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Full Length Article

Dynamic influences of different energy sources, energy efficiency, technological innovation, population, and economic growth toward achieving net zero emissions in the United Kingdom

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A R T I C L E I N F O

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A B S T R A C T

This article analyzed the effect of various energy sources, energy efficiency, technological innovation, population size, and GDP on greenhouse gas (GHG) emissions in the United Kingdom. The annual data spanning from 1990 to 2021 is examined utilizing the Autoregressive Distributed Lag (ARDL) model. Results reveal that a 1 % rise in GDP, population, and fossil fuel consumption led to a 0.11 %, 0.16 %, and 0.60 % increase in GHG emissions in the short-run while 0.28 %, 0.23 %, and 0.74 % in the long-run. Besides, a 1 % improvement in renewable energy, nuclear power, energy efficiency, and technological innovation cut GHG emissions by 0.25 %, 0.13 %, 0.21 %, and 0.29 % in the short-term and 0.39 %, 0.28 %, 38 %, and 48 % in the long-run. The robustness analysis through the Fully Modified Ordinary Least Squares (FMOLS), Dynamic Ordinary Least Squares (DOLS), and Canonical Cointegrating Regression (CCR) demonstrates the consistency of the long-term effects obtained from the ARDL technique. The investigation provides novel insights essential for designing and implementing policies that advance the UK power industry's net-zero goals through cleaner energy, efficiency, and green technology investments.

1. Introduction

The pursuit of transitioning energy networks from ecologically harmful fossil fuels to efficient and more green power sources has resulted in an increased focus on altering the energy equilibrium in the natural environment (Omri & Saadaoui, 2023). The majority of the chemicals that humans emit into the atmosphere, which have the capacity to modify the climate and contribute to global warming, consist primarily of GHGs, with carbon dioxide (CO_2) as the dominant component (Wang et al., 2024a). Global environmental challenges, including

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the exacerbation of rising temperatures, are experiencing a deteriorating trend. The increase in GHG emissions is a significant environmental challenge now faced by the global community (Raihan & Bari, 2024). The utilization of less ecologically sound technologies and increased consumption of fossil fuels and GHG emissions are consequences of efforts to enhance industrial productivity (Bildirici et al., 2023; Laureti et al., 2023). The ongoing success in the advancement of particular countries and the corresponding rise in production levels are expected to result in an upsurge in GHG production, a trend that is unlikely to be curbed in the near future. Thus, the achievement of a carbon-free energy system and net zero emissions are widely regarded as imperative goals in order to adhere to the temperature thresholds outlined in international treaties and agreements (Raihan et al., 2023). Presently, this issue has emerged as the paramount global concern. Nevertheless, multiple works have illustrated an encouraging connection between the expansion of clean power sources and economic development (Bogdanov et al., 2021; Chen et al., 2022; Hdom, 2019; Hieu & Mai, 2023; Khan et al., 2024; Shahbaz et al., 2020). Nonetheless, it is ought to acknowledge that the shift regarding renewables is accompanied by an initial escalation in energy costs, necessitating the provision of suitable governmental assistance to households. If the government were to emphasize the favorable environmental and public health outcomes resulting from these changes, it would be advisable to endorse them, irrespective of economic considerations, economic growth, and associated expenses (Wang et al., 2024b).

Contemporary theories aimed at decoupling economic growth from emissions emphasize the potential for sustainable development through innovation, technology, and systemic change. One prominent approach is the concept of "green growth," which suggests that it is possible to gain monetary expansion while reducing ecological consequences, particularly through the implementation of sustainable innovation and green energy sources. Circular economy principles also play a crucial role, advocating for resource efficiency, waste reduction, and the recycling of materials to lower emissions associated with production and consumption. Another significant theory is ecological modernization, which posits that funds for sound technologies and environment-friendly approaches can lead to both economic competitiveness and environmental improvements. Additionally, the "degrowth" movement challenges traditional growth paradigms, arguing for a reevaluation of consumption patterns and a focus on well-being rather than GDP as the primary measure of progress. Collectively, these theories highlight the necessity of strategic interventions, investment in durable structures, and behavioral changes as key to achieving a decoupled correlation between GDP development and GHG emissions.

Over its history, the United Kingdom has caused around 3 % of worldwide anthropogenic pollution. In the year 2021, the United Kingdom's GHG emission was 427 million tons of CO_2 equivalents ($MtCO_2e$). In the year 2021, the transportation sector in the UK emerged as the top source of pollutants, holding more than 25 % of the total emissions. As a result, there was an increase in emissions from energy supply, marking the first occurrence of such an increase since 2012. This can be attributed to a combination of heightened demand and a decrease in renewable generation compared to the previous year, 2020. The usage of energy as a significant economic element is sometimes disregarded in debates pertaining to the natural world (Liu et al., 2023). The escalating prevalence of extreme weather events poses an increasingly significant challenge for both human populations and ecological systems, mostly attributable to the phenomenon of climate change (Wang et al., 2024c). The escalation of the human population and advancements in infrastructure collectively contribute to a heightened occurrence of devastating catastrophes, leading to annual financial losses. The reduction of pollution in recent times has been ascribed to advancements in technology, the establishment of patents, and the deployment of renewables (Raihan et al., 2022).

In 2019, the United Kingdom achieved the distinction of being the first large economy to enact legislation pertaining to net zero emissions. This law mandates the nation to effectively neutralize all GHG emissions by the year 2050. The United Kingdom's recently revised Nationally Determined Contribution (NDC), which was presented in 2020, outlines a commitment to attain a 68 % cut in GHG emissions by 2030. A key component of the new UK government's plan to completely decarbonize power by 2030 is its pledge to double onshore wind and quadruple offshore wind. Furthermore, to decarbonize the power sector, the UK makes investments in nuclear and renewable energy. Besides, the UK seeks to increase energy efficiency and lessen its need for imported fossil fuels. In addition, to get net zero emissions, the UK is also investigating new technologies. The Energy Act 2023 will revolutionize the energy sector in the UK by bolstering energy security, facilitating the attainment of net zero, and guaranteeing that household bills remain cheap over a sustained period.

The interplay between technical advancement, energy efficiency, and GHG emissions is a multifaceted and dynamic process. On one hand, technological innovation has driven significant improvements in energy efficiency, particularly in areas such as electricity generation, transportation, and manufacturing procedures. Advances in materials science, computing power, and sensor technology have enabled more enhanced utilization of assets, reduced power consumption, and decreased the carbon footprint of various industries. For instance, the increasing usage of green energies has significantly minimized the reliance on fossil fuels and subsequently decreased GHG emissions from power generation (Raihan & Tuspekova, 2022). In addition to energy efficiency, innovation in technology has also resulted in the progress of clean technologies that directly reduce GHG emissions. Examples include carbon capture and storage (CCS) systems, which grab CO_2 releases from power generation facilities and production processes, and hydrogen fuel cells, which can replace fossil fuels in transportation and industrial applications. Moreover, emerging technologies like electrification of transportation and energy storage systems are poised to further reduce GHG emissions by facilitating more efficient and sustainable energy sources. The advancement of modern innovations, such as artificial intelligence (AI) and the Internet of Things (IoT), has also created opportunities for smart energy management and optimized energy use, further contributing to achieving net zero emissions. However, the connection between technological innovation, power efficiency, and GHG pollution is not without challenges. While innovation has driven significant progress, the pace and scale of technological advancements are not always sufficient to keep pace with growing energy demands. Moreover, the deployment of new technologies and infrastructure can sometimes cause greater power consumption and GHG emissions, particularly if not done sustainably. Consequently, the association between technological innovation and GHG emissions needs to be examined to address the obstacles and complexities in attaining the UK's target of net zero emissions.

Although the UK is implementing several policies and strategies toward achieving its net zero emissions goal, there is a research gap in the existing literature investigating the influences of the key determining factors toward achieving the net zero emissions goal by the UK. This work utilized the aforementioned backdrop as a foundation for examining the key determinants that contributed to fluctuations in GHG emissions within the United Kingdom from 1990 to 2021. The key aim of this analysis is to scrutinize the implication of different energy resources, incorporating fossil fuels, alternative power, and nuclear energy, as well as energy efficiency, technological innovation, population, and GDP, on the rise in GHG emissions in the United Kingdom. The present investigation enhances the scope of previous empirical studies by running the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) context to incorporate three distinct pathways of atmospheric emissions. These pathways include the economic network, the population passage, and the technical setup trail. The underlying study hypothesis posits that there exists a positive connection between GHG emissions and variables such as GDP, population, and fossil fuel usage. Conversely, it suggests an inverse correlation of GHG emissions with renewable energy, nuclear power, energy efficiency, and technological innovation.

Achieving net-zero emissions in the United Kingdom requires a comprehensive understanding of the dynamic interactions between various energy sources, technological advancements, and socio-economic factors. Fossil fuels remain a significant contributor to GHG emissions, necessitating a transition towards renewable and nuclear energy as sustainable alternatives. Energy efficiency measures and technological innovation play a crucial role in optimizing energy consumption and reducing carbon footprints. Additionally, population growth and economic expansion directly influence energy demand and emissions levels, making it essential to assess their impact in the pursuit of environmental sustainability. This study is justified by the urgent need to develop data-driven policies that balance economic growth with emission reduction strategies. By examining these interrelated factors, the research provides valuable insights for policymakers, energy planners, and stakeholders, guiding the UK toward a cleaner, more resilient energy future while ensuring economic stability and social well-being.

