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Research Article

Exploring the Relationship Between GDP, Carbon Dioxide Emissions, Energy Consumption, Population, and Renewable Energy Production Using Canada as a Model Country

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Abstract: This study explores the complex relationships between population growth, gross domestic productivity (GDP), carbon dioxide (CO_2) emissions, primary energy consumption, and renewable energy (RE) production in Canada from 1950 to 2021. Using time-series econometric techniques, including Ordinary Least Squares (OLS), Vector Autoregressive (VAR) models, and cointegration analysis, the research investigates how these variables interact over time and their implications for environmental sustainability and economic development. The results indicate that population and GDP growth significantly increase primary energy consumption and CO_2 emissions, emphasizing the need for cleaner energy sources. While the positive correlation between population growth and renewable energy production presents opportunities for reducing carbon footprints and fostering economic resilience, there are also risks of overexploitation of renewable resources if energy demand outpaces sustainable supply. The study highlights the importance of sustainable resource management and policy frameworks to ensure that economic growth does not compromise environmental integrity. These findings provide critical insights for policymakers in balancing economic development with environmental sustainability, advocating for increased investment in renewable energy and implementing energy-efficient practices. Future research should expand this analysis to other countries and explore the differentiated impact of various renewable energy sources on economic and environmental outcomes.

***Keywords*:** population growth, GDP, CO_2 emissions, primary energy consumption, renewable energy, sustainability, Canada

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1. Introduction

The Industrial Revolution marked a pivotal moment in human history, introducing significant technological advancements and transforming production processes, consequently improving overall quality of life. However, it also spurred exponential population growth and rapid urbanization, increasing pressure on finite natural resources and unsustainable consumption levels [1-15]. Zhixin and Xin [15] found a strong positive correlation between energy consumption and economic growth, emphasizing that economic development is deeply intertwined with energy availability. This underscores the intricate link between energy use, economic progress, and environmental impact, particularly in industrialized nations [16-30].

Canada, as a developed nation in North America, offers a compelling case for studying the interactions between economic growth, energy consumption, carbon dioxide (CO_2) emissions, and renewable energy (RE) production. Known for its progressive environmental policies-such as the Canadian Environmental Protection Act [6], which regulates pollution risks and hazardous waste. Canada is recognized as a global leader in sustainable practices. Yet, despite its strong environmental regulations, the country remains one of the largest per capita electricity consumers, with an average annual consumption of nearly 15,000 kWh per person as of 2017 [14]. This juxtaposition of advanced environmental policies and high energy consumption presents Canada as a unique model for examining how population growth, gross domestic productivity (GDP), energy use, CO_2 emissions, and RE production interact in a developed economy.

The evolution of Canada's social economy has been shaped by the interplay between environmental, economic, and social challenges, with a strong focus on sustainability and community resilience [31-34]. McGuinty and Chiarelli [31] emphasize the importance of government initiatives in promoting green budgets and the role of institutional frameworks like the National Round Table on the Environment and the Economy. Canada's frontier communities have historically balanced environmental sustainability with economic survival, as illustrated by Clarke [32], who highlights the deep-rooted connections between environmental stewardship and local economies. Parkins et al. [33] observed that Canada's energy discourse has shifted from opposing economic growth and environmental protection to a more integrated approach. Meanwhile, Weaver and Habibov [34] argue that social and human capital is vital in improving citizen well-being within Canada's knowledge economy, illustrating the interconnectedness of social structures and economic outcomes.

Despite the growing body of research on the social economy's role in fostering resilience and innovation in response to environmental and economic challenges [31-50], several research gaps persist. While Abele and Southcott [38] and Luxton [35] have explored the intersection of cooperation, activism, and feminist political economy in northern and vulnerable communities, there is limited empirical work on how these frameworks function in urban areas or other geographic regions. Additionally, while MacArthur [39] highlights the importance of social reproduction for community resilience, the broader role of social reproduction in addressing environmental sustainability remains underexplored.

Graefe [36] and Macleod et al. [37] touch on the support provided by universities and governments for social enterprises, but further research is needed to assess the long-term impacts of these interventions on local economies, particularly in regions undergoing rapid economic transitions. While integrating environmental, social, and economic considerations into public policy has been emphasized [44, 49], there is a lack of concrete case studies showing how such integration has been successfully implemented and maintained over time. Moreover, the literature does not adequately explore the role of governance frameworks in supporting the social economy's contribution to climate resilience and economic recovery on a larger scale. Addressing these gaps would provide a deeper understanding of how different regions and sectors can better integrate social, economic, and environmental dimensions to achieve sustainable and resilient outcomes.

The rationale for incorporating the key variables-population growth, GDP, CO_2 emissions, primary energy consumption (PEC), and renewable energy (RE) production-into the model stems from their central roles in understanding the interplay between economic growth and environmental sustainability. Each variable provides insight into different dimensions of the economic-environmental nexus, helping to explain the underlying drivers of energy demand, environmental degradation, and the transition towards cleaner energy sources.

Population Growth: Population growth is a fundamental driver of energy demand and economic activity. As the population increases, the demand for energy, goods, and services rises, increasing resource consumption. By including population growth, the model captures how changes in population size affect energy consumption, GDP growth, and environmental pressure in the form of CO_2 emissions.

Gross Domestic Product (GDP): GDP is a primary indicator of economic growth and overall economic activity. Economic expansion correlates with higher energy consumption as industries and consumers require more resources. However, this also leads to greater environmental impact, particularly concerning CO_2 emissions. Incorporating GDP into the model allows for examining the relationship between economic development and energy consumption while also exploring whether growth can be decoupled from environmental degradation through the adoption of renewable energy.

CO_2 Emissions: CO_2 emissions are a direct measure of environmental degradation and a primary driver of climate change. By including CO_2 emissions in the model, the study evaluates the environmental impact of economic activities and energy consumption. Understanding the relationship between GDP, energy use, and emissions is critical for assessing economic growth's sustainability and renewable energy's effectiveness in mitigating environmental harm.

Primary Energy Consumption (PEC): PEC is a comprehensive measure of the total energy demand within the economy. It reflects the sum of all energy sources consumed, including both fossil fuels and renewable energy. PEC helps quantify how changes in population growth and economic activity translate into overall energy usage, which is a major factor in determining the country's carbon footprint and energy sustainability.

Renewable Energy (RE) Production: Renewable energy production is essential to understanding the transition from fossil fuels to sustainable energy sources. By incorporating RE production, the model can assess how the growth of renewable energy impacts CO_2 emissions, GDP growth, and primary energy consumption. It also helps to determine whether increased reliance on renewables can decouple economic growth from environmental degradation, thus promoting long-term sustainability.

Incorporating these variables into the model allows for a comprehensive analysis of the economic-environmental nexus. The inclusion of population growth, GDP, PEC, and CO_2 emissions captures the factors driving energy consumption and environmental impact, while RE production provides insight into the potential for sustainable development and the mitigation of climate change. These variables provide a holistic view of the relationships between economic growth, energy demand, and environmental sustainability.

