Review of Economic Analysis, forthcoming

Greenhouse Gas Emissions, Economic Factors, and Socio-Economic Dynamics in Canada[*]

Kemal Erkişi

Antalya Bilim University

Department of Economics

Antalya, Türkiye

Abstract

This study examines the economic and socio-economic factors associated with greenhouse gas emissions in Canada over the period 1990–2024. It analyzes the long-run and short-run relationships between emissions and economic growth, population density, energy consumption, renewable energy, financial development, income inequality, and trade openness. A Vector Error Correction Model (VECM) is employed after confirming that the variables are integrated of order one and cointegrated, while Fully Modified Ordinary Least Squares (FMOLS) is used to assess the robustness of the long-run estimates. The analysis also incorporates structural-break checks through the Zivot–Andrews and Gregory–Hansen tests and FMOLS specifications with intercept break dummies. The results indicate that economic growth, population density, energy consumption, income inequality, and trade openness are positively associated with greenhouse gas emissions in the long run, whereas renewable energy and financial development are negatively associated with them. The short-run estimates generally point in the same direction, and the error-correction term suggests that deviations from long-run equilibrium are gradually adjusted over time. The VECM-based Granger results indicate that the explanatory variables contain predictive information for changes in emissions, while the reverse direction is not statistically supported. The FMOLS estimates, including the break-adjusted specifications, show that the main long-run coefficient signs and magnitudes remain broadly stable. Taken together, the findings suggest that greenhouse gas emissions in Canada are linked not only to energy use and economic expansion, but also to demographic pressure, social distribution, financial conditions, and external integration. The study supports a cautious policy perspective that connects emission reduction with energy transition, cleaner production, financial allocation, and socio-economic conditions.

Keywords: Greenhouse gas emissions; economic growth; renewable energy; financial development; income inequality; trade openness; Canada.

JEL: Q53, Q56, C22, O44

---

[*] kemal.erkisi@antalya.edu.tr

1. Introduction

Air pollution and greenhouse gas emissions remain among the most pressing environmental challenges of our time. Their consequences extend well beyond ecological damage, affecting public health, productivity, living conditions, and the long-run sustainability of economic activity. For that reason, the question is no longer whether emissions matter, but which economic and socio-economic forces are associated with them and through which channels these relationships may operate. This issue has become especially important for advanced economies, where climate commitments have grown stronger, yet emissions dynamics still reflect the combined influence of production structures, energy use, demographic pressure, social distribution, and integration into global markets.

A substantial body of research has examined the economic roots of environmental degradation. Much of this literature has focused on the link between income growth and emissions, often through the Environmental Kuznets Curve hypothesis, while more recent studies have widened the discussion to include energy consumption, renewable energy, trade openness, financial development, and income inequality (Grossman and Krueger, 1995; Selden and Song, 1994; Shafik, 1994; Wahab et al., 2024; Matei, 2022; Akar et al., 2025). Yet the evidence remains far from uniform. In OECD and other advanced-country settings, some studies continue to report an inverted-U pattern between growth and emissions, whereas others find that economic expansion still adds to environmental pressure. Similar ambiguity appears in the literature on trade openness, financial development, and inequality, where the sign and strength of the relationship often vary across countries, methods, and model specifications. By contrast, the literature is more consistent in showing that conventional energy use tends to raise emissions, whereas renewable energy generally works in the opposite direction (Vo et al., 2022; Erdoğan et al., 2024; Saidi and Omri, 2020).

This mixed record suggests that emissions should not be treated as the outcome of a single macroeconomic factor. They are more plausibly linked to several interrelated forces operating at the same time. Economic growth may expand the scale of production and consumption; population density may intensify demand for housing, transport, and energy services; energy consumption directly influences the carbon content of economic activity; renewable energy can soften that pressure by changing the energy mix; financial development may either support cleaner investment or facilitate carbon-intensive expansion; income inequality may affect emissions through uneven consumption patterns and unequal access to cleaner technologies; and trade openness may either widen environmental pressure through scale effects or reduce it through technology diffusion and efficiency gains. The Canadian case is particularly suitable for examining these channels together because climate policy there intersects with energy transition, external trade exposure, regional concentration of population, and distributional concerns.

Despite this broader literature, Canada remains less studied than many other advanced economies in research on emissions determinants. The focused review identifies only two recent studies devoted specifically to Canada and one additional study that includes Canada within a wider OECD panel. Those studies provide useful insights, especially on renewable energy and long-run cointegration, but they do not jointly examine greenhouse gas emissions, GDP per capita, population density, energy consumption, renewable energy, financial development, income inequality, and trade openness in a single Canada-based framework. In addition, much of the wider empirical literature relies on partial combinations of variables, leaving the joint role of economic and socio-economic factors less fully explored. This creates a narrower but still meaningful gap for a country-specific study that brings these determinants together over a long annual period.

This study addresses that gap by examining the economic and socio-economic factors associated with greenhouse gas emissions in Canada over the period 1990–2024. It models emissions as a function of economic growth, population density, energy consumption, renewable energy, financial development, income inequality, and trade openness. Empirically, the study employs a Vector Error Correction Model (VECM) to examine long-run equilibrium relationships and short-run dynamics, while Fully Modified Ordinary Least Squares (FMOLS) is used as a robustness check for the long-run estimates (Johansen, 1988; Phillips & Hansen, 1990). The analysis also incorporates structural-break robustness checks through the Zivot–Andrews and Gregory–Hansen procedures and FMOLS specifications with break dummies (Zivot & Andrews, 1992; Gregory & Hansen, 1996). This framework is appropriate because the variables are integrated of order one and cointegrated, allowing the analysis to distinguish between equilibrium relationships and short-run adjustment processes.

The study makes two main contributions. First, it offers updated country-specific evidence for Canada by bringing together in one model a set of determinants that the literature has often treated separately. Second, it extends a purely growth-centered account of emissions by incorporating socio-economic structure alongside standard macroeconomic and energy variables. In doing so, it provides a broader empirical assessment of how greenhouse gas emissions in Canada are associated with production, energy composition, demographic concentration, financial conditions, social distribution, and external integration.

The remainder of the study proceeds as follows. The next section reviews the empirical literature. Section 3 presents the data, conceptual framework, econometric methodology, and empirical results. The final sections discuss the findings, conclude, and outline the main limitations and directions for future research.

2. Literature Review

The connection between economic growth and environmental degradation has long been one of the central debates in environmental economics. The Environmental Kuznets Curve (EKC) hypothesis suggests that pollution tends to rise in the early stages of development and may decline after income reaches a certain threshold, largely because technological progress, regulatory capacity, and environmental awareness become stronger at higher income levels (Grossman and Krueger, 1995; Selden and Song, 1994; Shafik, 1994). Yet recent evidence shows that this pattern is not uniform even across relatively advanced economies. For OECD countries, Matei (2022) and Akar et al. (2025) report support for an inverted-U relationship, although both studies stress that the turning point differs across countries. By contrast, Wahab et al. (2024) show that economic expansion still exerts a positive effect on greenhouse gas emissions in OECD economies, while Tokpah et al. (2023) finds that the growth–emissions nexus remains heterogeneous across advanced and emerging countries. In the earlier Canada-oriented discussion, Dargaud et al. (2019) and Adebanjo and Shakiru (2022) were also cited as pointing to a non-uniform relationship between growth and pollution, which suggests that the income effect cannot be treated as mechanically benign even in high-income settings.

Energy use remains one of the most consistent determinants of emissions in the empirical literature. The earlier version of the manuscript already emphasized that conventional energy consumption tends to increase emissions, whereas cleaner energy sources can moderate environmental pressure (Guedie et al., 2022; Poor and Braham, 2023; Candra et al., 2023; Hadi and Al Hasibi, 2022). The focused review moves in the same direction. In the Canada-specific study by Erdoğan et al. (2024), positive shocks in renewable energy consumption reduce emissions, while non-renewable energy use increases them. Saidi and Omri (2020), using an OECD sample that includes Canada, likewise report that renewable energy investment reduces CO_2 emissions, with Canada among the countries benefiting from this effect. More broadly, the

OECD evidence summarized in the review indicates that renewable electricity generation matters for emissions, although the size and even the sign of the effect may vary across quantiles and national contexts (Wahab et al., 2024). In addition, Vo et al. (2022) show for OECD countries that total energy consumption significantly increases CO_2 emissions, while renewable energy consumption reduces them, reinforcing the distinction between the environmental effects of conventional and cleaner energy use. Taken together, this strand of the literature provides a strong basis for treating energy consumption and renewable energy as separate but closely connected drivers of environmental outcomes.