This research makes a valuable contribution by addressing a hitherto overlooked area of sustainable environment in the UK, which is of pointed significance. The novelty of the study is that it is a pioneering work investigating the linkages between GHG emissions and its drivers in the UK. Although recent studies investigated the impacts of different energy sources on carbon and ecological footprint in the UK (Caglar, 2023; Jin et al., 2024; Usman & Radulescu, 2022; Wang et al., 2023; Özbek & Naimoğlu, 2025), this research further covers gaps in knowledge regarding the integral part that nuclear energy, renewable energy, energy efficiency, and technological innovation play in the UK's target of reaching net zero emissions. This study utilized a recent and extensive dataset, including a 32-year period from 1990 to 2021, to ensure a full analysis. Furthermore, this research work stands out due to its utilization of novel econometric procedures such as ARDL, DOLS, FMOLS, and CCR methods to confirm the validity of the outcomes. A more comprehensive understanding of the issue, together with the essential facts and evidence presented in this study's findings, will prove advantageous to citizens, academics, economists, and administrators alike. This study provides valuable insights into the dynamic influences of various energy sources, technological advancements, and socio-economic factors on the United Kingdom's path toward net-zero emissions. By analyzing the interplay between fossil fuels, renewable energy, nuclear energy, and energy efficiency, the research highlights the necessity of transitioning to cleaner energy sources while optimizing energy consumption. Moreover, although the previous studies investigated the environmental impacts of different energy sources in the UK (Eweade et al., 2023; Jin et al., 2024; Usman & Radulescu, 2022; Wang et al., 2023; Özbek & Naimoğlu, 2025), the present study underscores the role of technological innovation in enhancing energy efficiency and reducing emissions, emphasizing the need for continuous investment in research and development. Additionally, it examines the impact of population growth and economic expansion, revealing potential challenges and opportunities in achieving sustainability. By integrating these factors into a comprehensive framework, the study offers policy recommendations that can guide government actions and industrial strategies to accelerate the UK's decarbonization efforts. Ultimately, the findings contribute to a deeper understanding of the complex relationships driving emissions reduction, supporting evidence-based decision-making for a sustainable and carbon-neutral future.

The contents of the manuscript are organized as follows: The Introduction section is followed by Section 2 which demonstrates a summary of the literature on the nexus between economy, energy, technology, population, and environment, as well as the research gap in the context of the UK. The theoretical framework of the study, data collection, and description of the econometric methodologies used for this investigation are provided later in Section 3. Furthermore, Section 4 presents the empirical outcomes from experimental tests and an in-depth discussion of the results. Finally, Section 5 describes the conclusions of the study, theoretical implications, managerial contributions, limitations of the study, and future research directions.

2. Literature review

2.1. Nexus between economy, energy, technology, population, and environment

Mehmood et al. (2023) demonstrated the effects of GDP, cleaner energy, and technological progress on the efforts of Group of Seven (G7) nations to reduce CO_2 emissions between 1990 and 2020. The research conducted using the CS-ARDL model revealed a beneficial correlation between CO_2 outputs and both GDP and the use of renewables. The reduction in emissions has been facilitated by the simultaneous increase in GDP and the implementation of cleaner power systems. The implementation of green electricity generation is responsible for a decline in the level of the ecosystem. Murshed et al. (2022) studied the ecological implications accompanying the utilization of renewable and nuclear energies, as well as the influence of economic expansion and complications within the G7 nations from 1995 to 2016. Their conclusions observed that nuclear power intake demonstrates efficacy in lessening CO_2 emissions and reducing carbon footprints over an extended period. However, it is seen that renewable power utilization has destructive consequences on the biodiversity within the G7 nations. Moreover, it has been shown that the environment is adversely affected by economic expansion, as higher levels of economic growth are found to contribute to increased CO_2 emissions and carbon footprints. Li and Haneklaus (2022) determined the relationship across cleaner energy, GDP, urbanization, trade openness, and the emissions of CO_2 across the G7 nations for the period 1979 to 2019. The conclusions of the ARDL scrutiny indicate that sustainable energy, nuclear power, and urbanization have a mitigating effect on ecological degradation.

Abbasi et al. (2021) adopted the ARDL technique to explore the influences of power utilization, GDP expansion, population increase, and industrialization on CO_2 emissions in the UK from 1970 to 2019. The results concluded that in the short term, economic expansion and industrialization have a substantial encouraging sway on CO_2 emissions. Conversely, in the sustained period, energy use, industrialization, and population growth lead to the promotion of ecological health. Moreover, Yilanci et al. (2023) checked how environmental ramifications linked with the utilization of electricity in the UK, spanning the time frame from 1850 to 2018. This finding demonstrates that energy usage has a major influence on biodiversity loss. Ramzan et al. (2023) reviewed the impact of sustainable technology along with financial globalization on environmental sustainability besides power transition in the UK. By incorporating data covering 1995 to 2020, they suggest that the implementation of clean technologies and the means of financial globalization have a mitigating influence on the ecological footprint. Conversely, it is seen that economic expansion is associated with environmental deterioration. Vanli (2023) explored the liaison between economic expansion, industrialization, and the environment in the United Kingdom. The study adopted the ARDL method and illustrated data from 1948 to 2018. The consequence of energy intake and imports of products on the environment is determined to be statistically insignificant.

In addition, Eweade et al. (2023) reviewed the interplay among transportation energy adoption, economic growth, clean power use, trade, globalization, and ecological footprint within the UK from 1990 to 2020 by exercising the ARDL and Fourier Toda-Yamamoto causality test. Their empirical evidence indicates an association between heightened levels of transportation energy use, the utilization of renewables, and the process of globalization, with a concomitant decrease in ecosystem damage. In contrast, they claimed that both GDP and trade have a negative influence on the ecology. Zhou et al. (2023) assessed the effectiveness of comprehensive green taxation, GDP expansion, and the application of renewables in mitigating the ecological footprint across the UK. They encompassed data from 1995 to 2018 and revealed that the implementation of environmental taxes, promotion of sustainable energy resources, and fostering financial development are effective strategies for enhancing environmental conditions within the UK. In their study, Caglar (2022) conducted an investigation of the influence of research and development (R&D) expenditures allocated to nuclear energy on CO_2 emissions in the UK. They adopted a non-linear ARDL methodology while also accounting for variables such as income, trade accessibility, and advancement in finances. The study used data from 1974 to 2020 and demonstrates that GDP expansion and trade openness have an unfavorable impact on ecological conditions, whereas nuclear energy, as well as financial improvement, has a beneficial influence on the environment level.

Kartel et al. (2023) analyzed the contribution of nuclear energy, income, and green electricity to ecosystem conditions across the USA from 1965 to 2018. They observed that the embracing of nuclear power, green electricity sources, and economic growth reduces the damage to nature, particularly in the upper and middle segments of the distribution. On the contrary, the enhancement of the economy has adverse effects on the environmental compatibility within the higher echelons. An investigation by Omri and Saadaoui (2023) assessed the influence of nuclear power, fossil fuels, and GDP on the releases of CO_2 in France from 1980 to 2020. The NARDL analysis demonstrated that the consumption of nuclear power was shown to be associated with a drop in France's EFP. Ali et al. (2020) investigated the association linking GDP, population, and emissions of CO_2 in Malaysia from 1970 to 2014. They found a detrimental link between population size and GDP and the natural health of Malaysia.

However, Zhang et al. (2023) reviewed the impression of renewables and nuclear energies on the emissions of CO_2, utilizing data obtained from the ten leading nations in nuclear power generation worldwide. The results suggested that ecological harm is distracted by population size, GDP, and the deployment of nuclear or renewables. These findings underscore the importance of implementing strategies aimed at reducing population growth and enhancing its eminence, along with fostering the development of sustainable economies and ensuring the security and effectiveness of nuclear and cleaner energy technologies. Jahangir et al. (2023) and Sadiq et al. (2023) explored that the use of nuclear power increases biodiversity compatibility within nations that heavily rely on nuclear energy. Wang et al. (2023) illustrated the effect of nuclear energy in stimulating financial improvement while minimizing the associated carbon emissions. The findings derived from an analysis of panel data encompassing 24 nations that have adopted nuclear energy between the years 2001 and 2020 indicate that both nuclear energy and renewables have the potential to mitigate carbon emissions. Nuclear energy exhibits a greater capacity for reducing carbon emissions compared to alternative power sources, particularly in countries such as Canada, Russia, Finland, South Korea, Slovenia, and the UK.

Wenlong et al. (2023), employing the CS-ARDL model, investigated the consequences of energy efficiency and technological advancement on ecosystem conditions across 10 Asian nations between 1995 and 2018. The findings show that both factors had a positive environmental influence. A dynamic panel data technique was used by Ahmad et al. (2024) to study the influences of technical innovation and power conservation on CO_2 emissions in 15 Asian economies between 1995 and 2021. The outcomes showed that by lowering CO_2 pollution, technological innovation and energy efficiency enhance ecological indicators. Javed et al. (2024) used the CS-ARDL structure to assess the effects of GDP, green technology innovation, and energy efficiency on the load capacity factor over the period 1990–2019. Results demonstrate that energy efficiency and the development of green technologies exert positive implications on the load capacity factor, suggesting their significant contribution to the achievement of sustainability goals.

2.2. Literature gap

Abundant research, including Hussain et al. (2022), Su et al. (2022), Rehman et al. (2022), and Umar et al. (2022), have reached the consensus that the escalation of population, GDP, and energy utilization causes to ecological destruction and the subsequent upsurge in pollution across various nations globally. Moreover, some recent studies examined the GHG emission trend across the industry, agriculture, and waste management sectors (Alola & Adebayo, 2023); uneven impacts of variations in fossil fuel prices on high-cleantech initiatives (Ozkan & Adebayo, 2024); effects of advancement in finances, technological innovation, and green power on ecological health (Kirikkaleli & Adebayo, 2021); interplay of green power, sustainable assets, and equitable markets (Ozkan et al., 2024), as well as the consequences of solar energy innovations, digitalization, and financial globalization on ecosystem quality (Adebayo et al., 2024). However, the existing body of research on the UK region is limited, with a dearth of current studies related to the contribution of different factors toward achieving net zero emissions. Hence, this paper highlighted the aforementioned knowledge gap by employing the STIRPAT model. Furthermore, the DOLS, the FMOLS, and the CCR approaches are used to verify the sturdiness of the ARDL findings. Even though a few investigations have been conducted on GHG emissions reduction and assessment in the UK, few empirical investigations have utilized econometric techniques to examine the relationship connecting GDP, population, renewables, fossil fuels, nuclear energy, energy efficiency, technological innovation, and GHG emissions in the UK. Hence, this research is highly relevant and will attempt to address the existing literature gap.