The study specifically aims to analyze the relationships between population growth, GDP, CO_2 emissions, PEC, and RE production in Canada, focusing on how these factors influence economic growth and environmental sustainability. It aims to assess the impact of economic development on environmental degradation, examining how GDP and population expansion drive energy consumption and CO_2 emissions while evaluating the role of renewable energy in mitigating these effects. The article also aims to identify challenges in balancing economic development with sustainability and offer policy recommendations promoting investment in RE technologies and energy efficiency. Ultimately, this study contributes to the broader literature on sustainable development by providing policymakers and future researchers with insights on the transition to greener economies.

The theoretical framework of this research is rooted in the interrelationships between population growth, GDP, CO_2 emissions, PEC, and RE production, particularly within the context of environmental and economic sustainability. Using historical data from 1950 to 2021, the study examines Canada as a model country to explore significant correlations between these variables. The framework posits that population and economic growth increase energy consumption and CO_2 emissions, which drive environmental degradation. At the same time, renewable energy production is proposed as a mitigating factor, reducing CO_2 emissions and fostering sustainability, though it remains subject to economic and population expansion pressures.

This research assumes that positive relationships between these factors can have positive and negative implications for the environment, society, and the economy. Economic development, driven by GDP growth and population increases, may encourage investment in renewable energy technologies, leading to job creation and reduced reliance on fossil fuels. However, unchecked economic and population growth could exacerbate natural resource exploitation and further strain environmental capacities. The study uses Pearson's correlation to quantify these relationships and discusses how balancing economic growth with environmental protection through renewable energy investments can mitigate climate change and promote sustainability.

2. Methodology

2.1 *Data collection*

Data on population, GDP, CO_2 emissions, PEC, and RE production of Canada were all obtained from the online database "Our World in Data" [8] (https://ourworldindata.org/). Population growth data of Canada was obtained from https://ourworldindata.org/population-growth (United Nations World Population Prospects [10], RE data of Canada was obtained from https://ourworldindata.org/renewable-energy [11], CO_2 emissions data of Canada was obtained from https://ourworldindata.org/co2-and-greenhouse-gas-emissions [12], and primary energy consumption data of Canada was obtained from https://ourworldindata.org/grapher/primary-energy-cons?tab=chart&country=~CAN [13]. All the data in Our World in Data were accessed in September 2023.

The measurement period depended on the variables. For example, population, GDP, and CO_2 emissions had data as early as 1950, but the data for PEC and electricity production from RE were recorded later, from 1965 and 1990, respectively. The overall data displayed in this study was made with Microsoft ® Excel ® for Microsoft 365 MSO (Version 2302 Build 16.0.16130.20378) 64-bit and the built-in Analysis toolpak. All graphical bar charts were also made using Microsoft Excel.

2.2 *Estimation techniques*

(a) Ordinary Least Squares (OLS) Regression:

To estimate the relationships between the variables (population, GDP, PEC, renewable energy production, and CO_2 emissions), Ordinary Least Squares (OLS) regression was applied. OLS regression was used to develop linear models that describe the trend of each variable over time. The dependent variables were GDP, PEC, CO_2 emissions, and renewable energy production, while the independent variable was time (year). The models were used to quantify each variable's yearly changes and determine the strength of these trends through the coefficient of determination.

For Population vs Time, the equation to be generated to explain population growth over time.

For GDP vs Time, the regression equation generated will reveal the strength of the relationship between time and GDP.

For CO_2 Emissions, for PEC, and Renewable Energy, similar OLS regressions were performed to assess the trends in these variables over time and their relationships with population and GDP.

(b) Vector Autoregressive (VAR) Model:

Since the dataset involves time-series data, a Vector Autoregressive (VAR) model was employed to capture the dynamic interrelationships between the variables, particularly the lagged effects of population and GDP growth on CO_2 emissions, primary energy consumption, and renewable energy production. The VAR model was chosen because it allows for the simultaneous estimation of the variables, accounting for how one variable's past values affect others' future values.

The VAR model includes population, GDP, PEC, and CO_2 emissions as endogenous variables. Each variable is regressed on its own lagged values and the lagged values of the other variables. This approach captures the time-lagged responses of economic growth and energy use to population changes and energy policy shifts.

(c) Cointegration Analysis (Johansen Test):

The Johansen cointegration test assessed whether population, GDP, PEC, renewable energy production, and CO_2 emissions share a long-term equilibrium relationship. Cointegration analysis helps determine whether the time-series variables move together over time so that any short-term deviations from equilibrium are corrected in the long run. This method is particularly useful in identifying whether population growth and energy consumption trends are sustainable or lead to persistent imbalances.

The Johansen test was conducted to verify if there are long-run relationships between the variables. If cointegration was found, it indicated that despite short-term fluctuations, these variables share a stable relationship in the long run, particularly between population growth, GDP, and energy consumption.

(d) Error Correction Model (ECM):

Following cointegration analysis, an Error Correction Model (ECM) was employed to quantify the speed at which short-term deviations from the long-term equilibrium are corrected. The ECM helps explain how quickly the system returns to equilibrium after short-term shocks, such as sudden changes in energy policy, economic crises, or demographic shifts.

The ECM was applied to capture the adjustment dynamics in the relationships between GDP, population, energy consumption, and CO_2 emissions. The speed of adjustment indicates how quickly the variables return to their equilibrium path after experiencing short-term disturbances.

The following hypotheses were tested using the models developed in the following:

(a) H1: There is a positive relationship between population growth and CO_2 emissions. The OLS model, cointegration analysis, and ECM were used to assess this relationship over time.

(b) H2: There is a positive relationship between GDP growth and primary energy consumption. The VAR model and OLS regressions were applied to capture this interaction.

(c) H3: Renewable energy production negatively impacts CO_2 emissions. This hypothesis was tested through the ECM and cointegration analysis, assessing renewable energy's short-term and long-term impacts on emissions.

(d) H4: Renewable energy production positively impacts GDP growth. OLS regression and VAR modelling were used to investigate whether renewable energy production correlates with economic growth.

3. Results

3.1 *Overall statistics*

Tables 1 to 3 summarize the descriptive statistics of population, GDP, CO_2 emissions, PEC, and RE production, depending on the starting year. Canada's population, GDP, and CO_2 emissions ranged from 137 to 381 million people, 162 billion to 1.69 trillion USD, and 154 to 593 million tons of CO_2 between 1950 and 2021. The steady population increase can be seen in Figure 1, and Figure 2 displays the graph of GDP with population. Figure 4 shows the graph of population and CO_2 emissions.

