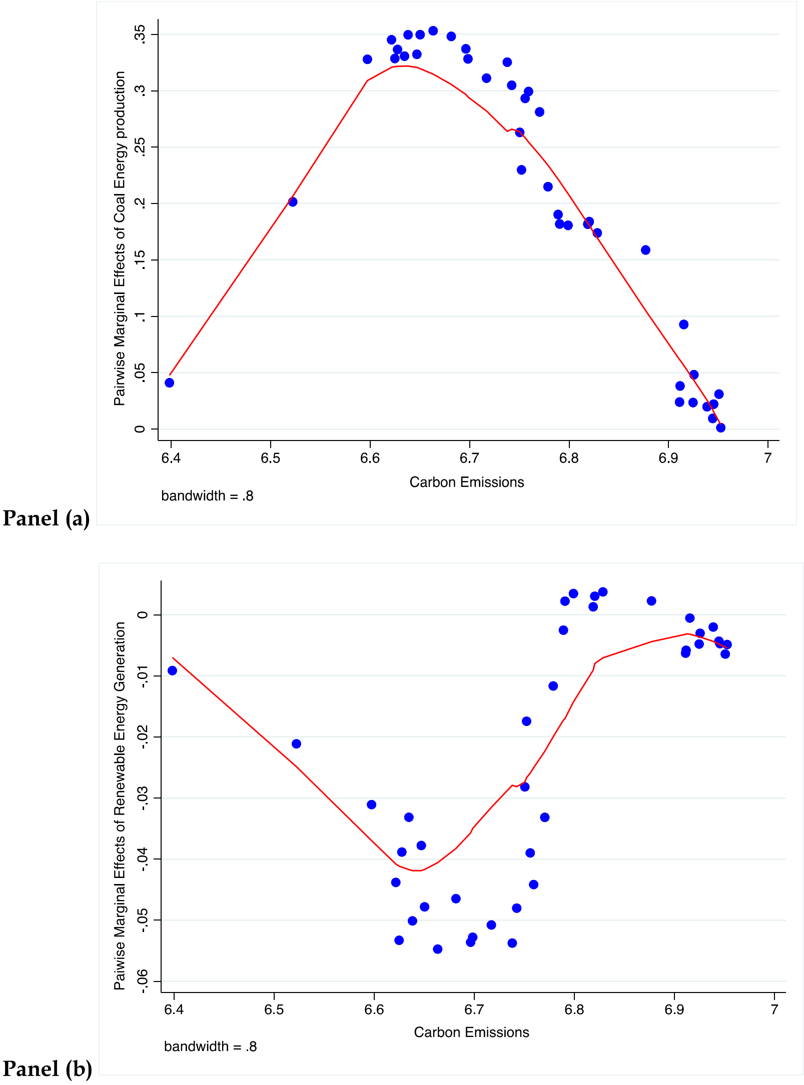


Fig. 9. Representation of pointwise marginal effect of renewable energy generation.

need to be transparent about their forecasting models and the assumptions used, allowing market participants to make informed decisions.

Panels a and b of Fig. 8 display the dynamic ARDL simulation. The simulation plot in panel a discloses that a +61% shock in renewable energy production decreases CO_2 emissions. In the same line, the simulation plot in panel b highlights that −61% shock in the coal production energy increases CO_2 emission in the beginning but the carbon emissions decrease thereafter. The findings highlight the inevitability of cutting down on coal production. Parallel to the findings of Osorio et al. (2020) coal capacity phase out risks missing the 2030 target. Considering the recent developments regarding the energy crisis related to the Ukraine–Russia tensions, Germany must promote other means of creating renewable energy production.

To confirm and support the evidence analysed in this research, a machine learning methodology was taken for testing and exploring the causal relationship between the dependent and independent variables of this study. By employing KRLS, pointwise derivatives were conducted to identify the causal-impact connection between the variables. As shown in Table 7, the value of the predictive power is 0.986, which means that the regressors explain 98.6% of the variation in carbon emissions. According to Table 7, the mean pairwise marginal effects of carbon emission, real GDP per capita, air transport, coal production and renewable energy are 0.007%, 0.025, 0.209 and −0.023 respectively., Only coal production and renewable energy are significant at a 1% significance level but real GDP per capita and air transport appear to be not insignificant. Thus, an empirical finding of a causal-impact connection is observed in two variables.

Table 7
Pointwise derivatives.