3. Methodology

3.1. Theoretical framework and data

The probe made the adoption of the widely recognized STIRPAT framework. The STIRPAT framework, extensively employed in academic circles, is an amended version of the IPAT paradigm that has been specifically designed to tackle the issue of mitigating ecological strain. The initial premise posits that individuals, economic prosperity, and technological advancements are the major catalysts for environmental strain. This is further expounded upon by the introduction of the IPAT model, which encompasses the interplay between population (P), affluence (A), and technology (T) in determining the overall impact (I) on the natural world. Building upon this framework, Dietz and Rosa (1994) have refined and expanded the IPAT structure, resulting in the development of the STIRPAT framework. The IPAT framework is depicted in Equation (1), wherein A represents the measure of wealth enjoyed, such as GDP, and T represents the advancements in energy efficiency that yield environmental benefits.

$$I = PAT \tag{1}$$

The IPAT framework, while possessing the capability to estimate individual coefficients as distinct parameters, is constrained in its capacity to comprehensively consider the complex interactions among population, economic factors, and technological advancements. The IPAT model was superseded by the STIRPAT framework as a result of its inherent limitations. Wang et al. (2022) proposed a modified form of the approach in order to mitigate the limitations of the initial STIRPAT paradigm. This extended version has been widely adopted in various applications. It exhibits superior performance and requires a reduced amount of time. The STIRPAT framework, when expressed as a formal equation, specifies an inclusive and measurable context for examining the influence of ecological factors. Equation (2) elucidates the correlation among population, affluence, innovation, and environment and expounds upon the manner in which these variables exert influence on the surroundings.

$$I = \beta P_t^{\alpha} \cdot A_t^{\gamma} \cdot T_t^{\phi} \cdot \varepsilon_t \quad (2)$$

The limited utility of the IPAT model arises from the exclusion of non-comparative alterations in the robust processes. The STIRPAT strategy differs from the IPAT model by selectively incorporating the advantages of the IPAT paradigm while excluding its limitations. The STIRPAT model facilitates the accurate computation of coefficients and the segregation of factors. This identification is incorporated to explore the factors contributing to changes in the ecosystem and acknowledges the important justifications for policy actions (Wu et al., 2021). A number of recent scholarly investigations have employed the STIRPAT framework as a means to elucidate the environmental ramifications (Chen & Mu, 2023; Rao et al., 2023; Sharif et al., 2023; Shu et al., 2023). Hence, this theory is employed in contemporary research inquiries to examine the determinants that promote GHG emissions (Aziz & Chowdhury, 2023; Huang et al., 2021). The present study introduces a theoretical framework, denoted as Equation (3), which aims to check the implication of several parameters, like population, GDP, and energy technologies, on GHG emissions.

$$GHG = \int (GDP, Population, Technologies) \quad (3)$$

The expanded STIRPAT framework incorporates all of these essential metrics. The present study used GDP as a proxy for affluence (A). Usman et al. (2022), Zhang et al. (2023), and Polat et al. (2024) have incorporated green and nuclear energy resources into the STIRPAT framework in order to enhance its technological component (T). Besides, Ahmad et al. (2024) incorporated power conservation and technical progress in the STIRPAT framework. Hence, the current analysis incorporates five technological components, namely renewables, nuclear energy, fossil fuels, energy efficiency, and technological innovation. Energy efficiency and technological advancement were included in the model, given their importance for energy transitions. Additionally, the variable on population was selected to check the influence of population dynamics on GHG pollution. The given equation, denoted as equation (3), can be reformulated like below:

$$G = \int (Y, P, F, R, N, E, T) \quad (4)$$

Where G represents GHG emissions, Y represents the GDP, P represents population, R represents renewable energy, F is for fossil fuels, N is for nuclear energy, E is for energy efficiency, and T is for technological innovation.

Equation (5) shown herein illustrates the modified form of Equation (4).

$$G_t = \beta_0 + \beta_1 Y_t + \beta_2 P_t + \beta_3 F_t + \beta_4 R_t + \beta_5 N_t + \beta_6 E_t + \beta_7 T_t + \varepsilon_t \quad (5)$$

The logarithmic expressions that correspond to the given equation are as follows:

$$LG_t = \beta_0 + \beta_1 LY_t + \beta_2 LP_t + \beta_3 LF_t + \beta_4 LR_t + \beta_5\, LN_t + \beta_6 LE_t + \beta_7 LT_t + \varepsilon_t \quad (6)$$

The theoretical foundation of this study is rooted in the STIRPAT model and the theory of sustainable development which contains the theories of energy transition, technological innovation, and demographic economics. The STIRPAT model provides a quantitative framework for analyzing the dynamic influences of population, affluence (economic growth), and technology on environmental impact, making it particularly relevant for assessing the role of fossil fuels, renewable energy, nuclear energy, technological innovation, and energy efficiency in achieving net zero emissions. Additionally, the theory of sustainable development underscores the need for an integrated approach that balances economic progress, energy transitions, and environmental sustainability. Technological innovation is considered a key driver in this transition, as it enhances energy efficiency and enables the large-scale deployment of low-carbon energy sources. Population dynamics also play a critical role, as changes in consumption patterns and energy demand influence emission levels. By incorporating these theoretical perspectives, this study aims to explore the complex interdependencies among energy sources, economic growth, and technological progress in the United Kingdom's pursuit of net zero emissions.

This work employs annual data from 1990 to 2021 for the United Kingdom. Table 1 summarizes a synopsis of the variables used for the empirical investigation. The statistics are collected from the World Development Indicators (WDI). The investigation period is limited to the years 1990–2021 because of the unavailability of data on GHG emissions, renewable energy, and energy efficiency prior to 1990 and beyond 2021. However, other factors, like governmental policy interventions or global energy price shocks, were not considered in the analysis due to the unavailability of data.

3.2. Econometric methodology

The ARDL simulations method, known for its advanced and dynamic nature, has been utilized to identify the anticipated coefficients of the regressors in issue over both shorter and longer periods. According to Udeagha and Breitenbach (2023), this particular model has the capability to independently evaluate the relationships between indicators across both shorter and longer periods. Additionally, it is able to generate and present graphical representations of movements in these indicators, whether they are upward or downward in nature. Furthermore, the ARDL structure is suitable for exploring a combination of integrated order zero I(0) or I(1) data. Abumunshar et al. (2020) asserted that to validate the long-term approximation of ARDL approaches, it is necessary to employ FMOLS, DOLS, and CCR, which have also been utilized in the present study. The aforementioned chronological econometric approaches have also been employed by Adebayo et al. (2021) and Olorogun (2023). Fig. 1 illustrates the flowchart of the empirical investigation.

3.2.1. Unit root tests

Checking the stationarity of all factors is a necessary to examining cointegration and estimating short- and long-term consequences. The study utilizes a battery of unit root assessments to check the accuracy of stationarity results: Augmented Dickey-Fuller test (ADF), Dickey-Fuller generalized least squares test (DF-GLS), and Phillips-Perron (P-P).

3.2.2. ARDL cointegration method

This investigation preferred the ARDL method over other approaches like Structural Equation Modeling (SEM) or Panel Data Analysis because it has several advantages (Raihan, 2024), remarkably in the perspective of energy consumption and supply challenges in the UK. Firstly, ARDL allows for different lag structures for the dependent and independent variables. This flexibility enables researchers to capture the dynamic adjustment of energy consumption or supply over time, which is crucial in understanding the time-sensitive nature of energy markets. Secondly, one of the main benefits of ARDL is that it can distinguish between short-run and long-run connections. Given the UK's efforts to shift to

Table 1
Data description.

Variables	Description	Measurement unit
G	GHG emissions	Total GHG emissions (Mt of CO_2 equivalent)
Y	Economic growth	GDP (constant British pound sterling)
P	Population	Number of total populations
F	Fossil fuel energy	% of total energy consumption
R	Renewable energy	% of total energy consumption
N	Nuclear energy	% of total energy consumption
E	Energy efficiency	GDP per unit of energy use (PPP $ per kg of oil equivalent)
T	Technological innovation	Number of patent applications (residents and non-residents)

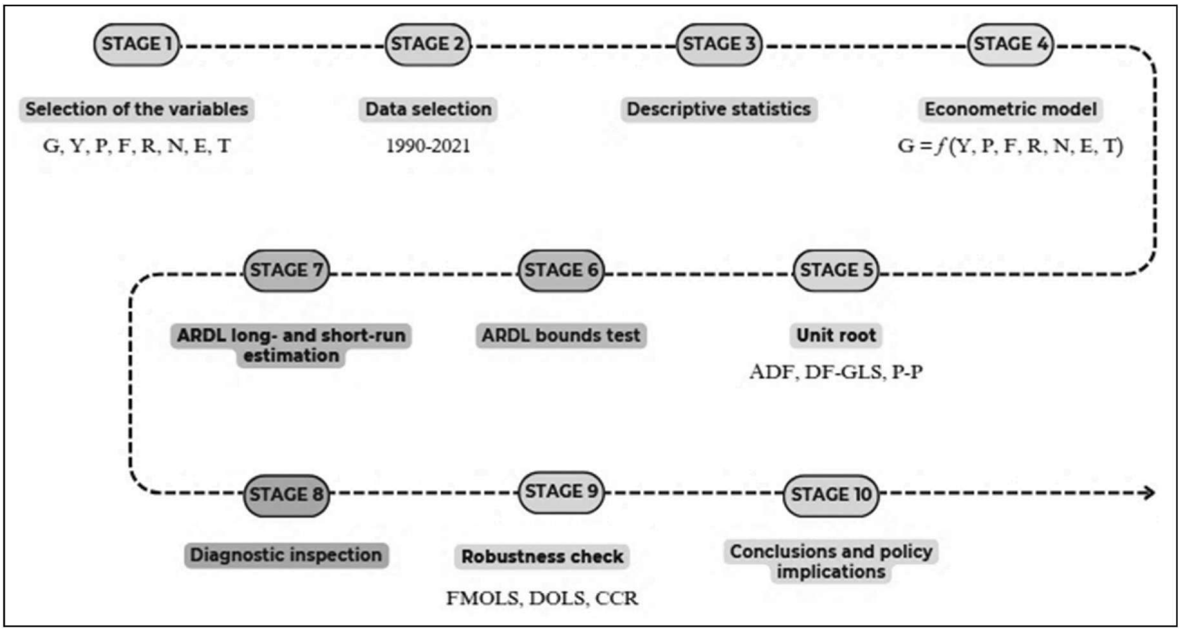

Fig. 1. The estimation flowchart.

clean power and the associated policy shifts, understanding both immediate impacts and longer-term trends is essential. Thirdly, ARDL is especially helpful when handling small sample sizes. For example, the present study collected energy-related data from the WDI, where data on GHG emissions, renewable power, and energy conservation are limited to 1990 and 2021. The characteristic of the ARDL method allows this investigation to conduct valid inferences even when datasets are not large. Fourthly, The ARDL model is effective when there is a single sustained link within the factors that constitute the model in a limited sample size. Fifthly, although GMM is designed to handle endogeneity, ARDL can also accommodate potential endogeneity issues through its framework without requiring complex instrument selection. This is important in energy economics, where variables can be interrelated (e.g., energy consumption affects GDP while GDP also influences energy consumption). Sixthly, ARDL can be incorporated regardless of whether the time series data are stationary or non-stationary, provided that they are of order 0 or 1. This is particularly advantageous in the energy sector, where many economic variables, such as prices, consumption, and output, are often non-stationary, and ARDL can help establish long-term equilibrium relationships among them. Seventhly, the ARDL model's structure makes it straightforward to implement and interpret in relation to energy economics, compared to the more complex frameworks needed for SEM or GMM. This simplicity can be useful for policymakers who need clear and actionable insights. Finally, the results derived from ARDL models can provide valuable policy implications, especially in the setting of the UK's power conservation, net-zero emissions targets, and the impact of sustainable electricity policies. The clear differentiation between short-run effects (e.g., policy impacts) and long-run impacts (e.g., structural changes in energy consumption) can aid in more effective policy decision-making. In summary, the ARDL method's ability to handle dynamic relationships, distinguish short- and long-term effects, accommodate small sample sizes, and manage various data types makes it particularly well-suited for addressing the UK's energy-specific challenges. Such characteristics are essential for developing robust economic insights into an evolving energy landscape.