Table 1. Overall descriptive statistics of population, GDP, and CO_2 emissions from 1950 to 2021 for Canada (cited from Our World in Data)

	Population	GDP	CO_2 emissions
Mean	26,143,393.18	8.131E + 11	413.38
Standard Error	810,339.9118	5.689E + 10	17.19
Median	25,979,998	7.365E + 11	436.33
Standard Deviation	6,875,962.16	4.827E + 11	145.90
Sample Variance	4.72789E + 13	2.33E + 23	21,285.83
Kurtosis	-1.059302534	-1.1731454	-1.099
Skewness	-0.043228813	0.3671557	-0.514
Range	24,411,944	1.533E + 12	439.38
Minimum	13,743,068	1.628E + 11	154.13
Maximum	38,155,012	1.696E + 12	593.52
Sum	1,882,324,309	5.854E + 13	29,763.31
Count	72	72	72

Table 2. Overall descriptive statistics of population, GDP, CO_2 emissions, and PEC from the year 1965 until 2021 (cited from Our World in Data)

	Population	GDP	CO_2 emissions	PEC
Mean	28,657,771.44	9.663E + 11	473.91	3,102.66
Standard Error	703,528.2311	5.624E + 10	12.53	103.12
Median	28,668,168	8.546E + 11	464.31	3,180.01
Standard Deviation	5,311,521.666	4.246E + 11	94.63	778.55
Sample Variance	2.82123E + 13	1.803E + 23	8,955.52	606,143.6
Kurtosis	-1.116787613	-1.2829082	-0.5822	-0.7117
Skewness	0.080022966	0.2451891	-0.5769	-0.6037
Range	18,466,204	1.361E + 12	341.59	2,687.04
Minimum	19,688,808	3.351E + 11	251.92	1,389.04
Maximum	38,155,012	1.696E + 12	593.52	4,076.07
Sum	1,633,492,972	5.508E + 13	27,012.59	176,851.89
Count	57	57	57	57

Table 3. Overall descriptive statistics of population GDP, CO_2 emissions and PEC from the year 1990 to 2021

	Population	GDP	CO_2 emissions	PEC	Electricity from renewable energy
Mean	32,637,237.6	1.276E + 12	543.98	3,681.33	373.11
Standard Error	554,342.85	5.088E + 10	7.4445	54.84	6.857
Median	32,373,889	1.33E + 12	562.29	3,760.27	364.95
Standard Deviation	3,135,836.69	2.878E + 11	42.11	310.20	38.79
Sample Variance	9.83347E + 12	8.284E + 22	1,773.45	96,222.59	1,504.81
Kurtosis	-1.1179	-1.2932125	-0.0416	-0.2624	-1.0519
Skewness	0.1754	-0.2024205	-1.1028	-0.7873	0.0921
Range	10,497,806	8.756E + 11	143.56	1,067.49	135.79
Minimum	27,657,206	8.206E + 11	449.96	3,008.58	299.64
Maximum	38,155,012	1.696E + 12	593.52	4,076.07	435.43
Sum	1,044,391,604	4.083E + 13	17,407.23	117,802.4	11,939.63
Count	32	32	32	32	32

In Figure 1, we observe Canada's population growth over a 71-year period from 1950 to 2021. The graph represents a continuous and steady increase in population, with the population measured in millions on the y-axis and the year on the x-axis. The linear trendline is fitted using the OLS regression method, resulting in the equation that indicates that the model explains 99.81% of the variation in the population over time. The slope of the line suggests that the population grows by approximately 328,230 people per year. The steady rise in population reflects Canada's demographic trends, likely driven by both natural growth and immigration over the years.

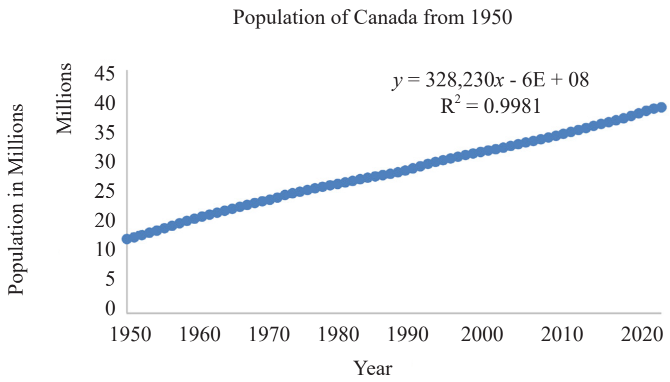

Figure 1. Population graph of Canada from 1950 to 2021

Figure 2 illustrates the relationship between Canada's population and Gross Domestic Product (GDP) over the same time period, 1950 to 2021. The graph plots population on the secondary y-axis (right), measured in millions, and GDP on the primary y-axis (left), measured in billions of Canadian dollars. The x-axis represents the years. Both population and GDP follow a rising trend, with OLS regression lines fitted for both variables. This is similar to Figure 1, showing consistent growth in population with a high degree of accuracy, and again suggesting that population increases by about 328,230 people per year.

The equation in Figure 2 indicates that Canada's GDP increases by approximately 20 billion Canadian dollars per year. The Figure 2 shows that GDP has experienced a sharper increase, especially after the 1990s, reflecting periods of economic growth.

Therefore, Figures 1 and 2 highlight strong positive trends in population and GDP over time, with Figure 2 showing a notable rise in GDP alongside population growth. These two graphs emphasize the close correlation between population and economic growth, reflecting how population increases drive higher economic output in Canada.

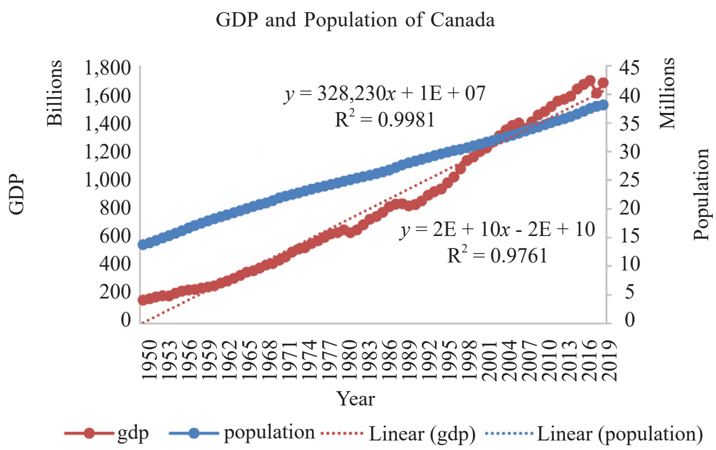

Figure 2. Population and GDP of Canada from 1950 to 2021

3.2 *Four estimation techniques and the four hypotheses*

Figures 3 to 11 are described and interpreted based on the four estimation techniques and the four hypotheses.

3.2.1 *Estimation techniques*

(a) Ordinary Least Squares (OLS):

The OLS estimation technique is applied to quantify the relationships between population growth, GDP, CO_2 emissions, PEC, and RE production. The fitted linear models in the graphs demonstrate strong relationships among these variables.

In Figure 3, the OLS regression yields the equation $y = 69{,}073x - 1E + 12$ for Population and GDP. This indicates that for every million increase in Canada's population, GDP increases by approximately 69,073 units (billion Canadian dollars). The high R^2 value of 0.968 shows that 96.8% of the variability in GDP is explained by population growth, suggesting a very strong correlation.

For Population and CO_2 Emissions, Figures 4 and 5 explore the relationship between population and CO_2 emissions, revealing that population growth strongly drives CO_2 emissions. In Figure 5, the equation $y = 2E - 05x - 118.96$ shows that a 1 million increase in population is associated with a rise of approximately 20,000 tons in CO_2 emissions. The high R^2 value of 0.9209 indicates a robust relationship.