LCO2	Avg.	SE	t	P > t	P25	P50	P75
LRGDP	0.007	0.052	0.14	0.89	−0.033	−0.000	0.058
LAIR	0.025	0.012	2.046	0.048	0.004	0.024	0.041
LCOP	0.209	0.024	8.401	0.000	0.070	0.222	0.328
LRNW	−0.023	0.005	−4.488	0.000	−0.045	−0.019	−0.003
Diagnostics							
Lambda	0.054	Sigma	4	R^2	0.986	Obs.	40
Tolerance	0.04	Eff. Df.	9.749	Looloss	0.6203		

Avg. is the average marginal effect; SE is the standard error; P25, P50, and P75 represent the 25th, 50th, and 75th percentile. Legend: CO2 represents Carbon emissions; RGDP represents Real GDP per capita; RNW represents renewable energy generation; AIR represent Air Transport; COP represent Coal Energy Production.

Moreover, the long-term variation between coal energy production and renewable energy generation is examined. Panels a and b of Fig. 9 represent plots for the pointwise derivative of coal production and renewable energy against carbon dioxide and CO_2. From panel a, it can be seen the differing marginal effect of coal energy production on CO_2 emissions. The plot indicates that the carbon emissions increase as coal energy production increases only up to a point, after which it has an adverse impact on carbon emissions. In the same line, panel b highlights the varying marginal effect of renewable energy production on CO_2 emissions. The plot in panel b highlights that a higher level of renewable energy decreases the CO_2 emissions up to a certain level, the threshold point, where the impact of renewable energy production on the carbon CO_2 emission will be positive which means a U-shape.

Based on the evidence of the diminishing impact of renewable energy on long-run carbon emissions and the positive relationship between coal energy production and carbon emissions unearthed in this study, the German government should establish a policy that boosts investment in renewable energy production or reduce the dependency on coal energy production.

6. Conclusion and policy directions

This paper adopted a variety of approaches to give a clear understanding of the renewable energy production, coal production, economic growth, air transport and carbon emissions relationship for the period between 1982–2020 in the context of Germany. The paper investigates the energy policy alternatives faced by Germany with regards to renewable energy investments or disinvestments, or coal production and impacts on carbon dioxide emissions through investigation of short and long-term relationships by utilizing ARDL, dynARDL, and Kernel-Based Regularized Least squares (KRLS) to capture future counterfactual shocks. The results of both ARDL and dynARDL suggest a significant positive long-term relationship with coal production, air transportation, real GDP per capita and carbon dioxide emissions, and a negative relationship between renewable energy production and emissions. Short-term relationships are evident between air transport and real GDP per capita and carbon emissions. The findings are also in line with the studies of Swain and Karimu (2020), Peñasco et al. (2021), Sharif et al. (2019a,b) and Frondel et al. (2010).

The results reveal that despite the energy supply and energy security issues faced by Germany, shifting to coal consumption significantly has a deteriorating impact on reaching the environmental policy targets. Thus, it is inevitable for German authorities to allocate funding to renewable energy investments to reach the goals highlighted by Energiewende. Germany needs to expand its strategies and policies to expand renewable energy sources while cutting down coal production. The results emphasize that a 69% increase in renewable energy production is required to reach the zero-carbon target of Germany in 2050. Thus, it is apparent that even Germany might witness significant difficulties to reach this target. The results of the dynamic ARDL also suggest that reaching the net-zero target may not be possible. Moreover, given the significant impact of air transportation in all analyses, the adoption of renewable energy in this industry is unavoidable. Undeniably, the shift to renewable energy for air transportation is complicated. However, the emissions caused by factors other than aircraft can be eliminated effortlessly, by utilizing vehicles without significant externalities to the environment, such as environmentally friendly handling vehicles, or transportation to the airports through the use of renewable energy using mechanisms as suggested by Postorino and Mantecchini (2014). Presumably, the encouragement of renewable energy is a necessity not only for aviation but in other industries as well, which is a direction for further studies. Despite the scope of the analyses, it is clear that the aviation industry demands to seek ways to depend less on fossil energy to reach environmental targets. The expansion of emission trading mechanisms and improved support schemes for renewable energy should be obligatory to limit carbon emissions by deploying renewable energy in many industries. The energy policy of Germany should ensure economic growth by considering the necessity to invest more in renewable energy and disinvest in non-renewable sources.

CRediT authorship contribution statement

Festus Fatai Adedoyin: Conceptualization, Methodology, Software, Investigation, Visualization, Writing – review & editing, Writing – original draft. **Naila Erum:** Writing – review & editing, Writing – original draft. **Dilvin Taşkin:** Writing – original draft. **Daouia Chebab:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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