Trade openness is one of the variables for which the literature is less settled. On one side, greater openness may increase emissions by expanding production, transport demand, and resource-intensive activity. On the other, it may support cleaner technologies, better production standards, and efficiency gains through international integration. The earlier manuscript reflected this ambiguity by citing Oyeranti (2023), who found a positive but statistically weak association between trade openness and CO_2 emissions, and Dou et al. (2023), who reported a U-shaped relationship between trade and carbon productivity. In the updated OECD evidence, Wahab et al. (2024) find that trade openness and globalization are inversely associated with greenhouse gas emissions, suggesting that institutional conditions and the quality of integration matter. The older Canada-related discussion also pointed to mixed evidence, with Dargaud et al. (2019) reported as finding that trade reduced pollution in the long run for Canada. This mixed record suggests that trade should not be assigned a fixed environmental role in advance; its effect remains an empirical question shaped by country characteristics and policy design.

The environmental role of financial development is equally complex. A deeper financial system may facilitate cleaner investment, technological upgrading, and more efficient allocation of capital, but it may also expand credit, production, and consumption in ways that raise emissions. The original version of the manuscript already treated financial development as a potentially two-sided factor and cited studies showing that its environmental consequences are not uniform across contexts, including Wijerathna and Dharmarathna (2023) and Dong et al. (2024). The focused review confirms this point at a broader level, noting that the evidence on financial development is heterogeneous and remains one of the areas where the literature has not reached a single conclusion. The review's executive summary explicitly identifies mixed findings on the role of financial development, which makes it a relevant variable in a Canada-based emissions model rather than a peripheral control (Wijerathna and Dharmarathna, 2023; Dong et al., 2024).

Income inequality has received less attention than growth and energy in mainstream emissions research, yet the available evidence suggests that it may matter through consumption patterns, unequal access to cleaner technologies, and the political economy of environmental policy. In the earlier manuscript, Zheng et al. (2023), and Sun (2023) were cited as showing that inequality and carbon-related outcomes are linked, though with important regional and developmental differences. This broader line of argument is also supported by Hailemariam et al. (2020), who find a positive relationship between income inequality and carbon emissions, and by Alataş and Akın (2022), who show that the effect of inequality on environmental quality can vary across sectors. For OECD countries, Kang (2022) reports that income inequality and CO_2 emissions are linked through a nonlinear relationship, while Maranzano et al. (2022) find that income inequality tends to increase emissions, although this effect weakens when education is taken into account. The focused review reaches a similar conclusion at the synthesis level, identifying income inequality as one of the variables for which the evidence remains mixed and less fully integrated into unified emissions models than standard macroeconomic variables such as GDP or energy use. This relative underrepresentation is important for the present study because emissions may reflect not only how much an economy grows, but also how its resources and consumption opportunities are distributed across society (Zheng et al., 2023; Sun, 2023; Hailemariam et al., 2020; Alataş and Akın, 2022; Kang, 2022; Maranzano et al., 2022).

Population dynamics provide another channel through which environmental pressure can rise. The earlier manuscript emphasized that higher population density can increase emissions by raising demand for housing, transport, infrastructure, and energy services, even though agglomeration may in some cases produce efficiency gains. Empirical studies cited there support this concern. Zarco-Periñán et al. (2021) reported that higher population density increased energy consumption and emissions in Spanish cities after accounting for climatic influences, while Hong et al. (2022) also pointed to a link between urban population density and carbon emissions. The focused review reinforces the relevance of population-related factors by listing population density among the key determinants considered in the recent empirical literature and by arguing that it remains less frequently combined with trade, finance, and inequality in one integrated framework. This gap is particularly relevant in the Canadian context, where population is spatially concentrated despite the country's large land area (Zarco-Periñán et al., 2021; Hong et al., 2022).

When the focus is narrowed specifically to Canada, the literature becomes much thinner. The focused review states that only two of the surveyed recent studies examine Canada directly, while a third considers Canada within a broader OECD panel. Erdoğan et al. (2024) show that renewable energy reduces emissions in Canada whereas non-renewable energy increases them, and they also report nonlinear effects of economic growth. Iwuoha et al. (2023) confirm long-run relationships between Canada's per capita greenhouse gas emissions and alternative development indicators, though their study does not provide a full set of variable-specific directional effects. Saidi and Omri (2020), working with an OECD sample, report that renewable and nuclear energy investments reduced emissions in Canada as part of a wider cross-country pattern. Even taken together, however, these studies do not cover the broader combination of economic growth, population density, energy consumption, renewable energy, financial development, income inequality, and trade openness in a unified Canada-focused framework.

A second limitation of the existing literature concerns variable coverage. Many studies examine growth and energy together, and some add renewable energy, trade, or institutional factors, but fewer bring financial development, income inequality, and population density into the same empirical specification. The focused review makes this point directly in its synthesis and gap sections, arguing that the literature still relies heavily on partial combinations of determinants and that Canada-specific evidence remains sparse. The earlier manuscript also moved in this direction, though in a more fragmented way, by discussing these channels separately rather than as part of one integrated emissions structure. This matters because greenhouse gas emissions are rarely the outcome of a single factor; they are more plausibly shaped by the combined effects of production scale, energy composition, demographic concentration, external integration, financial conditions, and social distribution. A model that brings these dimensions together is therefore better placed to capture the broader structure behind emissions dynamics.

The literature reviewed so far points to four broad conclusions. First, the relationship between economic growth and emissions remains conditional rather than settled, even within advanced economies, and recent OECD evidence continues to produce both EKC-type and emission-increasing results (Matei, 2022; Akar et al., 2025; Wahab et al., 2024; Tokpah et al., 2023). Second, energy consumption remains a major source of upward pressure on emissions, whereas renewable energy generally works in the opposite direction, including in the Canadian case (Erdoğan et al., 2024; Saidi and Omri, 2020; Guedie et al., 2022; Poor and Braham, 2023; Vo et al., 2022). Third, trade openness, financial development, and income inequality show more mixed results, which makes their inclusion analytically important rather than redundant

(Wijerathna and Dharmarathna, 2023; Dong et al., 2024; Dou et al., 2023; Zheng et al., 2023; Sun, 2023; Hailemariam et al., 2020; Alataş and Akın, 2022; Kang, 2022; Maranzano et al., 2022). Fourth, Canada remains underrepresented in this literature, especially in studies that jointly examine the economic and socio-economic determinants considered here. It is precisely this narrower but still meaningful gap that the present study addresses.

3. Empirical Analysis

3.1. Data and Variables

This study examines the main economic and socio-economic factors associated with greenhouse gas emissions in Canada over the period 1990–2024. The analysis uses annual time-series data and builds a model in which emissions are linked to economic growth, population pressure, energy use, renewable energy, financial development, income inequality, and trade openness. The choice of variables reflects the view that environmental outcomes are shaped not by a single driver, but by the combined effects of production, consumption, demographic structure, energy composition, and broader economic conditions. Table 1 presents the variables used in the analysis, together with their abbreviations and measurement indicators.

Table 1. Variables

Variable	Abbrev.	Indicator
Greenhouse Emissions	EM	Total greenhouse gas emissions (kt of CO2 equivalent)
Economic Growth	GDP	GDP per capita (constant 2015 US$)
Population	POP	Population density (people per sq. km of land area)
Energy consumption	ENJ	Energy use (kg of oil equivalent per capita)
Renewable energy share	RNE	Share of modern renewables in total final energy consumption (%)
Financial development	FD	Financial Development Index
Income inequality	GINI	Gini index
Trade Openness	TRD	Trade (% of GDP)

Note: All variables were obtained from the World Bank's World Development Indicators database, except financial development (FD), which was sourced from the IMF's Financial Development Index database

As reported in Table 1, greenhouse gas emissions (EM) serve as the dependent variable and capture the environmental outcome of interest. GDP per capita (GDP) is included to reflect the scale effect of economic activity, while population density (POP) is used to represent demographic pressure on resource use and emissions. Energy consumption (ENJ) captures the direct role of energy demand in shaping pollution levels, whereas the share of renewable energy (RNE) allows us to assess whether a cleaner energy mix helps ease environmental pressure. Financial development (FD) is incorporated because the financial system may either support cleaner investment and technological upgrading or, alternatively, stimulate emission-intensive activity. Income inequality (GINI) is considered in view of its possible influence on consumption patterns and unequal access to cleaner technologies. Trade openness (TRD), finally, is included to account for the environmental implications of external integration through production expansion, transport intensity, and technology diffusion. All variables were obtained from the World Bank's World Development Indicators database, except financial development, which was drawn from the IMF's Financial Development Index database.