To confirm cointegration across the factors, we employed the ARDL bounds testing method developed by Pesaran et al. (2001). The model is expressed as follows:

$$\begin{aligned}\Delta LG_t = {} & \beta_0 + \beta_1 LG_{t-1} + \beta_2 LY_{t-1} + \beta_3 LP_{t-1} + \beta_4 LF_{t-1} + \beta_5 LR_{t-1} \\ & + \beta_6 LN_{t-1} + \beta_7 LE_{t-1} + \beta_8 LT_{t-1} + \sum_{i=1}^{q} \alpha_1 \Delta LG_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LY_{t-i} \\ & + \sum_{i=1}^{q} \alpha_3 \Delta LP_{t-i} + \sum_{i=1}^{q} \alpha_4 \Delta LF_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LR_{t-i} + \sum_{i=1}^{q} \alpha_6 \Delta LN_{t-i} \\ & + \sum_{i=1}^{q} \alpha_7 \Delta LE_{t-i} + \sum_{i=1}^{q} \alpha_8 \Delta LT_{t-i} + \varepsilon_t \end{aligned} \tag{7}$$

where Δ is the first difference operator, and q is the optimal lag length.

The ARDL bounds testing approach relies on F-statistics suggested by Pesaran and Timmermann (2005). The analysis starts analyzing Equation (7), adopting the ordinary least squares (OLS), and conducting the F-test. The null hypothesis (H_0) of the test is the non-appearance of cointegrating interaction midst the factors. The F-statistics indicate the existence of an association between variables, with higher values indicating a long-term association, lower values confirming the H_0 of no cointegration, and inconclusive values designating a weak or no association.

3.2.3. *ARDL long- and short-run estimation*

The inquiry utilized the ARDL structure to demonstrate the long- and short-term connection among the factors. After establishing the identification of long-term correlations, this work estimates the error correction term (ECT) written as follows:

$$\begin{aligned}\Delta LG_t = {} & \beta_0 + \beta_1 LG_{t-1} + \beta_2 LY_{t-1} + \beta_3 LP_{t-1} + \beta_4 LF_{t-1} + \beta_5 LR_{t-1} \\ & + \beta_6 LN_{t-1} + \beta_7 LE_{t-1} + \beta_8 LT_{t-1} + \sum_{i=1}^{q} \alpha_1 \Delta LG_{t-i} + \sum_{i=1}^{q} \alpha_2 \Delta LY_{t-i} \\ & + \sum_{i=1}^{q} \alpha_3 \Delta LP_{t-i} + \sum_{i=1}^{q} \alpha_4 \Delta LF_{t-i} + \sum_{i=1}^{q} \alpha_5 \Delta LR_{t-i} + \sum_{i=1}^{q} \alpha_6 \Delta LN_{t-i} \\ & + \sum_{i=1}^{q} \alpha_7 \Delta LE_{t-i} + \sum_{i=1}^{q} \alpha_8 \Delta LT_{t-i} + \theta ECT_{t-1} + \varepsilon_t \end{aligned} \tag{8}$$

In Equation (8), ECT_{t-1} refers to the ECT, while θ represents the speed of adjustment to be estimated. The presence of long-run relationships is confirmed when θ is negative and statistically significant. In this case, any disequilibrium between the variables that occurred in the short-run can be corrected and the long-run equilibrium may be reached.

3.2.4. Robustness check

It is important to check the thoughtfulness of sustained effects gained from the ARDL framework prior to formulating policy recommendations. The robustness of the long-run coefficients obtained from this technique is checked using three techniques: the FMOLS (Phillips & Hansen, 1990), the DOLS (Stock & Watson, 1993), and the CCR (Park, 1992). FMOLS uses a semi-parametric method to analyze the long-run elements and allows for resolving common econometric challenges, including endogeneity, omitted variable bias, serial correlation, and estimation errors, even when dealing with small sample data. It also works better than other cointegration methods because it gives more accurate t-statistics for long-term analysis (Phillips & Hansen, 1990). The DOLS includes both lags and leads of regressors into the error covariance matrix, enabling the reduction of endogeneity and enhancing the accuracy of standard errors. In addition, the estimators derived from the DOLS have robust asymptotic properties, thereby providing robust statistical accuracy. Furthermore, the DOLS provides accurate estimations of the endogenous factor based on independent parameters across various degrees of integration in the context of systems with mixed orders of integration. Finally, the CCR is considered another technique for estimating cointegrating vectors within I(1) process models. Although there is some similarity with FMOLS, the main difference lies in their respective transformation approach. The FMOLS technique involves applying transformations to both the parameters and the data, while the CCR technique mainly concentrates on transforming the data (Park, 1992). It is remarkable that preceding investigations effectively documented the robustness of the FMOLS, DOLS, and CCR methodologies and their suitability for assessing the sensitivity of ARDL findings (Idroes et al., 2024; Khan & Liu, 2023; Pattak et al., 2023).

4. Results and discussion

Table 2 delivers a wide range of summary statistics. It can be seen that each parameter has 32 observations, representing the UK's yearly data spanning from 1990 to 2021. The similarity between mean and median values, coupled with skewness values close to zero, suggests that the data for all factors may be approximately normally distributed. Population and renewable energy have a positive skew, whilst the other variables show an inverse skew. Furthermore, Kurtosis was employed to ascertain if the series had a distribution with lighter or heavier tails than the normal distribution. The values below 3 suggest platy Kurtosis, while lower Jarque-Bera test values and high p-values suggest rejecting the null hypothesis and, consequently, the normality of all series.

The presence of multicollinearity was evaluated after selecting the variables. A high degree of correlation between independent model factors creates multicollinearity. Insufficient interpretation in the model creates interpretability problems which lead to the occurrence of overfitting. The results from Table 3 validate that the independent variable variance inflation factors (VIF) are below 10 which indicates no presence of multicollinearity in the model.

The key aim of this analysis was to probe the emergence of a long-lasting link between the series being analyzed. Therefore, a comprehensive analysis was undertaken to measure the integrated characteristics of the sequences by the utilization of various unit root assessments, which are ADF, DF-GLS, and P-P examinations. The outcomes of the unit root tests displayed in Table 4 reveal that all factors have unit roots at levels; however, they become stationary upon first differencing. Therefore, all series are I(1).

The identification of the appropriate lag length required for the simulation of the ARDL model and computation of the F-statistic relies on minimizing the Akaike Information Criterion. Table 5 revealed that the calculated F-statistic value of 13.29 is bigger than the critical upper bounds at all tested significance levels (10 %, 5 %, 2.5 %, and 1 %). Therefore, the ARDL model estimation reveals that the F-test statistic crosses the upper critical bound, thus providing evidence of cointegration and validating the specter of long-run linkages across the considerations.

Table 6 provides the short- and long-run coefficients attained from the ARDL estimation. In the short term, a 1 % rise in GDP is accompanied by a corresponding surge of 0.11 % in GHG emissions. In the long-term, this association is further amplified, with a 1 % surge in GDP resulting in a 0.28 % boost in GHG emissions. Likewise, a 1 % expansion in population led to an immediate rise of 0.16 % and a long-term boost of 0.23 % in pollution. In a similar vein, a 1 % spike in fossil fuel usage causes a subsequent growth of 0.60 % in GHG emissions in the short term and a 0.72 % rise over time. Additionally, it has been observed that a 1 % improvement in the utilization of renewables leads to a fall in GHG pollution by 0.25 % in the short term and 0.39 % in the long term. In a similar vein, a 1 % development in the consumption of nuclear power causes a drop in GHG by 0.13 % in the short-run and 0.28 % in the sustained period. Moreover, a 1 % improvement in energy efficiency consequences in a cut in GHG emissions by 0.21 % in the short term with 0.38 % in the long term. Finally, a 1 % progress in technological advancement is responsible for a short-run drop in GHG emissions by 0.29 % and 0.48 % in the long-term. In both the short- and long-run, the coefficients exhibit statistical significance, as indicated by low p-values.

Table 3
Results of VIF.

Variables	Coefficient variance	Uncentered VIF	Centred VIF
LY	0.00	172.36	1.11
LP	0.01	709.18	4.67
LF	0.00	512.66	2.35
LR	0.00	271.53	1.08
LN	0.00	369.24	1.99
LE	0.00	666.61	2.45
LT	0.01	1312.91	6.38
C	3.14	1678.29	NA

Table 2
Descriptive statistics.