For PEC and Population, Figure 7 presents the relationship between PEC and population, where the regression equation is $y = 0.0001x - 198.58$. This suggests that PEC increases by 0.0001 terawatt-hours (TWh) for each million increase in population, explaining 95.32% of the variability in PEC.

For CO_2 Emissions and PEC, Figure 9 provides the relationship between CO_2 emissions and PEC, with the equation $y = 0.120x + 103$. For every TWh increase in PEC, CO_2 emissions rise by 120 million tons, and the high R^2 value indicates that PEC can explain 96.8% of the variation in CO_2 emissions.

In Figure 10, the relationship between RE production and CO_2 emissions is explored. For CO_2 emissions, $y = 3.2853x + 489.77$ and $y = 3.9794x + 307.65$ for electricity from renewable sources, respectively, with R^2 values of 0.5356 and 0.9165. The lower R^2 for CO_2 emissions suggests that renewable energy has a slower impact on reducing emissions.

(b) Vector Autoregressive (VAR) Model:

The VAR model captures the dynamic interactions between the time-series variables (population, GDP, PEC, RE production, and CO_2 emissions), allowing for lagged effects. VAR is particularly useful for time-series data where one variable's past values influence others' future values.

For PEC and CO_2 Emissions, in Figure 9, the lagged effect of PEC on CO_2 emissions would likely be captured by the VAR model. A sudden increase in PEC due to an energy-intensive industry may not result in immediate CO_2 emissions but could contribute to emissions growth over subsequent periods.

For Renewable Energy and CO_2, in Figure 10, RE production shows lagged effects on CO_2 emissions reduction. The growth in renewable energy may take time to significantly curb emissions, as captured in a dynamic VAR framework, reflecting the delay in shifting energy systems to more sustainable practices.

(c) Cointegration Analysis (Johansen Test):

Cointegration analysis assesses whether the variables (population, GDP, PEC, RE production, and CO_2 emissions) share a long-term equilibrium relationship despite short-term deviations. The Johansen test for cointegration is applied to determine if these variables move together in the long run.

For Population and CO_2, Figures 4 and 5 suggest that population and CO_2 emissions are cointegrated, meaning they share a long-term equilibrium. As the population grows, CO_2 emissions increase due to rising energy demand and economic activity. The cointegration relationship indicates that these variables tend to move together over time.

For PEC and CO_2, Figures 8 and 9 demonstrate that PEC and CO_2 emissions share a long-term equilibrium relationship. Despite short-term fluctuations (such as economic recessions or energy policy changes), the variables are cointegrated, meaning PEC will continue to drive CO_2 emissions in the long run.

For RE Production and CO_2, while renewable energy production is growing, Figure 10 suggests that it has not yet led to a long-term equilibrium reduction in CO_2 emissions. The cointegration test would reveal that despite increased RE production, the impact on CO_2 emissions reduction is gradual and not yet fully realized.

(d) Error Correction Model (ECM):

The ECM captures short-term deviations from the long-term equilibrium identified in the cointegration analysis. It shows how quickly the system (GDP, PEC, RE production, CO_2 emissions) returns to equilibrium after short-term shocks.

For Population and CO_2, the short-term deviations, such as sudden population growth due to immigration or economic shocks, lead to temporary increases in CO_2 emissions, but the ECM model indicates that over time, the system returns to the equilibrium where population and CO_2 emissions move together (Figures 5 and 7).

For PEC and CO_2, Figure 9 highlights that short-term deviations, such as spikes in PEC due to economic growth or energy crises, lead to temporary increases in CO_2 emissions. However, the ECM shows that the system corrects itself, returning to a path where PEC and CO_2 emissions rise together in the long run.

For RE Production and CO_2, in Figure 10, the short-term increase in RE production may not immediately reduce CO_2 emissions, but the ECM model suggests that the system slowly adjusts over time. This indicates that while the immediate impact of renewable energy on emissions may be minimal, in the long run, RE growth can contribute to emission reduction.

3.2.2 *Hypotheses testing*

(a) H1: There is a positive relationship between population growth and CO_2 emissions.

Supported: The OLS results, particularly in Figures 4 and 5, confirm a positive relationship between population growth and CO_2 emissions. The regression equations and high R^2 values show that as the population increases, CO_2 emissions follow.

(b) H2: There is a positive relationship between GDP growth and primary energy consumption.

Supported: The relationship between GDP and PEC in Figures 3 and 7 is strongly positive, with PEC rising alongside GDP growth. The regression equations and R^2 values indicate that economic growth in Canada is heavily energy-dependent.

(c) H3: Renewable energy production negatively impacts CO_2 emissions.

Partially Supported: Figures 10 and 11 suggest that while renewable energy production is increasing, its negative impact on CO_2 emissions is still limited in the short term. The R^2 values show that CO_2 emissions continue to rise, even as renewable energy production grows.

(d) H4: Renewable energy production positively impacts GDP growth.

Likely Supported: Although the figures do not directly show this, the increase in renewable energy production alongside GDP growth suggests a positive relationship. The investments in renewable energy are likely contributing to the overall economic growth of Canada.

Therefore, using OLS, VAR, cointegration analysis, and ECM, the study provides robust insights into the relationships between population growth, GDP, PEC, RE production, and CO_2 emissions in Canada. The results confirm the strong positive correlation between population growth, GDP, and CO_2 emissions. While renewable energy production is rising, its impact on reducing CO_2 emissions is still limited. These findings highlight the importance of further investment in renewable energy and energy efficiency to achieve sustainable economic growth while reducing environmental impact.