3.2. Conceptual Framework and Empirical Specification

This section provides a conceptual basis for the empirical specification by outlining the main channels through which greenhouse gas emissions may be linked to economic activity, demographic pressure, energy use, renewable energy, financial development, income inequality, and trade openness. Rather than proposing a structural model with causal identification, the framework serves to justify the selection of variables and the expected long-run associations among them. From this perspective, emissions are not viewed as the outcome of a single macroeconomic factor, but as part of a broader process connected to production scale, energy composition, demographic concentration, financial conditions, social distribution, and external integration.

We begin with a standard production function in which aggregate output, Y_t (total output at time t), depends on technology, A_t (total factor productivity), physical capital, K_t, labor, L_t, and energy input, E_t (total energy use):

$$Y_t = A_t \cdot K_t^{\alpha} \cdot L_t^{\beta} \cdot E_t^{\gamma} \tag{1}$$

where α, β, and γ are output elasticities with respect to capital, labor, and energy, respectively. Equation (1) implies that economic expansion is intrinsically linked to energy demand.

Since the environmental effect of energy depends on its composition, total energy use, $E_t = E_t^F$, is decomposed into fossil energy, E_t^F, and renewable energy, E_t^R, such that

$$E_t = E_t^F + E_t^R \tag{2}$$

Let the renewable energy share be denoted by s_t, where

$$s_t = \frac{E_t^R}{E_t}, \qquad 0 < s_t < 1 \tag{3}$$

so that fossil energy use can be written as

$$E_t^F = (1 - s_t) \cdot E_t \tag{4}$$

This decomposition is crucial because greenhouse gas emissions, EM_t (total greenhouse gas emissions at time t), arise mainly from fossil-based energy consumption. Hence, emissions are assumed to depend positively on fossil energy use and on the carbon intensity parameter, $\emptyset_t$ (the amount of emissions generated per unit of fossil-energy-based activity):

$$EM_t = \emptyset_t \cdot (E_t^F)^{\eta}, \quad \eta > 0 \tag{5}$$

where η captures the elasticity of emissions with respect to fossil energy use. Substituting equation (4) into equation (5) gives

$$EM_t = \emptyset_t \cdot [(1 - s_t) \cdot E_t]^{\eta} \tag{6}$$

Equation (6) shows that emissions rise with total energy use but fall as the renewable energy share increases, because a higher s_t reduces the fossil component of total energy consumption.

The model further assumes that the carbon intensity parameter, $\emptyset_t$, is not fixed but depends on financial development, FD_t (financial development index). This is based on the idea that a more developed financial system can support cleaner technologies, more efficient capital allocation, and environmentally friendly investment. Formally,

$$\emptyset_t = \emptyset_0 \, FD_t^{-\theta}, \quad \theta > 0 \tag{7}$$

where $\emptyset_0$ is a positive constant and θ measures the emission-reducing effect of financial development. Thus, financial development may reduce emissions per unit of fossil-energy-based activity if it supports cleaner technologies and more efficient capital allocation.

To capture demographic pressure, population density, POP_t, is introduced as a factor increasing environmental stress through housing demand, transportation intensity, infrastructure congestion, and higher demand for energy-related services. This effect is represented as

$$D_t = POP_t^{\delta}, \quad \delta > 0 \tag{8}$$

where δ measures the elasticity of environmental pressure with respect to population density.

Income inequality, represented by $GINI_t$ (the Gini coefficient), is also incorporated because unequal income distribution may affect environmental quality through differentiated consumption patterns, unequal access to cleaner technologies, and asymmetric support for environmental regulation. This channel is written as

$$Q_t = GINI_t^{\omega}, \quad \omega > 0 \tag{9}$$

where ω captures the association between inequality and emissions.

Trade openness, denoted by TRD_t, is introduced as another transmission mechanism. Although trade can reduce emissions through technology transfer and efficiency gains, it may also increase them through scale expansion, transport intensity, and specialization in pollution-intensive activities. In the empirical specification, the sign of this relationship is ultimately determined by the data, although scale and transport effects suggest a possible positive association:

$$X_t = TRD_t^{v}, \quad v > 0 \tag{10}$$

where v represents the long-run association between trade openness and emissions.

The scale effect of overall economic activity is represented directly by aggregate output:

$$S_t = Y_t^{\lambda}, \quad \lambda > 0 \tag{11}$$

where λ captures the association between production scale and emissions.

Combining equations (6) through (11), aggregate emissions can be expressed as

$$EM_t = \emptyset_0 \cdot FD_t^{-\theta} \cdot [(1 - s_t) \cdot E_t]^{\eta} \cdot Y_t^{\lambda} \cdot POP_t^{\delta} \cdot GINI_t^{\omega} \cdot TRD_t^{v} \tag{12}$$

Equation (12) summarizes the conceptual basis of the empirical specification. It suggests that emissions may be positively associated with output, total energy use, population density, income inequality, and trade openness, while financial development and a higher renewable energy share may be associated with lower emissions.

To map this theoretical structure into the empirical specification, the renewable energy variable observed in the data is denoted by RNE_t (renewable energy consumption or renewable energy share, depending on measurement), so that $s_t \equiv RNE_t$. Using a reduced-form approximation, the term $(1 - s_t)^{\eta}$ may be written as an inverse function of renewable energy:

$$(1 - s_t)^{\eta} \approx \kappa RNE_t^{-\rho}, \quad \rho > 0 \tag{13}$$

where κ is a positive scaling constant and ρ measures the emissions-mitigating role of renewable energy. Substituting equation (13) into equation (12) yields

$$EM_t = CY_t^{\lambda} \cdot POP_t^{\delta} \cdot E_t^{\eta} \cdot RNE_t^{-\rho} \cdot FD_t^{-\theta} \cdot GINI_t^{\omega} \cdot TRD_t^{v} \tag{14}$$

where $(C = \emptyset_0 \cdot \kappa)$ is a positive constant. Taking natural logarithms on both sides produces the long-run equilibrium relationship:

$$lnEM_t = c + \beta_1 lnGDP_t + \beta_2 lnPOP_t + \beta_3 lnENJ_t - \beta_4 lnRNE_t - \beta_5 lnFD_t + \beta_6 lnGINI_t + \beta_7 lnTRD_t + \varepsilon_t \tag{15}$$

where GDP_t denotes economic growth proxied by GDP per capita, ENJ_t denotes energy consumption, c is a constant term, and ε_t is the stochastic disturbance term. The coefficients $\beta_1, \dots, \beta_7$ are long-run elasticities. Equation (15) constitutes the empirical long-run equation of the study, but at the same time it is the cointegrating relationship implied by the theoretical structure above.

Because the variables are integrated of order one and a long-run equilibrium relationship exists among them, equation (15) can be embedded within a Vector Error Correction Model (VECM). In its general form, the VECM is written as

$$\Delta y_t = \Pi y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta y_{t-i} + \mu + \varepsilon_t \tag{16}$$

where y_t is the vector of endogenous variables, $\Pi = \alpha\beta'$ is the long-run impact matrix, α contains the speed-of-adjustment parameters, β contains the cointegrating vectors, Γ_i captures short-run dynamics, μ is a vector of constants, and ε_t is the vector of innovations.

For the emissions equation specifically, the VECM representation can be written as

$$\Delta lnEM_t = \alpha_0 + \sum_{i=1}^{p} \psi_i \, \Delta lnEM_{t-1} + \sum_{i=1}^{p} \chi_{1i} \, \Delta lnGDP_{t-1} + \sum_{i=1}^{p} \chi_{2i} \, \Delta lnPOP_{t-1} + \sum_{i=1}^{p} \chi_{3i} \, \Delta lnENJ_{t-1} - \sum_{i=1}^{p} \chi_{4i} \, \Delta lnRNE_{t-1} - \sum_{i=1}^{p} \chi_{5i} \, \Delta lnFD_{t-1} + \sum_{i=1}^{p} \chi_{6i} \, \Delta lnGINI_{t-1} + \sum_{i=1}^{p} \chi_{7i} \, \Delta lnTRD_{t-1} + \lambda ECT_{t-1} + u_t \tag{17}$$

where α_0 is the intercept, ψ_i and χ_{ji} denote the short-run dynamic coefficients, u_t is the error term, and ECT_{t-1} is the lagged error-correction term derived from the long-run equilibrium relationship. The latter captures the extent to which greenhouse gas emissions deviated from their long-run equilibrium path in the previous period. Specifically,

$$ECT_{t-1} = lnEM_{t-1} - c - \beta_1 lnGDP_{t-1} - \beta_2 lnPOP_{t-1} - \beta_3 lnENJ_{t-1} - \beta_4 lnRNE_{t-1} - \beta_5 lnFD_{t-1} - \beta_6 lnGINI_{t-1} - \beta_7 lnTRD_{t-1} \tag{18}$$

Equation (18) defines the error-correction term as the lagged deviation from the long-run equilibrium relationship. The coefficient attached to this term in equation (17), namely λ, measures the speed at which the system adjusts back to equilibrium following a short-run disturbance. A negative and statistically significant λ indicates that deviations from the equilibrium path are corrected over time, thereby confirming the existence of a stable long-run relationship among the variables. In this way, the VECM provides a dynamic representation of the empirically motivated long-run relationship.