Variables	LG	LY	LP	LF	LR	LN	LE	LT
Mean	6.45	28.09	17.93	4.46	0.79	2.34	2.20	10.14
Median	6.51	28.16	17.92	4.47	0.40	2.37	2.22	10.70
Maximum	6.79	28.35	18.02	4.50	2.61	2.57	2.79	10.40
Minimum	6.00	27.76	17.86	4.38	−0.51	1.99	1.54	9.84
Std. dev.	0.23	0.18	0.05	0.02	1.02	0.11	0.42	0.15
Skewness	−0.35	−0.50	0.35	−0.71	0.48	−0.12	−0.13	−0.07
Kurtosis	1.99	1.97	1.67	2.46	1.70	2.38	1.59	1.94
Jarque-Bera	2.01	2.75	2.98	2.71	3.49	3.81	2.71	1.51
Probability	0.36	0.25	0.22	0.25	0.17	0.20	0.25	0.47

Note: LG = GHG emissions, LY = economic growth, LP = population, LF = Fossil fuel, LR = Renewable energy, LN = Nuclear energy, LE = Energy efficiency, LT = technological innovation.

Table 4
The results of unit root tests.

Variables	ADF		DF-GLS		P-P	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
LG	−0.99	−6.81***	−0.85	−3.51***	−0.89	−6.71***
LY	−0.61	−5.95***	−0.51	−5.96***	−0.69	−5.95***
LP	−1.05	−3.87***	−1.40	−3.88***	−1.23	−3.87***
LF	−0.64	−6.60***	−0.83	−3.63***	−1.01	−6.50***
LR	−0.90	−3.90***	−0.40	−3.67***	−0.92	−3.91***
LN	−0.05	−5.27***	−0.28	−5.09***	−0.01	−5.27***
LE	−0.46	−4.18***	−0.49	−4.01***	−0.47	−4.20***
LT	−0.61	−4.56***	−0.66	−4.28***	−0.61	−4.57***

Note: ***$p < 0.01$.

Table 5
ARDL bounds analysis outcomes.

Test statistic	Estimate	Significance level	I(0)	I(1)
F-statistic	13.29	10 %	2.08	3.00
K	7	5 %	2.39	3.38
		2.5 %	2.70	3.73
		1 %	3.06	4.15

Table 6
Findings of ARDL long- and short-run.

Variables	Long-run			Short-run		
	Coefficient	t-statistic	p-value	Coefficient	t-statistic	p-value
LY	0.28***	3.12	0.00	0.11**	2.94	0.01
LP	0.23**	2.19	0.04	0.16**	2.18	0.04
LF	0.72***	8.05	0.00	0.60***	4.96	0.00
LR	−0.39***	−3.19	0.00	−0.25***	−3.43	0.00
LN	−0.28***	−4.53	0.00	−0.13***	−3.94	0.00
LE	−0.38***	−3.61	0.00	−0.21***	−3.23	0.00
LT	−0.48***	−3.94	0.00	−0.29***	−3.45	0.00
C	39.94	1.28	0.13	–	–	–
ECT (−1)	–	–	–	−0.61***	−3.86	0.00
R^2	0.99					
Adjusted R^2	0.99					

Note: LY = economic growth, LP = population, LF = Fossil fuel, LR = Renewable energy, LN = Nuclear energy, LE = Energy efficiency, LT = technological innovation, ***$p < 0.01$, **$p < 0.05$.

Furthermore, the long-term relationships across the variables are verified by the calculation of the ECT which is negative and statistically significant at 1 %, suggesting that about 61 % of the change from long-term equilibrium has been rectified. In addition, the model demonstrates good explanatory power, as indicated by R^2 values of 0.99. This suggests that the explanatory variables explain 99 % of the changeability in total GHG emissions. Furthermore, the validity of the ARDL conclusions is checked based on a battery of diagnostic tests reported in Table 7. The lower statistic and insignificant p-value of the Jarque-Bera test confirmed the normality of the residuals, while there was no serial correlation or heteroskedasticity identified by the insignificant p-values of the estimated coefficients from the Breusch-Godfrey Lagrange Multiplier and Breusch-Pagan-Godfrey tests. The insignificant p-value of the estimated coefficient from the Ramsey RESET test also suggests proper specifications of the model. Moreover, sometimes, the endogeneity problem may occur in the context of time series analysis which means the error component in the equation may be associated with one or more forecasting variables. This study employed the endogeneity test by Hausman (1978) to ascertain the presence of endogeneity in regression models. Excessive instruments for system observations can lead to overfitting of endogenous variables in time series estimates, potentially compromising the test's ability to detect excessive constraints. The results from Table 7 indicate that the coefficient in the Hausman specification test is not statistically significant and supports the null hypothesis of "no endogeneity" accepted. This suggests no endogenous issues with the regression model and the coefficient estimates are consistent. Finally, the CUSUM and CUSUM of squares evaluations are implemented to assess the stability of long-run parameters (Fig. 2). The findings in Table 7 and Fig. 2 suggest the stability and robustness of the ARDL findings.

Table 7
The results of diagnostic tests.

Diagnostic tests	Coefficient	p-value
Jarque Bera	1.48	0.55
Breusch-Godfrey LM	1.33	0.47
Breusch-Pagan-Godfrey	1.09	0.43
Ramsey RESET	1.34	0.59
Endogeneity	2.17	0.64

The outcomes of the robustness check are shown in Table 8. The conclusions demonstrated that the FMOLS, DOLS, and CCR estimators uniformly and reliably perform well. As a result, this gives rise to the production of similar results as reported in the extended ARDL simulations over a prolonged period. The ARDL estimations are supported by the existence of significantly positive coefficients for LY, LP, and LF, as well as the negative coefficients of LR, LN, LE, and LT observed consistently across all three models. Additionally, the greater estimates of R^2 (0.99) exhibit the consistency of the estimate. The results of the robustness checks reveal that a 1 % rise in GDP, population, and fossil fuel consumption led to a nearly 0.3 %, 0.3 %, and 0.8 % increase in GHG emissions while a 1 % improvement in renewable energy, nuclear power, energy efficiency, and technological innovation cut GHG emissions by 0.4 %, 0.3 %, 0.4 %, and 0.5 % in the long-run.

The results point out that GDP, population expansion, and fossil fuels caused a surge in GHG emissions in the United Kingdom. Contrariwise, green and nuclear power resources, as well as energy conservation and technological innovation, have been observed to reduce emissions on both time horizons. The findings corroborate those of Li and Haneklaus (2022), Murshed et al. (2022), and Mehmood et al. (2023), who indicated that GDP has detrimental consequences on the environment, whereas nuclear and green power consumption enhances natural health by mitigating pollutants in G7. Furthermore, Abbasi et al. (2021) found a significant positive association among energy use, GDP, population, and pollutants in the UK. Ramzan et al. (2023) also highlighted a negative relationship between GDP growth and biodiversity in the UK. Yilanci et al. (2023) and Vanli (2023) stated that electricity use has substantial destructive consequences on natural health in the UK.

Furthermore, Wang et al. (2023) demonstrated that the adoption of nuclear power and renewables mitigates carbon emissions in the United Kingdom. According to Zhou et al. (2023), the usage of renewables and the advancement of monetary expansion have been identified as effective strategies for enhancing ecological conditions within the United Kingdom. According to Caglar (2022), economic expansion has a detrimental consequence on the natural world. However, it is noteworthy that nuclear energy exerts a significant effect in enhancing the ecosystem level, specifically within the context of the United Kingdom. Furthermore, this probe's findings are aligned with Wenlong et al. (2023), Ahmad et al. (2024), and Javed et al. (2024), who reported that energy conservation and technical development upgrade the ecological condition by reducing emissions. In contrast, this probe's outcomes are in partial disagreement with Zhang et al. (2023), who asserted that ecological destruction is affected by many elements such as population, GDP, renewables, and nuclear energy. The study highlighted the necessity of implementing strategies aimed at reducing population growth. Additionally, it emphasized the importance of adopting a sustainable economic model and enhancing the security and efficacy of both nuclear and green energy sources.

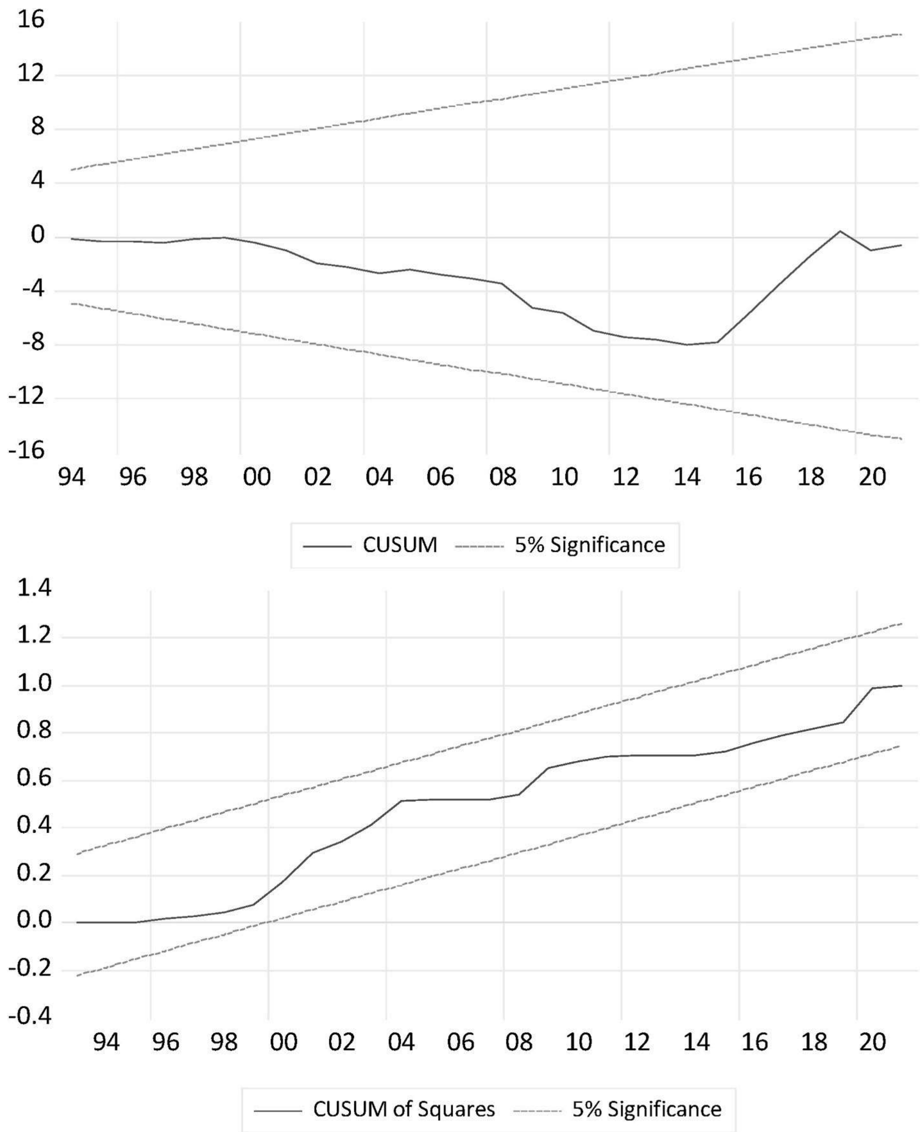

Fig. 2. Results of CUSUM and CUSUM square tests.