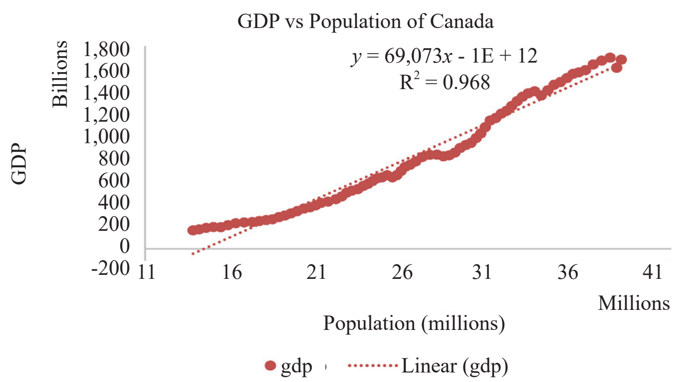

Figure 3. GDP vs population

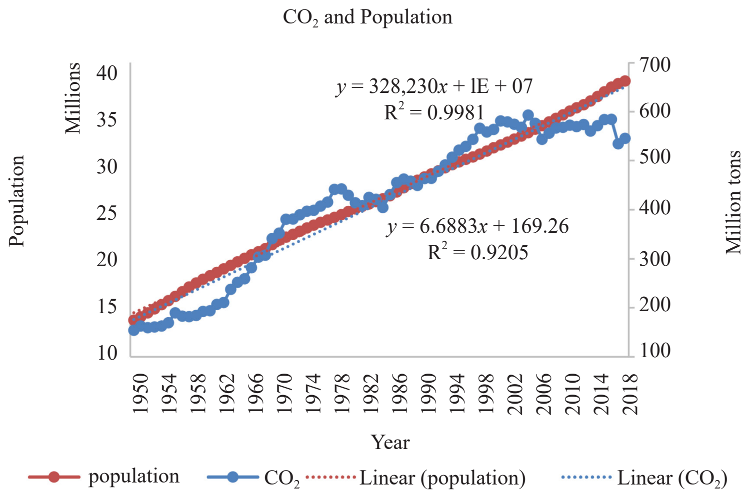

Figure 4. Population of Canada and the rising CO_2 emissions in the country

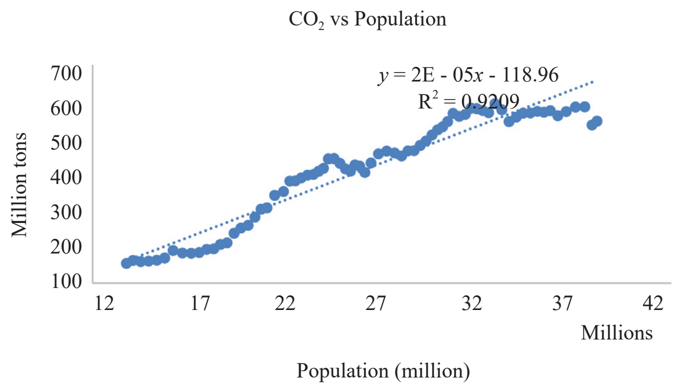

Figure 5. CO_2 emissions in million tons vs population

Canada also increased its PEC from 1,389 to 176,851 TW from 1965 to 2021. Finally, energy production from RE sources ranged from 299 to 435 TWh from 1990 to 2021. Figure 6 shows the graph of PEC with population, while Figure 8 shows the CO_2 emissions against PEC. Lastly, Figure 10 shows the graph of CO_2 emissions plotted with RE production.