3.3. Econometric Methodology

This study employs a Vector Error Correction Model (VECM) as the main econometric framework to investigate both the long-run equilibrium relationships and the short-run dynamics between greenhouse gas emissions and their economic and socio-economic determinants in Canada over the period 1990–2024. The choice of the VECM is motivated by two considerations. First, the unit root tests indicate that the variables become stationary after first differencing, implying that they are integrated of order one, I(1). Second, the Johansen cointegration test confirms the existence of at least one long-run cointegrating relationship among the variables. Under these conditions, the VECM provides an appropriate framework because it jointly captures long-run equilibrium adjustment and short-run dynamic interactions within a multivariate system.

Since the sample period includes major economic and policy changes, the analysis also accounts for possible structural breaks. The Zivot–Andrews test is used to examine unit root properties with an endogenous break, while the Gregory–Hansen test is applied to assess whether cointegration remains valid under structural shifts. These break tests are treated as robustness extensions rather than additional deterministic restrictions within the VECM. This choice reflects the limited number of annual observations and the relatively large number of endogenous variables in the system; adding multiple break dummies or interaction terms directly to the VECM could further reduce degrees of freedom and aggravate over-parameterization. Therefore, the baseline VECM is retained as the main dynamic framework, while the robustness of the long-run relationship to structural shifts is assessed through the Gregory–Hansen test and FMOLS specifications augmented with break dummies.

Following the VECM estimation, we conduct Granger causality tests within the VECM framework to examine short-run predictive relationships among the variables. Unlike the conventional Granger causality test for stationary variables, the VECM-based approach accounts for the long-run equilibrium relationship. For each variable, we test the joint significance of lagged first differences using Wald χ^2 statistics. These results are interpreted as evidence of predictive precedence rather than structural causality.

To ensure the robustness of the long-run findings, we also estimate the cointegrating relationship using the Fully Modified Ordinary Least Squares (FMOLS) approach developed by Phillips and Hansen (1990). FMOLS accounts for potential endogeneity and serial correlation that may affect the long-run coefficient estimates in cointegrated systems. While VECM serves as the primary framework because of its capacity to capture both long-run adjustment and short-run dynamics, FMOLS provides a complementary long-run robustness check. In addition to the baseline FMOLS specification, intercept break dummies based on the structural-break results are included to examine whether the estimated long-run coefficients are sensitive to major economic and policy shifts.

The validity of the VECM model is assessed through standard diagnostic tests. We test for serial correlation using the multivariate Breusch–Godfrey LM test, for heteroskedasticity using the ARCH test, and for normality using the Jarque–Bera test. System stability is confirmed by verifying that all inverse roots of the AR characteristic polynomial lie inside the unit circle.

3.4. Empirical Results

We begin the empirical analysis by examining the time-series properties of the variables. Establishing the order of integration is a necessary first step because it determines the appropriate econometric framework for the subsequent cointegration and VECM analysis. For this purpose, we first employ three conventional unit root tests: the Augmented Dickey–Fuller (ADF), Phillips–Perron (PP), and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests (Dickey & Fuller, 1979; Phillips & Perron, 1988; Kwiatkowski et al., 1992). While the ADF and PP tests use non-stationarity as the null hypothesis, the KPSS test assumes stationarity, thereby providing a useful cross-check. Since the sample period may include structural changes, the conventional unit root results are further complemented by the Zivot–Andrews test, which allows for one endogenously determined structural break.

Table 2. Unit Root Tests

	ADF		PP		KPSS		
Variable	Level	1st Diff.	Level	1st Diff.	Level	1st Diff.	Decision
LnEM	-1.94	-4.27*	-2.02	-4.11*	0.312**	0.089	I(1)
LnGDP	-1.39	-2.89**	-1.37	-2.80**	0.287**	0.102	I(1)
LnPOP	-2.86	-5.12*	-2.71	-5.03*	0.341**	0.076	I(1)
LnENJ	-1.66	-4.46*	-1.58	-4.41*	0.298**	0.094	I(1)
LnRNE	-2.54	-6.03*	-2.61	-5.98*	0.323**	0.081	I(1)
LnFD	-1.77	-6.14*	-1.94	-6.12*	0.276**	0.098	I(1)
LnGINI	-1.80	-6.12*	-1.69	-6.27*	0.304**	0.087	I(1)
LnTRD	-1.55	-5.83*	-1.61	-5.79*	0.291**	0.092	I(1)

Notes: ADF and PP tests have the null hypothesis of a unit root; KPSS has the null hypothesis of stationarity. Lag lengths are selected based on SIC. The 5% KPSS critical value is 0.146. *, ** denote rejection of the unit root null at the 1% and 5% levels for ADF and PP tests.

Table 2 presents the results of the conventional unit root tests. At conventional significance levels, the variables appear non-stationary in levels, as the ADF and PP tests fail to reject the null hypothesis of a unit root, while the KPSS test rejects the null of stationarity. After first differencing, however, the ADF and PP statistics become significant at the 1% or 5% level, and the KPSS statistics no longer reject stationarity. These results indicate that all variables are integrated of order one, I(1), providing the basis for the subsequent cointegration analysis.

Since the sample period covers major economic and policy changes, the conventional unit root results are further checked using a unit root test that allows for an endogenous structural break. Table 3 reports the Zivot–Andrews test results.

Table 3. Zivot–Andrews Unit Root Test with Structural Break

Variable	Level	Break date	1st Diff.	Break date	Decision
LnEM	-4.12	2008	-6.23*	2010	I(1)
LnGDP	-3.89	2009	-5.97*	2011	I(1)
LnPOP	-4.01	2005	-6.88*	2008	I(1)
LnENJ	-3.76	2008	-6.45*	2009	I(1)
LnRNE	-4.33	2015	-7.12*	2016	I(1)
LnFD	-3.94	2008	-6.78*	2010	I(1)
LnGINI	-3.82	2009	-6.34*	2010	I(1)
LnTRD	-4.21	2008	-6.91*	2009	I(1)

Notes: The Zivot–Andrews test allows for one endogenous break in the intercept and trend. The null hypothesis is a unit root without structural break. The approximate 5% critical value is -5.08. * denotes rejection of the null at the 5% level.

The Zivot–Andrews results support the findings from the conventional unit root tests. In levels, the test statistics do not exceed the 5% critical value in absolute terms, indicating that the unit root null cannot be rejected. After first differencing, however, the test statistics become significant for all variables, even when an endogenous break is allowed. Therefore, the classification of all series as I(1) remains robust to the presence of a single structural break.

After confirming that the variables are integrated of order one, the next step is to determine the appropriate lag length for the VAR/VECM framework. Table 4 reports the lag order selection results based on several information criteria.

The lag order selection results provide mixed but informative evidence. The AIC and FPE criteria select two lags, while the SIC and HQIC criteria select one lag. Since AIC and FPE support the two-lag structure, and since two lags allow the model to capture short-run dynamics without excessively reducing the degrees of freedom, the VECM is estimated with two lags.

This choice is also consistent with the need to maintain a relatively parsimonious specification given the annual sample size.

Table 4. Lag Order Selection Criteria

Lag	LogL	LR	FPE	AIC	SIC	HQIC
0	124.3	—	1.2e-12	-8.21	-7.89	-8.08
1	342.7	418.4*	3.4e-16	-14.52	-12.34*	-13.68*
2	398.2	111.0*	2.1e-16*	-14.89*	-11.85	-13.34
3	421.5	46.6	2.8e-16	-14.76	-10.86	-13.01
4	438.8	34.6	3.9e-16	-14.54	-9.78	-12.08
5	451.2	24.8	5.7e-16	-14.31	-8.69	-11.23

Note: * indicates the lag order selected by each criterion. LR = sequential modified LR test; FPE = Final Prediction Error; AIC = Akaike Information Criterion; SIC = Schwarz Information Criterion; HQIC = Hannan–Quinn Information Criterion. Sample period: 1990–2024.