Table 8
Robustness test results.

Variables	FMOLS		DOLS		CCR	
	Coefficient	t-statistic	Coefficient	t-statistic	Coefficient	t-statistic
LY	0.28***	3.17	0.25**	2.89	0.26**	3.08
LP	0.27**	2.19	0.23**	2.13	0.29**	2.06
LF	0.78***	8.78	0.77***	7.98	0.79***	7.49
LR	−0.42**	−2.73	−0.40**	−2.76	−0.43**	−2.77
LN	−0.27***	−4.39	−0.26***	−4.45	−0.25***	−4.34
LE	−0.35***	−3.49	−0.37***	−3.53	−0.38***	−3.49
LT	−0.49***	−3.81	−0.44***	−3.67	−0.48***	−3.86
C	27.12	1.62	28.95	1.64	27.31	1.65
R^2	0.99		0.99		0.99	
Adjusted R^2	0.98		0.98		0.98	

Note: LY = economic growth, LP = population, LF = Fossil fuel, LR = Renewable energy, LN = Nuclear energy, LE = Energy efficiency, LT = technological innovation, ***$p < 0.01$, **$p < 0.05$.

The positive coefficients of economic growth, population size, and fossil fuel energy consumption on GHG emissions in the UK reflect fundamental economic and environmental dynamics. Economic growth increases industrial activity, transportation, and energy demand, leading to higher carbon emissions, particularly when reliant on fossil fuels. A larger population amplifies energy consumption, transportation needs, and resource use, further driving emissions. Fossil fuel energy consumption directly contributes to GHG emissions, as coal, oil, and natural gas release carbon dioxide and other pollutants when burned. Conversely, the negative coefficients of renewable energy consumption, nuclear energy consumption, energy efficiency, and technological innovation suggest their mitigating effects on emissions. Renewable and nuclear energy provide low-carbon alternatives, reducing reliance on fossil fuels. Energy efficiency improvements lower energy demand and emissions by optimizing resource use across industries and households. Technological innovation drives advancements in cleaner energy, carbon capture, and sustainable industrial practices, contributing to emission reductions. In the UK's context, stringent climate policies, investment in renewables, and technological advancements have reinforced these relationships, enabling economic growth while curbing emissions.

The United Kingdom has experienced significant changes in its dynamics due to the combination of rapid economic expansion and the escalating utilization of fossil fuels. These factors have particularly impacted the nation's unique characteristic of having a high population density. The developed economy of the region has experienced substantial fluctuations over the course of the last two decades, resulting in a reduced reliance on heavy industry. Abbasi et al. (2021) argue that the UK's consumption and advancement outlines are being transformed by the extension of the provision economy, advancements in modern technologies and light production, and the emergence of more diverse lifestyles. Consequently, these changes present novel challenges for environmental sustainability. Nevertheless, the UK has significantly enhanced its people's visibility regarding environmental concerns and strengthened its legislative framework pertaining to the environment. The UK government has established a target, as outlined in the Climate Change Act, to achieve a substantial fall in GHG emissions inside the UK by the year 2050. Furthermore, a strategic trajectory has been devised to guide the nation towards the attainment of this objective. The establishment of the Committee on Climate Change (CCC) through the Act serves the purpose of ensuring that pollution targets are based on empirical information and subject to impartial evaluation.

Furthermore, the present analysis demonstrates that the magnitude of population size plays a big part in emission growth, hence underscoring the urgency for swift governmental intervention. Consequently, the implementation of population stabilization measures might be considered a feasible approach to mitigating the escalating issue of GHG emissions. The utilization of ecologically detrimental fuels is on the rise due to the growth of the population. The anticipated trajectory of global energy consumption over the next three decades is projected to increase by 50 %, primarily hammered by population expansion and developing economies. The facilitation of a global transition to affordable and environmentally friendly energy sources would be significantly enhanced by the reduction of population growth, contributing to the achievement of Sustainable Development Goal (SDG) target 7. The contemporary period has observed a major boost in the need for energy as a result of the simultaneous development of industry and globalization at a global level (Raihan et al., 2025). The adoption of fossil fuels has followed a significant surge in GHG emissions, consequently adding to ecological pressure (Raihan et al., 2024). The increasing degradation of the environment has resulted in a heightened acknowledgment of the ecosystem, prompting nations to embrace renewable energy alternatives to satisfy their energy demand (Raihan, 2023). Nevertheless, because of governmental initiatives, there has been a noticeable drop in the utilization of fossil fuels within the United Kingdom, accompanied by a simultaneous rise in the adoption of renewables and nuclear power.

Recently, the UK has established itself as a notable worldwide performer in the field of green electricity production, a development that has occurred with relatively little fanfare. Renewable sources account for approximately 42 % of the power generated in the United Kingdom, constituting approximately 6 % of the kingdom's overall energy consumption. The primary source of renewable energy in the United Kingdom is derived from offshore and onshore wind. Not only does it surpass other renewable resources by 13.8 % of the overall power production in the UK, but it also surpasses the unified production of coal, oil, and other sources by 6.5 %. The UK currently holds a prominent position in the global offshore wind sector, having successfully placed over 700 turbines. At the moment, the UK's fully operational offshore wind capacity is at 13.9 GW. In addition, 77 GW projects involving planning, development, and construction are now underway. In order to encourage the growth of offshore wind projects, the government has proposed the Crown Estate Bill and wants to expedite the consenting process. By 2030, offshore wind capacity is expected to reach 50 GW, including 5 GW from floating wind, according to the UK's British Energy Security Strategy (BESS). This is a component of a larger technique to attain the UK's 2050 aim of net zero carbon emissions. Furthermore, the UK is actively expediting the implementation of onshore wind projects, with Scotland and Wales spearheading the largest endeavors in Europe, both in operation and currently being constructed. This multifaceted approach aligns with the carbon budgets and is vital in ensuring the nation's progress concerning succeeding net zero emissions. The current paper's results of the negative rapport between renewable energy and GHG emissions are aligned with current renewable energy strategies like offshore and onshore wind expansion in the UK.

Nonetheless, there are regional disparities in the UK's energy policy and implementation. For example, Scotland and England exhibit significant regional disparities in their approaches to energy production, particularly regarding renewable energy leadership and reliance on nuclear power. Scotland has found itself as a leader in green energies, harnessing its abundant natural assets, such as wind, hydro, and solar power. With desired goals for mitigating carbon releases and producing 100 % of its electrical energy from renewable resources by 2020 (which it met), Scotland boasts a landscape dotted with onshore and offshore wind farms, and hydropower installations, predominantly in rural areas. This commitment has energized local economies and promoted job creation in green technologies. In contrast, England's energy strategy has been heavily reliant on nuclear power, which accounts for a substantial portion of its electricity production. While England is beginning to invest more in renewable technologies, the legacy of nuclear infrastructure remains strong, and the energy mix often prioritizes the stability and baseload generation that nuclear power provides. This reliance can lead to regional disparities, as areas closer to nuclear facilities or those with established energy sectors may benefit economically compared to regions where renewable initiatives are still developing. Consequently, while Scotland moves towards a more sustainable, decentralized energy future, England grapples with balancing the benefits of its nuclear capabilities with the urgent need to expand renewable energy resources to meet both environmental goals and energy security.

Despite the potential safety hazards concerning the implementation of large-scale nuclear power plants, many developed and emerging nations have experienced a substantial upsurge in their electrical energy creation by instigating nuclear power resources (Jahangir et al., 2023). It may be argued that nuclear power facilities, despite their higher financial requirements, have the ability to successfully address environmental deterioration and promote cleaner economic activities, in contrast to fossil fuels. The UK has prioritized the integration of nuclear energy into its overarching plan to attain carbon neutrality by the year 2050, in conjunction with renewable energy sources. At present, the United Kingdom possesses a total of nine functional nuclear reactors situated across five distinct sites, collectively generating an electrical capacity of 5.9 GW. The United Kingdom government has established a goal of achieving a power generation capacity of 24 GW from nuclear energy by the year 2050.

Nevertheless, the current nuclear capacity in the UK is about twice as high as the maximum installed capacity that has ever been attained. The potential avenues for exploration in the field of nuclear energy include the improvement of gigawatt-scale nuclear power, the usage of small modular reactors (SMRs) and advanced modular reactors (AMRs), as well as the further advancement of nuclear fusion technology. By the early 2030s, the UK government hopes to have the first SMR in place. The government launched Great British Nuclear (GBN) in July 2023 and awarded subsidies totaling £157 million to assist the development of SMR. The government is anticipated to reveal which of the six projects that made the shortlist for the subsidies will be awarded contracts in the spring of 2024. By 2050, the UK government intends to boost nuclear power by up to 24 GW. The government thinks that because SMRs are smaller and can be built off-site, they could be able to help with this. The present study's results of the negative rapport between GHG emissions and nuclear energy are aligned with the UK's nuclear energy strategies like SMRs, which are a potential low-carbon energy source that could help the UK reach its net zero emissions goal by 2050.

While both green and nuclear power can help to cut GHG emissions in the UK, renewable energy has a more significant impact for several reasons. Firstly, the primary GHG emission reduction benefits of nuclear power largely come from replacing coal and gas with low-carbon nuclear electricity, but this does not necessarily reduce overall emissions if it leads to increased coal imports. On the contrary, clean energy can minimize pollutants by directly replacing fossil fuels in different zones such as heating, transport, and production. Secondly, renewable energy can provide greater flexibility in a low-carbon energy system, enabling the UK to integrate various intermittent assets, such as solar and wind power, into the grid while maintaining a balance between supply and demand. Furthermore, renewable energy has the potential for greater geographical and economic diversification, reducing reliance on centralized power plants. Besides, renewable energy infrastructures are more affordable, easier to construct, and capable of aiding the UK in succeeding its net-zero emissions goals. Instead, the construction of new nuclear power facilities is more costly than that of renewable energies like solar or wind. In terms of technology, nuclear systems have been more likely than comparable-sized renewable energy projects to have delays, higher construction cost overruns, and longer lead times.