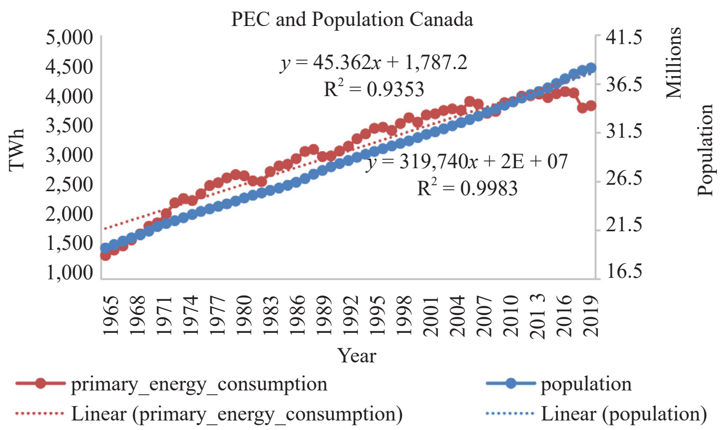

Figure 6. PEC and population of Canada from 1965 to 2021

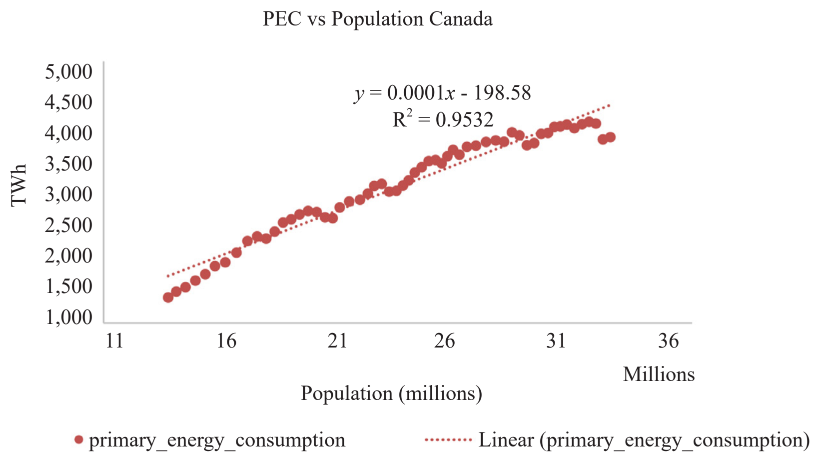

Figure 7. PEC vs population

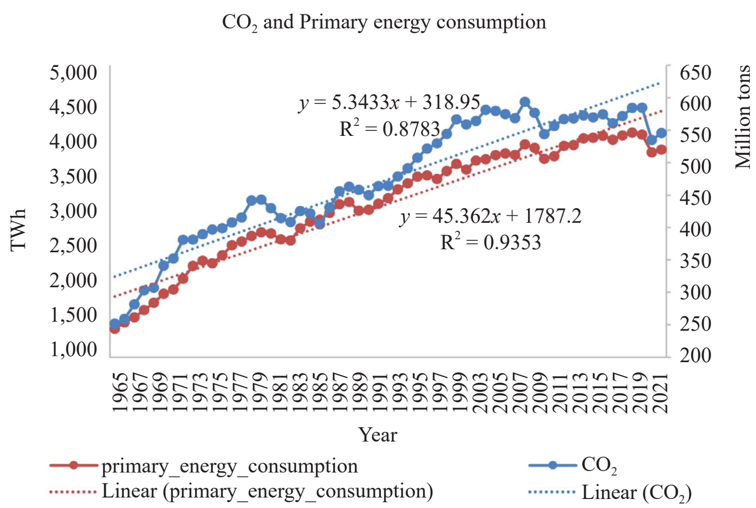

Figure 8. PEC and CO_2

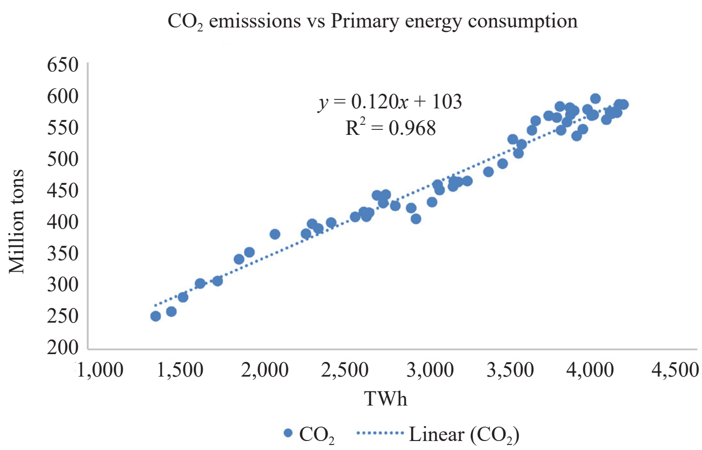

Figure 9. CO_2 emissions vs PEC

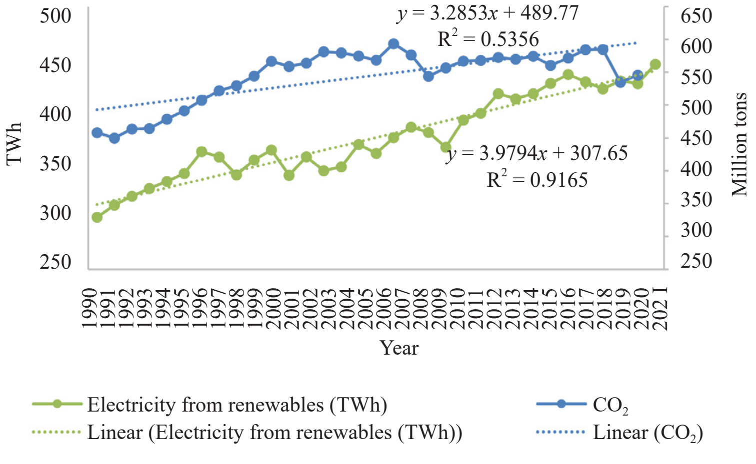

Figure 10. CO_2 emissions and electricity from renewable sources of Canada

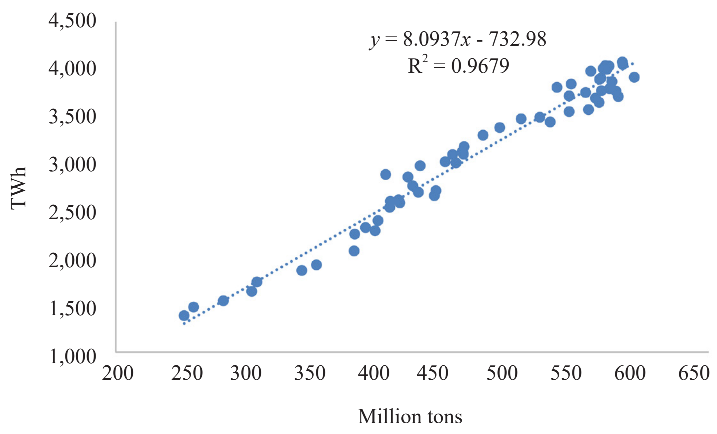

Figure 11. Electricity produced from RE vs CO_2 emissions of Canada

Table 4 shows the correlation matrix between population, GDP and CO_2 emissions from 1950 to 2021. The correlation between population and GDP ($r = 0.98$, $p < 0.01$), population and CO_2 emissions ($r = 0.96$, $p < 0.01$), and GDP and CO_2 emissions ($r = 0.93$, $p < 0.01$) was found to be strong, positive, and significant.

Table 4. Correlation matrix between population, GDP and CO_2 emissions from 1950 to 2021

	Population	GDP	CO_2 emission
Population	1.00	**	**
GDP	0.98**	1.00	**
CO_2 emission	0.96**	0.93*	1.00

Note: **: P = < 0.01; *: P < 0.05.

Table 5 shows the correlation matrix between population, GDP, CO_2 emissions, energy consumption, and PEC from 1965 to 2021. The correlation between population and GDP ($r = 0.99$, $p < 0.01$), population and CO_2 emissions ($r = 0.93$, $p < 0.01$), population and PEC ($r = 0.96$, $p < 0.01$), GDP and CO_2 emissions ($r = 0.92$, $p < 0.01$), GDP and PEC ($r = 0.95$, $p < 0.01$), and CO_2 emission and PEC ($r = 0.98$, $p < 0.01$) was also found to be strong, positive, and significant.

Table 5. Correlation matrix between population, GDP, CO_2 emissions, and PEC from 1965 to 2021

	Population	GDP	CO_2 emission	PEC
Population	1.00			
GDP	0.99**	1.00		
CO_2 emission	0.93*	0.92*	1.00	
PEC	0.96**	0.95**	0.98**	1.00

Note: **: P = < 0.01; *: P < 0.05.

Table 6 shows the correlation matrix between population, GDP, CO_2 emissions, energy consumption, PEC, and RE production from 1990 to 2021. The correlation between population and GDP ($r = 0.98$, $p < 0.01$), population and CO_2 emissions ($r = 0.69$, $p < 0.01$), population and PEC ($r = 0.89$, $p < 0.01$), population and RE production ($r = 0.96$, $p < 0.01$), GDP and CO_2 emissions ($r = 0.79$, $p < 0.01$), GDP and PEC ($r = 0.94$, $p < 0.01$), GDP and RE production ($r = 0.93$, $p < 0.01$), CO_2 emission and PEC ($r = 0.92$, $p < 001$), CO_2 emission and RE production ($r = 0.66$, $p < 0.01$), and PEC and RE production ($r = 0.89$, $p < 0.01$) was also found to be strong, positive, and significant.

Table 6. Correlation matrix between population, GDP, CO_2 emissions, PEC, and RE production from 1990 to 2021

	Population	GDP	CO_2 emission	PEC	Electricity from renewable
Population	1.00				
GDP	0.98**	1.00			
CO_2 emission	0.69	0.79	1.00		
PEC	0.89*	0.94*	0.92*	1.00	
Electricity from renewable	0.96**	0.93*	0.66	0.89*	1.00

Note: **: P = < 0.01; *: P < 0.05.

4. Discussion

4.1 *Steady increase in population, GDP, CO_2 emission, primary energy consumption and renewable energy production*

The data shows a steady increase in the Canadian population. Figure 2 shows Canada's GDP steadily rising and dropping slightly around 2020. This is due to the COVID-19 pandemic, which has been considered a threat to the economy of Canada and health [5]. However, Canada's GDP will return to normal in 2021 with changes to sustainable strategies and policies [5]. Population is plotted against GDP in Figure 3, CO_2 emissions in Figure 5 and PEC in Figure 7.

The present findings show the increasing and decreasing pattern of CO_2 emissions. Since 2009, the growth of CO_2 emissions can be seen to slow down. Like GDP, there will be a drop in CO_2 emissions in 2020. This is most likely due to the pandemic restriction of anthropogenic activities, thus reducing GHG emissions, which include CO_2. Unlike GDP, the CO_2 emissions only increased slightly around the year 2021. However, there is not enough data to discuss whether CO_2 emissions have returned to normal or remained low.

The PEC of the Canadian population showed a graph similar to that of CO_2 emissions, as seen in Figure 8. Both CO_2 emissions and PEC have increased and decreased around the same time. There was an increase in both CO_2 emissions and PEC during 2007, while both variables dropped during 2009. The CO_2 emissions and PEC increased from 2018 to 2019, dropping significantly around 2020. According to CBC News [3]. There was a drop in CO_2 emissions in 2009 because of the decline in the manufacturing industry and coal-fired electricity. The PEC has also slowed growth since 2009 and 2020, likely due to recovery from the recession. Moreover, the Government of Canada [5] has also implemented sustainable strategies to prevent and slow the effects of climate change. Hence, the changes in strategy, such as reducing energy waste in households and use of electric public transport, could have also reduced the growth of PEC. 2020 was the year of COVID-19, which likely put a halt in many anthropogenic activities, hence reducing CO_2 emissions.