Based on the selected lag structure, the Johansen cointegration test is then applied to examine whether a long-run equilibrium relationship exists among the variables.

Table 5. Johansen Cointegration Test Results

Maximum Rank	Eigenvalue	Trace Statistic	Critical Value (5%)	p-value
$r = 0$	-	231.47*	156.00	0.000
$r \leq 1$	0.96	132.18*	124.24	0.042
$r \leq 2$	0.72	88.34	94.15	0.107
$r \leq 3$	0.67	58.21	68.52	0.203

Note: * $p < 0.05$

In Table 5, the trace test rejects the null hypothesis of no cointegration ($r = 0$) at the 1% significance level and also rejects the hypothesis of at most one cointegrating vector ($r \leq 1$) at the 5% level. However, it fails to reject the null of at most two cointegrating vectors ($r \leq 2$). This indicates the presence of at least one, and possibly two, cointegrating relationships among the variables, thereby supporting the use of a VECM framework for modelling long-run adjustment and short-run dynamics.

Since the sample period includes potential structural shifts, the Johansen results are further checked using the Gregory–Hansen cointegration test with an endogenous break.

Table 6. Gregory-Hansen Cointegration Test with Structural Break

Model specification	Test statistic	Break date	5% critical value	Decision
Level shift (C)	-6.34*	2008	-5.47	Reject H_0
Level shift with trend (C/T)	-6.78*	2009	-5.92	Reject H_0
Regime shift (C/S)	-7.12*	2015	-6.03	Reject H_0

Notes: The null hypothesis is no cointegration with structural break. The dependent variable is LnEM, and all explanatory variables are included in the long-run relationship. * denotes rejection of the null hypothesis at the 5% significance level. Critical values are from Gregory and Hansen (1996).

As reported in Table 6, the Gregory–Hansen test rejects the null hypothesis of no cointegration across all three specifications. The estimated break dates are 2008, 2009, and 2015, which are economically plausible given the global financial crisis and the post-Paris Agreement policy environment. These results indicate that the long-run relationship among the variables remains valid even when structural breaks are allowed. Therefore, the evidence from the Gregory–Hansen test supports the Johansen cointegration findings and strengthens the basis for estimating the VECM.

Having confirmed the presence of a long-run relationship through both the Johansen and Gregory–Hansen cointegration tests, we proceed with the estimation of the Vector Error Correction Model (VECM). The VECM is used as the main dynamic framework because it allows the analysis to capture long-run equilibrium adjustment together with short-run changes. Table 7 reports the normalized long-run cointegrating coefficients for the emissions equation. Since the variables are expressed in logarithmic form, the estimated coefficients can be interpreted as long-run elasticities.

Table 7. VECM Long-Run Cointegrating Coefficients

Variable	LnGDP	LnPOP	LnENJ	LnRNE	LnFD	LnGINI	LnTRD
Coef.	0.176*	0.419*	0.361*	-0.162*	-0.103*	0.248*	0.115*
Std.Err.	0.045	0.071	0.049	0.058	0.017	0.061	0.014
t-Stat.	3.91	5.90	7.37	-2.79	-6.06	4.07	8.21

Note: Long-run coefficients are normalized based on the cointegrating vector. Lag length is selected as 2 according to the AIC criterion. *p<0.01, **p<0.05

The long-run estimates reveal several notable patterns. Economic growth (LnGDP), population density (LnPOP), energy consumption (LnENJ), income inequality (LnGINI), and trade openness (LnTRD) have positive and statistically significant coefficients, indicating that these variables are positively associated with greenhouse gas emissions in the long run. Among them, population density and energy consumption display relatively larger elasticities, with coefficients of 0.419 and 0.361, respectively. By contrast, renewable energy share (LnRNE) and financial development (LnFD) have negative and statistically significant coefficients, suggesting that a higher renewable energy share and deeper financial development are associated with lower emissions over the long run. Overall, the long-run VECM estimates are consistent with the expected signs derived from the conceptual framework.

While the normalized coefficients describe the long-run equilibrium relationship, the error-correction specification reported in Table 8 provides information on short-run dynamics and the speed at which deviations from the long-run path are adjusted.

The error-correction term (ECT) is negative and statistically significant at the 1% level, with a coefficient of -0.162. This indicates that deviations from the long-run equilibrium are gradually corrected over time. Specifically, approximately 16.2% of the previous year's disequilibrium is adjusted within one year, implying a moderate speed of adjustment. This result supports the presence of an error-correction mechanism linking short-run movements to the long-run equilibrium relationship.

Regarding the short-run dynamics, the first lag of energy consumption (ΔLnENJ) has the largest statistically significant coefficient among the explanatory variables, with a value of 0.281. This suggests that short-run changes in energy consumption are closely associated with changes in greenhouse gas emissions. Population density and trade openness also have positive and statistically significant short-run coefficients, while renewable energy and financial development show negative coefficients in the first lag. Overall, the signs of the significant short-run coefficients are broadly consistent with the long-run estimates. The model summary statistics, including an R^2 of 0.724 and a statistically significant F-statistic, suggest that the short-run specification has reasonable explanatory power.

While the long-run and short-run VECM estimates describe the magnitude and direction of the relationships between emissions and the explanatory variables, they do not indicate whether past changes in these variables help predict subsequent changes in emissions. For this purpose, VECM-based Granger causality tests are conducted. In this context, Granger causality is interpreted as predictive precedence rather than structural causality. The tests examine whether lagged changes in each explanatory variable improve the prediction of changes in greenhouse gas emissions, while accounting for the long-run equilibrium relationship identified earlier.

Table 8. VECM Error Correction Model - Short-Run Dynamics

Error Correction Term	Coefficient	Std. Error	t-Stat.
ECT(-1)	-0.162*	0.036	-4.50
ΔLnEM(-1)	0.118	0.084	1.40
ΔLnEM(-2)	0.059	0.087	0.68
ΔLnGDP(-1)	0.085**	0.033	2.58
ΔLnGDP(-2)	0.038	0.030	1.27
ΔLnPOP(-1)	0.112*	0.029	3.86
ΔLnPOP(-2)	0.049	0.031	1.58
ΔLnENJ(-1)	0.281*	0.043	6.53
ΔLnENJ(-2)	0.121**	0.045	2.69
ΔLnRNE(-1)	-0.072**	0.027	-2.67
ΔLnRNE(-2)	-0.038	0.029	-1.31
ΔLnFD(-1)	-0.052*	0.013	-4.00
ΔLnFD(-2)	-0.024	0.015	-1.60
ΔLnGINI(-1)	0.082**	0.032	2.56
ΔLnGINI(-2)	0.041	0.034	1.21
ΔLnTRD(-1)	0.061*	0.011	5.55
ΔLnTRD(-2)	0.033**	0.012	2.75
Model Summary Statistics		Value	
R^2		0.724	
F-stat.		9.67 (p=0.000)	
Log-likelihood		435.82	
AIC		-13.58	
SC		-12.21	

Note: Standard errors are in parentheses. Lag length is selected as 2 according to the AIC criterion. * $p < 0.01$, ** $p < 0.05$

Table 9. VECM Granger Causality Test Results

Dependent Variable: ΔLnEM	χ^2	df	p-value	Decision
ΔLnGDP → ΔLnEM	7.23	2	0.027	exists
ΔLnPOP → ΔLnEM	14.92	2	0.001	exists
ΔLnENJ → ΔLnEM	44.18	2	0.000	exists
ΔLnRNE → ΔLnEM	7.14	2	0.028	exists
ΔLnFD → ΔLnEM	16.02	2	0.000	exists
ΔLnGINI → ΔLnEM	6.55	2	0.038	exists
ΔLnTRD → ΔLnEM	30.81	2	0.000	exists
All variables (joint)	98.24	14	0.000	exists

Table 9 presents the VECM-based Granger causality results with greenhouse gas emissions (ΔLnEM) as the dependent variable. The results indicate that lagged changes in all explanatory variables have statistically significant predictive content for changes in emissions at conventional significance levels. Among these variables, energy consumption ($\chi^2 = 44.18$, $p < 0.001$) and trade openness ($\chi^2 = 30.81$, $p < 0.001$) display the largest Wald statistics, followed by financial development and population density. The joint test also rejects the null hypothesis that all explanatory variables jointly have no predictive content for emissions ($\chi^2 = 98.24$, $p < 0.001$). These findings suggest that past movements in the selected economic, energy-related, and socio-economic variables help predict short-run changes in greenhouse gas emissions within the estimated VECM framework.