However, both renewable energy and nuclear power face technological and public policy challenges. Technological constraints on renewable energy include intermittency, scalability, and energy storage limitations. For nuclear power, key challenges include high upfront costs, long lead times, and the lack of a proven method for disposing of nuclear waste. Public policy challenges on renewable energy include navigating complex planning processes, securing funding for grid infrastructure upgrades, and implementing laws that encourage a shift to a low-carbon economy. For nuclear power, significant policy challenges involve addressing public acceptability concerns, managing radioactive waste disposal, and navigating complex regulatory requirements. To overcome these constraints, the UK government must implement targeted strategies to support the expansion of low-carbon energy technologies, enhance public understanding and acceptance, and promote a coordinated national energy strategy that balances competing priorities and interests.

The present study revealed that improving energy efficiency helps to reduce GHG emissions in the UK. There are several methods that energy efficiency might lower GHG emissions. GHG emissions can be decreased by using less energy overall, particularly from fossil fuels. The air quality may also be enhanced by this. Indirect GHG emissions from the production of power can be decreased through energy efficiency. GHG emissions can be decreased by lowering the overall need for electricity through increased energy efficiency. Monthly energy bills can be decreased by using energy more efficiently. Besides, GHG emissions can be decreased by raising the power conservation of residences and commercial buildings through the installation of renewable energy processes such as solar panels, low-carbon heating systems, and insulation. Through a number of initiatives, such as decarbonizing homes, utilizing electric heat pumps, utilizing renewable energy, increasing industrial energy efficiency, decreasing the demand for energy-intensive materials, and altering consumer behavior, the UK is dedicated to lowering GHG emissions. Combating climate change, lessening the impact on the environment, and reaching net-zero emissions by 2050 are the objectives.

Finally, this investigation's outcomes suggest that increasing technical advancement would help the UK to achieve net zero emissions. Numerous technological advancements, such as CCS, cleaner energy, energy efficiency, green transportation, low-carbon, electric, circular economy, and carbon offset technologies, can lead to a fall in GHG emissions. In addition, smart home systems, energy-efficient appliances, carbon footprint calculators, energy usage trackers, food waste apps, LED lighting, and other developments can all contribute to lowering GHG emissions. In addition to having a robust academic and research sector and a culture that draws in talent and investment, the UK is a leader in technological innovation. The UK is moving toward a net-zero energy system through a range of tactics and technology. Large-scale nuclear power, solar energy, and offshore wind are among the technologies being used in the UK. Technologies like hydrogen generation, long-duration energy storage, and compact modular reactors are being developed in the UK. Innovation in technology is essential to the UK's energy transition since it will lower costs, boost efficiency, and incorporate clean power resources into the grid.

To support the UK in attaining net zero by 2050, various pledges and strategies were adopted in the 2021 Net Zero Strategy. Implementation of this effort can reduce emissions in order to reach targets via the sixth carbon budget, which spans the years 2033–2037. Additionally, an update to the present initiatives was drawn in the 2023 Net Zero Growth Plan, with an accent on the application and ascending up of technology for decarbonizing industry, transportation, residences, and power. Additionally, this update complied with the High Court's 2022 ruling that required the government to provide more specific information about its plans to achieve net zero. To lessen the burden on working people, the prime minister amended policy positions and outlined a new strategy for achieving net zero in September 2023. Later, the Labour administration uncovered a number of further net zero-related determines in 2024. These included the Sustainable Aviation Fuel (Revenue Support Mechanism) Bill (to encourage the production of this fuel), the Crown Estate Bill (to remove restrictions and make it easier to invest in public infrastructure), and the Great British Energy Bill (to create a public clean power firm to boost renewable energy venture). House insulation, biodiversity, management of land, and water resources are all areas that the government has pledged to address in its climate change plans, which will help the UK achieve net-zero emissions and adapt to the changing climate.

5. Conclusions and policy implications

5.1. Conclusions

The establishment of a sustainable ecosystem poses a significant challenge for developed nations in the current century. This study aims to identify a potential strategy for mitigating GHG emissions, a critical factor contributing to environmental degradation within the United Kingdom. The United Kingdom is a well-established developed nation that effectively adopts green energy sources alongside nuclear power. Consequently, the investigation seeks to explore the impacts of many factors, including GDP, fossil fuels, nuclear energy, renewables, energy efficiency, technological innovation, and population, on GHG emissions within the UK. The time frame of this investigation is the years 1990–2021. The ARDL structure is incorporated for empirical reasons, whereas the FMOLS, DOLS, and CCR approaches are utilized for their validation. Additionally, the STIRPAT framework provides the theoretical framework for this work. The findings indicate that the United Kingdom's emissions are mostly influenced by factors like GDP, population growth, and fossil fuel adoption. However, the conclusions demonstrated that green and nuclear energy, as well as energy conservation and technological innovation, performs a noteworthy role in cutting the emissions of the United Kingdom. Consequently, it is necessary for the United Kingdom to foster the transformation of its energy portfolio to achieve net zero emissions. This entails reducing dependency on fossil fuels and shifting toward a stronger dependence on nuclear power and clean power alternatives as well as improving energy efficiency and developing green technologies.

5.2. Theoretical implications

This research used the STIRPAT framework that offers a robust theoretical foundation for examining the complex interrelationships between various factors influencing GHG emissions. By incorporating variables such as different energy sources, energy efficiency, technological innovations, population growth, and GDP, STIRPAT facilitates a nuanced understanding of how these elements interact and dynamically affect environmental outcomes. The framework posits that environmental impact is not solely a function of population and affluence but is also significantly influenced by technological advancements and the specific energy sources (fossil fuels, renewables, and nuclear) utilized. This allows us to disentangle the direct and indirect effects of energy-related policies and practices on emissions, thereby highlighting the roles of renewable versus fossil fuel sources, the significance of energy efficiency improvements, and the potential of technological innovations in mitigating climate change. Additionally, STIRPAT's adaptability to incorporate stochastic elements and nonlinear relationships makes it well-suited for capturing the complexities of socio-economic systems and their environmental impacts over time, ultimately informing more effective climate policies and sustainability strategies.

Investigating the complex implications of different energy sources, energy efficiency, technological innovation, population, and GDP on achieving net-zero emissions in the United Kingdom has profound theoretical implications across several fields of study, including economics, energy systems modeling, environmental science, policy-making, and sustainable development. The interdependencies between energy sources, GDP, and emissions suggest the need for a systems-based approach. Understanding the feedback loops and emergent properties within this system is essential for modeling and decision-making. This aligns with complexity theory, which emphasizes how interconnected components influence overall system behavior. Exploring the transitions from fossil fuels to cleaner energies allows for analysis under transition theory frameworks, such as the Multi-Level Perspective (MLP) or the Technological Innovation Systems (TIS) framework. These theories provide insights into how societal, technological, and policy changes can co-evolve to achieve net-zero goals. By analyzing the trade-offs and synergies between economic development and environmental sustainability, this investigation contributes to the debate on sustainable development. It raises questions about how to stabilize economic advancement with ecological integrity and the potential redefinition of growth metrics (e.g., degrowth or green growth) in light of climate objectives. Investigating the impacts of power resources and efficiency measures also invites considerations of social equity and justice. The sharing of gains and problems linked to energy transitions can lead to theoretical discussions about energy justice frameworks, equity in energy access, and the socio-economic implications of policy choices.

The position of technological innovation in cutting pollutants underlines the necessity of innovation theories, including the diffusion of innovations and socio-technical systems. Understanding how new technologies can be effectively integrated into existing infrastructures and behaviors is key to achieving net-zero goals. Examining population growth and demographic changes invites considerations of behavioral economics and sociology, particularly regarding consumption patterns, resource use, and public acceptance of energy policies. Understanding these dynamics can inform effective communication and policy strategies that align behavioral change with net-zero objectives. Investigating how different energy systems and efficiency measures impact emissions necessitates an exploration of governance frameworks. This includes understanding policy instruments, regulatory measures, and institutional arrangements that facilitate or hinder the shift to net zero. The dynamic impacts of these factors will require the development of long-term, scenario-based approaches to predict outcomes and inform policy. This helps the literature on strategic foresight and scenario planning in the area of environmental policy.

The investigation can inform the development of Integrated Assessment Models (IAMs) that incorporate the interrelationships between energy sources, economic expansion, and emissions. Such models can specify novel insights into potential pathways to net-zero emissions, highlighting trade-offs and modeling uncertainties. Finally, the theoretical implications of this investigation include considerations of resilience and adaptive capacity in energy systems. Understanding how dynamic interactions can lead to vulnerability or robustness is critical for formulating strategies that withstand future uncertainties related to climate change and energy transitions. In sum, this comprehensive investigation not only advances theoretical perspectives on energy, economics, and sustainability but also generates practical ideas that could guide policy suggestions and strategic planning toward achieving net zero emissions in the UK.

5.3. Managerial contributions

The adoption of various strategies can enable the UK to mitigate the implication of GDP growth on releases of GHGs. To begin with, the mitigation of GHG pollution and the development of GDP can be achieved by the distribution of resources concerning sustainable infrastructure, for instance, clean energy sources, sustainable transportation networks, and environmentally friendly buildings. Furthermore, the carbon footprints of enterprises and sectors can be diminished through the promotion of innovative sustainable technologies and practices, which in turn can provide new economic prospects. Furthermore, implementing sustainable finance regulations, such as green bonds, can efficiently allocate financial resources towards environmentally conscious initiatives and businesses. This not only has the ability to stimulate economic progression but is also responsible for the fall of harmful pollutants. It is feasible to simultaneously foster economic growth, reduce emissions, and minimize power use by incentivizing funds for energy-efficient innovations and infrastructure. One approach to achieving this objective would involve providing incentives to both commercial and residential customers, encouraging them to adopt energy-efficient practices such as replacing appliances and redesigning buildings.