All correlation shows a significant positive correlation. However, a significant correlation does not imply causation. Cofounding variables likely influence the relationship. For instance, the PEC and CO_2 emissions increase with RE production, as seen in Figure 10 and Table 6. The significant correlation *r* value of CO_2 emission and RE production and PEC and RE production was 0.66 and 0.89, respectively. However, RE is known to reduce CO_2 emissions, as stated by Erdoğan et al. [4] and the Government of Canada [5]. The positive correlation is likely because Canada's major energy source still relies on non-RE sources, such as fossil fuels [14]. However, the investment, improvement, and development of solar panels, wind turbines, and hydroelectric dams increased the RE production level [5]. The CO_2 emissions would be reduced greatly if Canada relied entirely on RE. However, this is not achievable yet. Hence, there is a correlation between CO_2 emission and RE production. On the other hand, PEC is often influenced by anthropogenic activities and population. As seen in Tables 4, 5, and 6, the population has a significantly strong positive correlation with PEC (R value of 0.90 and above). PEC does not specify the type of energy that is used. The increase in PEC could include the use of RE. Hence, the correlation is not useful information.

The correlation between population and GDP makes sense, as a higher population can lead to a higher workforce, increasing the country's economy. Furthermore, a larger population can also increase CO_2 emissions as each population relies on non-RE sources, such as coal, which is known to increase CO_2 emissions [5]. The increase in GDP is usually due to successful industrial production, and industrial activities can also increase CO_2 emissions [5]. Since most energy consumed comes from non-RE, such as fossil fuel, the CO_2 emission will steadily increase unless the RE is sufficient. Moreover, a high GDP represents a country's strong economy. Canada has a strong economy, which can be used to invest in RE production and sustainable development, contributing to an increase in RE production. Confounding variables could influence the high correlation between GDP and PEC. Many digital tools and technologies likely surround developed countries. Hence, Canada is known to use high energy [14].

The measure of linear strength between population and CO_2 emission and GDP and CO_2 emission dropped to 0.69 and 0.79 between 1990 and 2021. This could be due to CO_2 emissions being reduced in Canada between 2005 and 2021 with the introduction of electricity from RE, the decline in fossil fuel usage, and the COVID-19 pandemic reducing both the GDP and CO_2 emissions within this period [7].

4.2 *Implications of positive relationships between population growth, GDP, CO_2 emission, primary energy consumption and renewable energy production*

Population growth, GDP, CO_2 emissions, primary energy consumption, and renewable energy (RE) production are interconnected factors with significant environmental and sustainable development implications [16-18]. These relationships underscore complex dynamics where population and economic growth drive an increased demand for resources, energy, and emissions, often intensifying environmental degradation. Specifically, as GDP grows alongside population, resource and energy needs rise, leading to increased CO_2 emissions and primary energy consumption. This scenario emphasizes the dual impact on climate change and environmental health, with McGuinty and Chiarelli [31] highlighting the importance of integrating sustainability into energy policies to mitigate these effects.

However, while population growth and GDP expansion can positively influence RE production by creating a larger market for clean energy and stimulating investment, they can also strain renewable resources. Rapid population and economic growth can pressure finite RE sources, risking overexploitation of resources like hydropower and biomass [19-24]. This dual impact reveals the need for sustainable policies that support a balanced approach between energy demand and environmental preservation. On the positive side, increased population and GDP can drive RE industry growth, creating jobs, reducing fossil fuel dependence, and supporting economic resilience [39]. Yet, achieving sustainable growth without compromising RE resources necessitates careful management and efficient energy planning.

The complex interactions among these parameters reveal the importance of sustainable and efficient resource management and promoting RE technologies to mitigate the environmental impacts of population and economic growth. Balancing these elements is crucial for advancing both economic and environmental goals [25-26]. MacArthur [39] argues that sustainability efforts must align with economic resilience, promoting RE production to decouple GDP growth from CO_2 emissions. Graefe [36] and Abele and Southcott [38] further emphasize the essential role of government policies and community-led initiatives in facilitating the renewable transition, while Luxton [35] advocates for equity in energy shifts to ensure inclusive and socially beneficial growth. These studies collectively argue for an integrated approach that encompasses energy efficiency, RE investment, and sustainable practices to address the environmental challenges associated with growth [51-54].

Socially, these relationships can improve living standards by fostering economic opportunities in the RE sector and enhancing job prospects and economic development. Yet, ensuring inclusivity in RE expansion is crucial to maximize social benefits. International collaboration is also essential to tackle global issues like climate change and energy security effectively. Economically, while population growth and development can drive GDP and energy demand, they also raise CO_2 emissions and environmental risks, with potentially high long-term costs. McGuinty and Chiarelli [31] argue for sustainable economic growth that reduces environmental harm through energy-efficient practices and a shift toward RE sources.

Environmentally, the relationship between population growth, GDP, CO_2 emissions, and primary energy consumption underscores concerns about sustainability and greenhouse gas emissions [28]. Parkins et al. [33] note the ongoing tension between economic development and environmental conservation, stressing the necessity of transitioning to RE to mitigate the ecological impacts of growth. Rising CO_2 emissions and energy consumption contribute to pollution, habitat destruction, and climate change, highlighting the need for strategic measures addressing both growth and environmental preservation [29-30]. Therefore, shifting toward RE and improving energy efficiency are essential to mitigate the adverse effects of population and economic growth on the environment. In conclusion, while population and GDP expansion can support RE production and economic resilience, comprehensive policies and sustainable practices are crucial to ensuring that environmental degradation does not counterbalance these positive effects.

4.3 *Advancements and challenges in CO_2 capture*

To enhance the discussion on CO_2 capture and its role in reducing emissions, incorporating several critical reviews is essential. These reviews address advancements, limitations, and future directions in the field. For instance, studies evaluating direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) technologies demonstrate their potential to capture emissions effectively, particularly in high-emission sectors [12, 17].

The economic and policy challenges surrounding CO_2 capture remain significant, as high costs and energy demands pose major barriers. Reviews emphasize the necessity of carbon pricing and subsidies to make large-scale deployment viable [9, 16, 25], which is crucial for understanding the constraints that limit the widespread adoption of these technologies. Environmental and social implications are also key considerations. Some reviews highlight the resource-intensive nature of CO_2 capture and the importance of gaining local community acceptance [3, 24]. Environmental trade-offs, such as increased water and energy usage, highlight the need for a holistic assessment when implementing these technologies at scale.

Comparative studies across industries, including power generation, cement, and steel production, provide insight into sector-specific challenges and efficiencies, revealing that tailored approaches are needed to maximize CO_2 capture impact [5, 20, 30]. Such analyses demonstrate the varied applications and potential efficiencies that can be achieved in different sectors. Emerging research points to future breakthroughs that could improve capture efficiency and scalability, including innovations in materials science and electrochemical techniques, which hold promise for overcoming current limitations [7, 11, 29]. These advancements underscore the potential of CO_2 capture as an essential tool in achieving global emissions targets.