To examine whether a similar predictive pattern exists in the opposite direction, Table 10 reports bidirectional Granger causality tests between emissions and each explanatory variable.

Table 10. Direction of VECM-Based Granger Predictive Relationships

H_0: No causality	χ^2	df	p-value	Causality Direction
ΔLnGDP → ΔLnEM	7.23	2	0.027	ΔLnGDP → ΔLnEM
ΔLnEM → ΔLnGDP	1.56	2	0.458	No
ΔLnENJ → ΔLnEM	44.18	2	0.000	ΔLnENJ → ΔLnEM
ΔLnEM → ΔLnENJ	3.21	2	0.201	No
ΔLnRNE → ΔLnEM	7.14	2	0.028	ΔLnRNE → ΔLnEM
ΔLnEM → ΔLnRNE	1.08	2	0.583	No
ΔLnFD → ΔLnEM	16.02	2	0.000	ΔLnFD → ΔLnEM
ΔLnEM → ΔLnFD	2.14	2	0.343	No
ΔLnGINI → ΔLnEM	6.55	2	0.038	ΔLnGINI → ΔLnEM
ΔLnEM → ΔLnGINI	0.92	2	0.631	No
ΔLnTRD → ΔLnEM	30.81	2	0.000	ΔLnTRD → ΔLnEM
ΔLnEM → ΔLnTRD	3.67	2	0.159	No
ΔLnPOP → ΔLnEM	14.92	2	0.001	ΔLnPOP → ΔLnEM
ΔLnEM → ΔLnPOP	2.38	2	0.304	No

Note: Significant results indicate predictive precedence in the Granger sense. They should not be interpreted as structural causality. No statistically significant reverse predictive relationship from emissions to the explanatory variables is detected.

The results in Table 10 show that the statistically significant Granger relationships are unidirectional in a predictive sense. Lagged changes in each explanatory variable help predict changes in greenhouse gas emissions, whereas lagged changes in emissions do not significantly improve the prediction of changes in GDP, energy consumption, renewable energy, financial development, income inequality, trade openness, or population density. The p-values for the reverse directions are above conventional significance levels, suggesting that no statistically significant reverse predictive relationship is detected within the estimated VECM framework.

These findings should be interpreted carefully. The absence of reverse Granger predictability does not imply that environmental policies have no effect on macroeconomic variables, nor does it establish policy invariance. Rather, it indicates only that, within the sample period and model specification, past changes in emissions do not add statistically significant predictive information for subsequent changes in the selected economic and socio-economic variables. In this sense, the Granger causality results are best understood as evidence on short-run predictive dynamics rather than as structural causal effects.

The relatively stronger predictive roles of energy consumption and trade openness suggest that these variables are important components of the short-run emissions dynamics in the estimated system. However, policy implications should be drawn cautiously and in conjunction with the long-run VECM estimates, the structural-break cointegration tests, and the FMOLS robustness results.

To assess whether the long-run estimates are robust to the choice of estimator and to the structural breaks identified earlier, we re-estimate the cointegrating relationship using the Fully Modified Ordinary Least Squares (FMOLS) approach. Unlike the VECM, which estimates a dynamic system, FMOLS provides a single-equation long-run estimator that corrects for potential endogeneity and serial correlation in cointegrated regressions. Table 11 reports the baseline FMOLS estimates together with specifications augmented by the 2009 and 2015 intercept break dummies. This provides a complementary check on whether the main long-run associations are sensitive to the estimation method and to the inclusion of structural-break controls.

Table 11. Robustness Check - FMOLS Long-Run Estimates with Intercept Breaks

Variable	M1 (Baseline)	M2 (+ D2009)	M3 (+ D2015)	M4 (+ Both)
LnGDP	0.184* (0.049)	0.182* (0.050)	0.180* (0.050)	0.178* (0.051)
LnPOP	0.431* (0.076)	0.429* (0.077)	0.427* (0.077)	0.425* (0.078)
LnENJ	0.365* (0.053)	0.362* (0.054)	0.360* (0.054)	0.357* (0.055)
LnRNE	-0.170** (0.069)	-0.168** (0.070)	-0.172** (0.069)	-0.170** (0.070)
LnFD	-0.107* (0.019)	-0.106* (0.019)	-0.108* (0.019)	-0.107* (0.020)
LnGINI	0.250* (0.065)	0.248* (0.066)	0.251* (0.065)	0.249* (0.066)
LnTRD	0.116* (0.016)	0.114* (0.016)	0.113* (0.016)	0.111* (0.017)
D2009 (intercept)	—	0.007 (0.013)	—	0.006 (0.014)
D2015 (intercept)	—	—	-0.009 (0.012)	-0.008 (0.013)
R^2	0.982	0.982	0.982	0.983
Adj. R^2	0.975	0.975	0.975	0.975

Notes: Standard errors in parentheses. D2009 = 1 for $t \geq 2009$ (post-crisis period), 0 otherwise. D2015 = 1 for $t \geq 2015$ (post-Paris period), 0 otherwise. * $p < 0.01$, ** $p < 0.05$.

Table 11 reports the FMOLS long-run estimates for the baseline specification and for alternative specifications including the 2009 and 2015 intercept break dummies. The results are highly stable across all four specifications. The signs, magnitudes, and statistical significance of the main coefficients remain largely unchanged after the inclusion of the break dummies. Economic growth, population density, energy consumption, income inequality, and trade openness remain positively associated with greenhouse gas emissions, whereas renewable energy share and financial development remain negatively associated with emissions.

The break dummy coefficients are statistically insignificant in the specifications in which they are included. This suggests that the main long-run associations are not driven solely by discrete level shifts associated with the post-2009 or post-2015 periods. In particular, the coefficients of energy consumption and renewable energy remain close to their baseline values across the break-adjusted specifications. Therefore, the FMOLS results provide additional evidence that the long-run relationships identified in the VECM are robust to the inclusion of intercept break controls.

Given that the variables are trending and cointegrated, the high R^2 values should not be interpreted as independent evidence of model quality. Rather, the main relevance of Table 11 lies in the stability of the coefficient signs and magnitudes across the baseline and break-adjusted specifications.

As an additional robustness exercise, Appendix Table A1 reports a limited post-2015 slope-break specification. The statistically insignificant interaction terms suggest that the main long-run associations are not strongly sensitive to post-2015 slope changes in the selected energy- and trade-related variables.

3.5. Model Diagnostics

Having estimated the primary VECM specification and conducted the long-run robustness checks, we next evaluate the statistical adequacy of the VECM framework. Before interpreting the empirical results, it is important to examine whether the model satisfies the main diagnostic requirements for valid inference. To this end, we perform a series of residual and stability diagnostics.

We test for serial correlation using the multivariate Breusch–Godfrey LM test, which is appropriate for vector autoregressive systems. Heteroskedasticity is examined using the ARCH-LM test applied to each individual equation, allowing us to check for time-varying volatility in the residuals. Normality of the residuals is assessed through the Jarque–Bera test for each equation, which is useful given the relatively small sample size. Finally, system stability is evaluated by verifying that all inverse roots of the AR characteristic polynomial lie inside the unit circle.

Table 12. Summary of VECM Diagnostic Tests

Component	**LM (Autocorrelation)**	**ARCH-LM (Heteroskedasticity)**	**JB (Normality)**	**Stability**
System	✓ (0.163)	–	–	Stable
ΔLnEM	–	✓ (0.351)	✓ (0.210)	–
ΔLnGDP	–	✓ (0.265)	✓ (0.238)	–
ΔLnPOP	–	✓ (0.337)	✓ (0.294)	–
ΔLnENJ	–	✓ (0.330)	✓ (0.371)	–
ΔLnRNE	–	✓ (0.299)	✓ (0.331)	–
ΔLnFD	–	✓ (0.284)	✓ (0.268)	–
ΔLnGINI	–	✓ (0.362)	✓ (0.222)	–
ΔLnTRD	–	✓ (0.383)	✓ (0.236)	–

Notes: ✓ indicates that the null hypothesis is not rejected at the 5% significance level. Values in parentheses are p-values. LM refers to the multivariate Breusch-Godfrey serial correlation test at lag 4. ARCH-LM denotes the lag-1 test for conditional heteroskedasticity. JB refers to the Jarque-Bera normality test. Stability is confirmed when all inverse roots of the AR characteristic polynomial lie inside the unit circle.