Renewable and nuclear energies demonstrate significant potential in the UK. The implementation of policies aimed at boosting the exploitation of renewables has the prospect of alleviating the hostile influences of economic progression on emissions of GHGs and toning down dependency on non-renewable fossil fuels. The process of internalizing the financial implications of pollution and motivating organizations and persons to decrease their releases of CO_2 can be accomplished by executing carbon pricing schemes such as carbon taxes and cap-and-trade approaches. The implementation of carbon pricing has the potential to generate sufficient financial resources to support endeavors aimed at promoting sustainable energy sources and environmentally conscious lifestyles. In the United Kingdom, a substantial amount of the nation's GHG outputs can be attributed to the transportation sector. The promotion of ecologically sustainable means of transport for instance hybrid or electric automobiles, cycling, and public transport, can minimize GHGs and stimulate economic growth within the transportation industry. The United Kingdom is gradually implementing these ideas, serving as a potential model for other European nations. Moreover, in light of the relationship concerning population expansion and emissions of GHGs, this investigation posits that fostering heightened environmental consciousness among the populace represents the most logical approach to mitigating emissions.

In the UK, clearer pathways for incentivizing renewable energy adoption and dropping dependency on fossil fuels include enhancing governmental policy frameworks, such as implementing more aggressive carbon pricing mechanisms and providing attractive subsidies for renewable technologies. Increasing investment in R&D can also drive innovation in energy efficiency and storage solutions, facilitating a smoother transition to sustainable resources. Strengthening grid infrastructure to accommodate a higher share of renewables, alongside introducing tax benefits for businesses and households that invest in renewable energy solutions, will further promote adoption. Additionally, community engagement initiatives and education campaigns can raise awareness and support for renewable energy projects, fostering a cultural shift towards sustainability. Finally, establishing clear, long-term targets for emissions reduction will provide businesses and consumers with the necessary certainty to invest in cleaner alternatives, ultimately making strides toward a greener energy future.

Although nuclear energy provides various benefits, such as carbon-free electrical energy, impressive power productivity, minimal environmental impact, and reliable power sources, there are potential risks, such as astronomical initial expenditures, radioactive waste, and potentially disastrous breakdowns. The UK can manage risk with nuclear power through regulatory oversight, waste management, financing, safety culture, emergency preparedness, and environmental considerations. Government incentives can play an effective role in overcoming public resistance to nuclear power in the UK by addressing safety concerns, and financial barriers, and promoting the perceived benefits of nuclear energy. Implementing policies such as providing grants for renewable energy ventures, tax breaks for nuclear power corporations, and funding research into advanced nuclear technologies can enhance public perception by showcasing the commitment to safety and innovation. Public education campaigns that highlight the reliability of nuclear energy in reducing carbon emissions and achieving energy independence can further bolster support. Additionally, offering incentives for communities hosting nuclear facilities, such as infrastructure improvements or direct financial benefits, may foster local acceptance. By actively engaging stakeholders and ensuring transparency in nuclear operations, the government can build trust, demonstrating that nuclear power is a viable and safe option for the UK's energy future.

To reach the UK's net-zero emissions target by 2050 through investments in offshore wind and SMRs, actionable steps should include establishing clear regulatory frameworks and inducements to invite private ventures in these technologies. The government can enhance funding for R&D to optimize the conservation and reliability of offshore wind and SMRs. Additionally, facilitating public-private partnerships would support the construction of necessary infrastructure and grid connectivity. Implementing streamlined planning processes will expedite project approvals, while targeted skill development programs can ensure the workforce is equipped with new technologies. Engaging local communities in project planning through consultation and job creation initiatives will also bolster support for these developments. Finally, establishing a long-term energy strategy that includes a balanced mix of renewables and nuclear, along with strategic assessments of economic impacts, will provide a roadmap that aligns with the UK's climate goals while ensuring energy security and economic growth.

Moreover, energy efficiency is crucial for decreasing emissions and enhancing environmental sustainability. Since energy efficiency is a rapid and economical method of lowering GHG emissions, it is a crucial component in reaching net-zero emissions. Investing in on-site generating, lowering lighting use, putting heat reduction measures in place, monitoring and establishing goals, and training staff are some strategies to improve energy efficiency. Installing renewable energy systems, low-carbon heating systems, and insulation can all increase the residence's energy efficiency. A home's environmental effect and energy efficiency can be evaluated with Energy Performance Certificates (EPCs). Since the UK's energy supply is more than 50 % low carbon, electric heat pumps provide a lower carbon option to gas boilers. By updating their equipment, digitizing their websites, and gathering and tracking energy and processing data, businesses can increase their energy efficiency. Energy consumption can be decreased by recycling products and lowering the demand for commodities that require a lot of energy. By carpooling, biking, telecommuting, reducing their travel, and consuming less meat and dairy, people can lower their GHG emissions.

Finally, effective regulations for gaining net-zero emissions in the UK through technological innovation include: boosting public funding for R&D in important areas such as advanced nuclear power, hydrogen production, CCS, long-duration energy storage, and efficient building technologies; and establishing market mechanisms that encourage private sector investment and the quick adoption of these innovations in industries, transportation, and energy generation. These should be combined with strong policy frameworks to control emissions and stimulate demand for low-carbon solutions, such as carbon pricing and energy efficiency models for buildings and vehicles. Targeted R&D funding, market development and incentives, regulatory frameworks, and sector-specific efforts are important policy areas to concentrate on. To take advantage of industry knowledge and investment, the UK might encourage solid collaborations within the public and financial sectors, enable people to take part in the shift to net zero by educating them about the advantages of clean technology innovation, and work together with other nations to exchange best practices and hasten the development of clean technologies worldwide.

Energy efficiency plays an essential part in driving technological innovation, as it often stimulates the expansion of new innovations and practices that reduce energy utilization while maintaining or enhancing performance. By prioritizing energy efficiency, businesses and governments in the UK can foster innovation in various sectors, from manufacturing to transportation, leading to the creation of advanced materials, smart systems, and renewable energy solutions. This synergy can contribute significantly to financial expansion and sustainability by lowering energy costs, reducing GHG emissions, and minimizing environmental impact. Policymakers, therefore, should focus on creating supportive frameworks that can provide funds for energy-efficient technologies, such as grants, tax incentives, and research funding. Additionally, implementing regulatory standards that demand higher efficiency performance can accelerate innovation cycles and market transformation, ultimately leading to a greener economy, improved energy security, and achieving net zero emissions.

The United Kingdom's pursuit of net-zero emissions by 2050 necessitates a multifaceted policy approach that integrates energy transition, technological advancements, and economic growth while addressing demographic dynamics. The shift from fossil fuels to renewable energy sources, such as wind and solar, has been instrumental in reducing carbon emissions, but policy support through subsidies, carbon pricing, and regulatory frameworks remains crucial to accelerate this transition. Energy efficiency improvements, driven by stringent building regulations and incentives for low-carbon technologies, contribute to reducing overall energy demand and enhancing sustainability without compromising economic growth. Technological innovation, including advancements in CCS and cleaner energy, plays a pivotal role in mitigating emissions from hard-to-abate sectors, necessitating increased public and private R&D investment. Population growth and urbanization present challenges for energy demand management, requiring policies that promote smart grids, sustainable transport, and green infrastructure. Economic growth, while essential for prosperity, must be decoupled from carbon emissions through circular economy principles, carbon taxation, and green finance initiatives. The findings suggest that a balanced approach combining market-based mechanisms, regulatory interventions, and targeted investments will be essential for the UK to achieve net-zero emissions while sustaining economic stability and social equity.

5.4. Limitations and future research perspectives

The elucidation of the factors that stimulate GHG emissions in the United Kingdom is achieved by an analysis of the STIRPAT model. However, this research possesses several significant limitations. One of the shortcomings of the model is the assumption of a linear relationship concerning GDP, population, nuclear energy, renewables, fossil fuels, energy efficiency, technological innovation, and GHG emissions. This study's focus is limited to the examination of the UK's GHG emissions, excluding the analysis of land use changes, forest cover, and agricultural techniques, which are potential factors that could impact these emissions. Future research may enhance the comprehension of the connections between GHG emissions and their primary indicators by incorporating supplementary variables into the scrutiny and employing more advanced statistical approaches. Carbon taxes, incentives for renewables, restrictions on fossil fuel usage, governmental policy interventions, and global energy price shocks represent a limited selection of measures that warrant investigation in order to enhance our comprehension of their efficacy in reducing emissions in the United Kingdom. Furthermore, this study did not consider external shocks (e.g., global energy prices), which can be considered in future studies. Another limitation is the data gaps. The investigation period is limited to the years 1990–2021 down to the unavailability of data on GHG emissions, renewable energy, and energy efficiency prior to 1990 and beyond 2021. Future research might consider a wide range of datasets including the latest available data. Finally, it is worth considering that research endeavors may be undertaken to explore the potential of CCS and other emerging innovations, in mitigating the emissions of the United Kingdom. Moreover, future studies may also consider other areas for further investigation, such as the integration of technological advancements in energy storage or the role of energy policy in influencing GHG emissions. It would also be valuable to conduct future research investigating the necessity of understanding the social and political acceptance of nuclear energy versus renewables, especially in light of evolving environmental concerns. Moreover, analogous studies are necessary for developing nations, including Saudi Arabia, to comprehend the dynamic impacts of diverse energy sources, innovative technologies, and socio-economic factors on the trajectory toward net-zero emissions.

CRediT authorship contribution statement

Asif Raihan: Visualization, Formal analysis, Writing – original draft, Data curation, Methodology, Conceptualization, Software. **Syed Masiur Rahman:** Writing – review & editing, Investigation, Visualization, Supervision, Validation. **Mohammad Ridwan:** Writing – review & editing, Validation, Data curation, Formal analysis, Writing – original draft, Visualization, Investigation, Software. **Tapan Sarker:** Supervision, Writing – review & editing, Investigation, Validation, Visualization. **Ousama Ben-Salha:** Validation, Writing – review & editing, Investigation. **Md Masudur Rahman:** Investigation, Writing – review & editing. **Grzegorz Zimon:** Investigation, Writing – review & editing. **Malayaranjan Sahoo:** Writing – review & editing. **Bablu Kumar Dhar:** Writing – review & editing, Investigation. **Md Mustaqim Roshid:** Writing – review & editing, Investigation. **Alaeldeen Ibrahim Elhaj:** Investigation, Writing – review & editing. **Syed Azher Hussain:** Writing – review & editing, Investigation. **A.B.M Mainul Bari:** Writing – review & editing, Investigation. **Samanta Islam:** Writing – review & editing. **Sirajum Munira:** Project administration, Investigation, Writing – review & editing, Validation, Visualization.

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.

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