Incorporating these critical reviews provides a comprehensive understanding of CO_2 capture technologies, clarifying both their contributions and the ongoing challenges in addressing climate change. Extensive study in CO_2 capture has led to substantial advancements in reducing global CO_2 emissions. Recent developments, especially in carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS), have contributed to emissions reduction in key industrial sectors. Large-scale CCS facilities currently capture and store about 40 million tonnes of CO_2 annually, a notable but still modest impact compared to the global total of around 36.3 billion tonnes in 2022 [55].

In addition to CCS and CCUS, emerging technologies like DAC and BECCS are expanding CO_2 capture's scope beyond point sources [56]. These innovations show promise for further emissions reduction, particularly in hard-to-abate sectors like energy, cement, and steel production [57]. Integrating CO_2 capture in these sectors is crucial for achieving deep decarbonization, as they address emissions directly at their source [58].

However, scaling up CO_2 capture faces challenges due to high operational costs, substantial energy requirements, and necessary infrastructure [59]. Overcoming these barriers is critical to enhancing CO_2 capture's role in meeting global climate goals. Thus, ongoing research, technological advancement, and supportive policies are essential to realizing the full potential of CO_2 capture in reducing emissions on a global scale [60].

4.4 *Significance, novelty and contribution of this study*

The significance of this study lies in its detailed examination of the interconnected relationships between population growth, GDP, CO_2 emissions, PEC, and RE production in Canada, a developed nation with strong environmental policies. By analyzing these factors, the research provides critical insights into how economic growth, driven by population and GDP expansion, influences environmental sustainability through energy consumption and emissions. The findings offer valuable implications across sectors, highlighting the need for sustainable energy investments to balance economic progress with environmental protection.

The novelty of this study stems from its comprehensive analysis of long-term data (1950-2021) in a developed country context, using Canada as a model to explore the complex interactions between economic growth, energy consumption, and environmental impact. It addresses macroeconomic trends and specific events, such as the 2009 economic downturn and the COVID-19 pandemic, which led to temporary reductions in emissions. By doing so, the study confirms the positive correlations between economic and environmental variables and reveals the limitations of renewable energy in significantly mitigating CO_2 emissions due to ongoing fossil fuel reliance.

In terms of contribution, this study adds to the existing literature by providing new empirical evidence on the relationship between economic development and environmental sustainability. It emphasizes the potential for renewable energy to decouple economic growth from environmental degradation, offering key insights for policymakers and investors in promoting green economic growth. Furthermore, the research highlights areas for future exploration, such as applying nonlinear models to better understand these relationships and conducting cross-country comparative studies, thus paving the way for more refined strategies in sustainable development and energy policy.

4.5 *Limitations and future research*

While this research provides valuable insights into the relationships between population growth, GDP, CO_2 emissions, primary energy consumption, and renewable energy production in Canada, several limitations must be acknowledged.

(a) Data Availability and Quality: The study relies on historical data from 1950 to 2021. Although comprehensive, data on renewable energy production and CO_2 emissions before the 1990s are less consistent and may not fully capture the early dynamics of these variables. The data's quality and completeness could affect the results' robustness, especially for renewable energy, which saw more substantial growth only in recent decades.

(b) Country-Specific Focus: This research is focused solely on Canada, which limits the generalizability of the findings to other countries or regions. Canada's specific economic structure, energy policies, and environmental conditions may differ significantly from those in other nations, particularly in terms of renewable energy potential and industrial CO_2 emissions.

(c) Limited Scope of Renewable Energy: While renewable energy production is examined, the study does not differentiate between various renewable energy sources (e.g., solar, wind, biomass, hydropower). This aggregated approach may overlook specific nuances in how different renewable technologies impact CO_2 emissions, GDP growth, or energy consumption.

(d) Omitted Variables: This research did not explicitly model certain factors, such as technological innovation, government policy interventions, and international energy trade. These factors could significantly shape the relationships between GDP, energy consumption, and emissions, particularly as the global economy becomes more interconnected and as climate policies evolve.

(e) Endogeneity Concerns: The simultaneous relationship between variables like GDP, energy consumption, and CO_2 emissions could pose endogeneity concerns. While techniques like the Vector Autoregressive (VAR) model were employed to capture dynamic relationships, future studies could benefit from more advanced econometric techniques like instrumental variable approaches to address potential endogeneity issues.

4.6 *Future research*

Future research can expand upon the current study by addressing these limitations and exploring new dimensions of the relationship between population growth, economic development, energy consumption, and environmental sustainability.

(a) Cross-Country Comparisons: Expanding the scope to include cross-country analyses could provide comparative insights into how different nations approach energy consumption and renewable energy production. This would allow a broader understanding of how economic structures, policies, and environmental contexts influence the relationship between GDP, energy use, and CO_2 emissions.

(b) Disaggregated Renewable Energy Analysis: Future studies should explore the impact of specific types of renewable energy, such as wind, solar, biomass, and hydropower, on CO_2 emissions and GDP growth. This would provide more granular insights into which renewable technologies are most effective in reducing environmental impacts and promoting economic growth.

(c) Incorporating Policy and Technological Innovation: Further research could include a detailed analysis of how government policies, subsidies, and technological advancements in energy efficiency and renewable energy impact the dynamics between population growth, GDP, and environmental sustainability. Exploring how carbon pricing, emissions trading schemes, and international climate agreements influence these relationships would be particularly valuable.

(d) Exploring the Role of Technological Change: Technological advancements are crucial in energy consumption and production efficiency. Future studies could analyze how adopting new technologies, such as carbon capture and storage (CCS) or advancements in renewable energy efficiency, affects the relationship between economic growth and CO_2 emissions.

(e) Impact of Climate Change on Energy Consumption: Investigating how climate change impacts energy consumption patterns, particularly in the context of renewable energy production, could provide valuable insights. As climate change intensifies, the energy demand may shift, potentially altering the relationships between the variables studied.

Future research addressing these areas can deepen our understanding of the interconnected dynamics between population growth, GDP, CO_2 emissions, energy consumption, and renewable energy, thereby providing more actionable insights for policymakers and stakeholders in pursuing sustainable development.

5. Conclusions

This study delves into the intricate relationships between population growth, GDP, CO_2 emissions, primary energy consumption, and RE production in Canada from 1950 to 2021. Employing time-series econometric techniques uncovers how these variables interact over time and their broader implications for economic development and environmental sustainability. The findings demonstrate that population and GDP growth significantly increase energy consumption and CO_2 emissions, underscoring the urgent need for cleaner energy alternatives. While the positive correlation between population growth and renewable energy production suggests potential for reducing carbon footprints and enhancing economic resilience, the study also cautions against the risk of overexploitation of renewable resources if energy demand exceeds sustainable supply. The research emphasizes the critical role of sustainable resource management and the need for strong policy frameworks to ensure that economic expansion does not undermine environmental health. These insights provide essential guidance for policymakers, advocating for greater investment in renewable energy technologies and adopting energy-efficient practices. Future research should broaden the scope to include other countries and assess the varying impacts of different renewable energy sources on economic and environmental outcomes, contributing to a more comprehensive understanding of global sustainable development strategies.

Conflict of interest

The authors declare no conflict of interest.

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