The diagnostic results reported in Table 12 indicate that the VECM specification satisfies the main residual and stability requirements. The multivariate Breusch-Godfrey LM test yields a p-value of 0.163, so the null hypothesis of no serial correlation cannot be rejected. The ARCH-LM test statistics are also statistically insignificant across the individual equations, with p-values ranging from 0.265 to 0.383, suggesting no evidence of conditional heteroskedasticity. Similarly, the Jarque-Bera test fails to reject the null hypothesis of normally distributed residuals for each equation, with p-values above the 5% threshold. Finally, the stability condition is satisfied, as all inverse roots of the AR characteristic polynomial lie inside the unit circle.

Taken together, these diagnostic checks suggest that the estimated VECM is statistically adequate for interpreting the long-run relationships, short-run dynamics, and Granger predictive relationships reported above.

4. Discussion

The findings of this study suggest that greenhouse gas emissions in Canada are associated with a combination of economic, demographic, energy-related, financial, and social factors rather than with a single source of environmental pressure. The long-run estimates indicate that economic growth, population density, energy consumption, income inequality, and trade openness are positively associated with emissions, whereas renewable energy and financial development are negatively associated with them. These patterns are broadly consistent across the VECM and FMOLS estimates. Moreover, the structural-break checks provide additional support for the stability of the long-run relationship: the Gregory–Hansen test confirms cointegration under alternative break specifications, and the FMOLS estimates with 2009 and

2015 intercept dummies show that the main coefficient signs and magnitudes remain largely unchanged. Therefore, the results should be interpreted as robust long-run associations and short-run predictive dynamics rather than as evidence of structural causality.

One of the clearest empirical patterns concerns energy consumption. Both the long-run and short-run estimates show a positive association between energy use and greenhouse gas emissions. In the VECM-based Granger framework, lagged changes in energy consumption also contain statistically significant predictive information for subsequent changes in emissions. This does not imply structural causality, but it does indicate that energy use is closely linked to the emissions dynamics observed in the estimated system. For Canada, this finding is consistent with the view that the environmental consequences of economic activity depend strongly on the structure and intensity of energy use. Growth alone does not explain emissions dynamics; the way production, transport, and consumption are powered remains central.

Economic growth also has a positive long-run coefficient. This suggests that, over the sample period, rising income has been associated with higher greenhouse gas emissions rather than with an automatic decline in environmental pressure. This finding does not necessarily contradict the broader Environmental Kuznets Curve discussion. Rather, it indicates that within the period examined here, the scale-related component of growth appears to have remained important. In a high-income economy such as Canada, income growth may be compatible with lower emissions only when it is accompanied by sufficient changes in energy composition, production technology, and environmental regulation. The result should therefore be read as evidence of a positive long-run association between income and emissions during the sample period, not as a structural law governing the growth–environment relationship.

The positive coefficient of population density should also be interpreted carefully. The result suggests that demographic concentration is associated with higher emissions, possibly through greater demand for housing, transport, infrastructure, and energy-related services. However, the Canadian context requires caution because population density changes relatively slowly over time and may also capture broader macroeconomic or urbanization-related trends. For this reason, the finding should not be interpreted as a direct causal effect of density on emissions. Rather, it indicates that demographic pressure is one component of the broader emissions pattern observed in the data. This interpretation is consistent with the idea that environmental outcomes may depend not only on national income or energy use, but also on how population and economic activity are spatially organized.

The renewable energy result is consistent with expectations from both the conceptual framework and much of the empirical literature. The negative long-run coefficient suggests that a higher renewable energy share is associated with lower greenhouse gas emissions. The short-run estimates point in the same direction for the first lag. This finding supports the view that changes in energy composition are relevant for reducing environmental pressure. However, the result should be understood as an association within the estimated time-series framework rather than as a complete evaluation of renewable energy policy. The effectiveness of renewable energy expansion may depend on the extent to which it substitutes for fossil energy, the pace of grid transformation, and the sectoral distribution of energy demand.

Financial development is also negatively associated with emissions across the main and robustness estimates. One possible interpretation is that a more developed financial system may facilitate cleaner investment, technological upgrading, and more efficient allocation of capital. However, this mechanism should be treated cautiously. Financial development may reduce emissions when it supports green finance, energy efficiency, and low-carbon investment, but it may also increase emissions if it expands credit to carbon-intensive production and consumption. In the Canadian case, the negative coefficient suggests that the environmental association of financial development is closer to the cleaner-investment channel during the period examined. Nevertheless, the aggregate nature of the data does not allow us to identify the specific financial mechanisms behind this relationship.

Income inequality shows a positive long-run association with greenhouse gas emissions. This result suggests that environmental pressure may be linked not only to production scale and energy demand, but also to the social distribution of resources. A possible channel is that unequal income distribution may shape consumption patterns, access to cleaner technologies, and political support for environmental regulation. At the same time, this finding should not be overstated. Since inequality may also proxy for broader socio-economic changes, the coefficient should be interpreted as evidence of an empirical association rather than as a distinct structural effect. The result nevertheless indicates that distributional conditions may be relevant when discussing the social dimension of environmental sustainability.

Trade openness is positively associated with emissions in the long run, and lagged changes in trade openness have predictive content for short-run changes in emissions. This suggests that, during the sample period, the scale, transport, and production-composition effects of external integration may have outweighed any cleaner-technology gains associated with trade. This result should not be read as an argument against trade itself. Rather, it suggests that the environmental implications of trade depend on the carbon intensity of production, logistics, and supply chains. From this perspective, trade-related environmental policy should focus less on restricting openness and more on aligning trade expansion with cleaner production standards, transport efficiency, and low-emission supply-chain practices.

The error-correction term provides further insight into the adjustment process. Its negative and statistically significant coefficient indicates that deviations from the long-run equilibrium are gradually corrected over time. The estimated speed of adjustment suggests that the return to equilibrium is moderate rather than immediate. This implies that shocks to emissions dynamics may persist for several years before the system fully adjusts. The result is important because it suggests that both adverse shocks and corrective changes may have delayed effects. However, this adjustment mechanism should be interpreted within the limits of the estimated VECM framework and not as evidence of a fully specified structural transition process.

The Granger causality results should be interpreted in a predictive, not structural, sense. The tests indicate that lagged changes in the explanatory variables help predict changes in emissions, while lagged changes in emissions do not add statistically significant predictive information for the selected economic and socio-economic variables. This does not mean that environmental degradation is economically irrelevant, nor does it imply that emission-reduction policies would have no macroeconomic consequences. It only shows that, within the sample period and model specification, the dominant predictive direction runs from economic, energy-related, demographic, financial, and social variables toward emissions. Therefore, the Granger results complement the long-run estimates by describing short-run predictive dynamics, but they should not be used as evidence of policy invariance or structural causality.

The Canadian case points to an emissions pattern that is connected not only to energy use and economic scale, but also to demographic pressure, trade openness, income distribution, renewable energy, and financial development. The results are mainly confirmatory, yet they are still informative because the main relationships remain stable after structural breaks and alternative long-run estimation are taken into account. For this reason, the policy interpretation should remain cautious. The findings suggest that emission reduction in Canada may require coordination across energy transition, cleaner production, financial allocation, trade-related environmental standards, and distribution-sensitive policy design. However, the analysis does not identify causal policy effects. Stronger causal claims would require further research using structural models, external instruments, sectoral data, or comparative panel designs.

5. Conclusion

This study examined the economic and socio-economic factors associated with greenhouse gas emissions in Canada over the period 1990–2024. Using a VECM framework supported by FMOLS robustness estimates, the analysis shows that emissions are linked to a broad set of economic, demographic, energy-related, financial, and social variables. In the long run, economic growth, population density, energy consumption, income inequality, and trade openness are positively associated with greenhouse gas emissions, whereas renewable energy and financial development are negatively associated with them. The short-run results generally move in the same direction, and the negative and statistically significant error-correction term indicates that deviations from the long-run equilibrium are gradually adjusted over time.

The additional robustness checks provide further support for the long-run results. The Zivot–Andrews test shows that the integration properties of the variables remain valid when an endogenous structural break is allowed. The Gregory–Hansen test indicates that the cointegrating relationship remains present under alternative break specifications. In addition, the FMOLS estimates with 2009 and 2015 intercept break dummies show that the main coefficient signs and magnitudes remain largely stable after accounting for major economic and policy shifts. These results suggest that the long-run associations identified in the study are not driven solely by unmodelled structural breaks.

The VECM-based Granger results add a short-run predictive dimension to the analysis. They suggest that the selected economic and socio-economic variables contain useful predictive information for changes in emissions, while the reverse direction is not statistically supported in the estimated model. This pattern is consistent with the broader finding that emissions dynamics in Canada are closely connected to changes in economic activity, energy use, population pressure, trade openness, financial development, and income distribution.

The findings point to a broad but cautious policy interpretation. Emission reduction in Canada appears to be connected not only with energy use and economic scale, but also with demographic concentration, trade openness, income distribution, renewable energy, and financial development. This suggests that environmental policy should not be treated as a narrow emissions-control issue alone. A more integrated approach would link the energy transition with cleaner production, trade-related environmental standards, financial mechanisms that support low-emission investment, and distribution-sensitive policy design. At the same time, the results should be understood as evidence of long-run associations and short-run predictive dynamics rather than as estimates of causal policy effects.

6. Limitations and Future Research Directions

This study has several limitations that should be acknowledged when interpreting the findings. First, the analysis focuses only on Canada over the period 1990–2024. Although this country-specific design allows a closer examination of the Canadian case, it also means that the results should not be generalized automatically to other economies with different energy systems, trade structures, demographic patterns, or institutional settings. Second, the study relies on aggregate annual time-series data. This provides a clear long-run perspective, yet it may conceal important differences across sectors, provinces, and emission sources. In a country such as Canada, where economic activity, energy use, and environmental pressures vary substantially across regions, aggregate data may smooth over heterogeneity that could matter for policy design.

A further limitation concerns the empirical framework itself. The VECM approach is suitable for the data structure used in this study because the variables are integrated of order one and cointegrated, allowing the analysis to distinguish between long-run equilibrium relationships and short-run adjustments. The FMOLS estimates and structural-break robustness checks also support the stability of the long-run results. Even so, the model remains an aggregate linear time-series framework. As such, it cannot fully capture sector-specific dynamics, nonlinear responses, threshold effects, or deeper structural mechanisms behind the observed relationships. This point is especially relevant in the context of environmental policy, where transitions in energy systems, trade regimes, or financial conditions may generate heterogeneous or nonlinear responses over time.

These limitations also point to several directions for future research. One promising extension would be to move from aggregate national data to sectoral or provincial evidence in order to identify where the strongest sources of environmental pressure originate and whether the relationships among growth, trade, inequality, financial development, and emissions differ across regions. Another useful step would be to examine alternative indicators of environmental degradation, such as carbon dioxide emissions, ecological footprint, or consumption-based measures, to assess whether the main findings remain stable across different environmental outcomes. Future studies may also consider nonlinear models, threshold specifications, structural approaches, or external instruments to examine whether the relationships reported here vary across policy regimes or stages of energy transition. Finally, comparative studies that place Canada alongside other advanced economies could help clarify which results are country-specific and which reflect broader patterns linking economic structure and environmental performance.

REFERENCES

Adebanjo, S. A., & Shakiru, T. H. (2022). Dynamic relationship between air pollution and economic growth in Jordan: An empirical analysis. *Journal of Environmental Science and Economics, 1*(2), 30–43. https://doi.org/10.56556/jescae.v1i2.17

Akar, G., Kaplan, E. A., Güler, İ., & Şahin, S. (2025). Has the Environmental Kuznets Curve hypothesis become stronger? A comparative analysis for OECD countries and selected late-industrializing Asian economies. *Journal of Environmental Management, 394*, Article 127575. https://doi.org/10.1016/j.jenvman.2025.127575

Alataş, S., & Akın, T. (2022). The impact of income inequality on environmental quality: A sectoral-level analysis. *Journal of Environmental Planning and Management, 65*(10), 1949–1974. https://doi.org/10.1080/09640568.2022.2050684

Candra, O., Chammam, A., Nuñez Alvarez, J. R., Muda, I., & Aybar, H. Ş. (2023). The impact of renewable energy sources on the sustainable development of the economy and greenhouse gas emissions. *Sustainability, 15*(3), Article 2114. https://doi.org/10.3390/su15032114

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American Statistical Association, 74*(366), 427–431. https://doi.org/10.1080/01621459.1979.10482531

Dong, K., Wang, S., Hu, H., Guan, N., Shi, X., & Song, Y. (2024). Financial development, carbon dioxide emissions, and sustainable development. *Sustainable Development, 32*(1), 348–366. https://doi.org/10.1002/sd.2649

Dou, Y., Chen, F., Kong, Z., & Dong, K. (2023). Re-estimating the trade openness–carbon emissions nexus: A global analysis considering nonlinear, mediation, and heterogeneous effects. *Applied Economics, 55*(57), 6793–6808. https://doi.org/10.1080/00036846.2023.2166659

Erdoğan, E., Serin Oktay, D., Manga, M., Bal, H., & Algan, N. (2024). Examining the effects of renewable energy and economic growth on carbon emission in Canada: Evidence from the nonlinear ARDL approaches. *Evaluation Review, 48*(1), 63–89. https://doi.org/10.1177/0193841X231166973

Gregory, A. W., & Hansen, B. E. (1996). Residual-based tests for cointegration in models with regime shifts. *Journal of Econometrics, 70*(1), 99–126. https://doi.org/10.1016/0304-4076(69)41685-7

Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics, 110*(2), 353–377. https://doi.org/10.2307/2118443

Guedie, R., Ngnemadon, A. S. A., Fotio, H. K., & Nembot, L. (2022). Disaggregated analysis of the effects of energy consumption on greenhouse gas emissions in Africa. *Energy Economics Letters, 9*(2), 75–90.

Hadi, S. P., & Al Hasibi, R. A. (2022). An integrated renewable energy system for the supply of electricity and hydrogen energy for road transportation which minimizes greenhouse gas emissions. *International Journal of Sustainable Energy Planning and Management, 35*, 65–82. https://doi.org/10.54337/ijsepm.7039

Hailemariam, A., Dzhumashev, R., & Shahbaz, M. (2020). Carbon emissions, income inequality and economic development. *Empirical Economics, 59*(3), 1139–1159. https://doi.org/10.1007/s00181-019-01664-x

Hong, S., Hui, E. C. M., & Lin, Y. (2022). Relationships between carbon emissions and urban population size and density, based on geo-urban scaling analysis: A multi-carbon source empirical study. *Urban Climate, 46*, Article 101337. https://doi.org/10.1016/j.uclim.2022.101337

Iwuoha, V. C., Anoruo, E., & Nwala, K. (2023). Investigating the relationship between Canada's environmental quality and GDP-alternative measures: An error correction approach. *Advances in Management and Applied Economics, 13*(2), 1–25. https://doi.org/10.47260/amae/1321

Johansen, S. (1988). Statistical analysis of cointegration vectors. *Journal of Economic Dynamics and Control, 12*(2–3), 231–254. https://doi.org/10.1016/0165-1889(88)90041-3

Kang, J.-H. (2022). Impacts of income inequality and economic growth on CO_2 emissions: Comparing the Gini coefficient and the top income share in OECD countries. *Energies, 15*(19), 6954. https://doi.org/10.3390/en15196954

Kwiatkowski, D., Phillips, P. C. B., Schmidt, P., & Shin, Y. (1992). Testing the null hypothesis of stationarity against the alternative of a unit root. *Journal of Econometrics, 54*(1–3), 159–178. https://doi.org/10.1016/0304-4076(92)90104-Y

Maranzano, P., Cerdeira Bento, J. P., & Manera, M. (2022). The role of education and income inequality on environmental quality: A panel data analysis of the EKC hypothesis on OECD countries. *Sustainability, 14*(3), Article 1622. https://doi.org/10.3390/su14031622

Matei, I. (2022). The environmental Kuznets curve: Empirical evidence from OECD countries. In J. Xu & B. Yang (Eds.), *Energy consumption, conversion, storage, and efficiency*. IntechOpen. https://doi.org/10.5772/intechopen.108631

Oyeranti, O. A. (2023). Does trade openness exacerbate carbon dioxide emission? Evidence from Nigeria. *International Journal of Social Science and Economic Research, 8*(1), 109–128. https://doi.org/10.46609/IJSSER.2023.v08i01.007

Phillips, P. C. B., & Hansen, B. E. (1990). Statistical inference in instrumental variables regression with I(1) processes. *Review of Economic Studies, 57*(1), 99–125. https://doi.org/10.2307/2297545

Phillips, P. C. B., & Perron, P. (1988). Testing for a unit root in time series regression. *Biometrika, 75*(2), 335–346. https://doi.org/10.1093/biomet/75.2.335

Poor, N., & Braham, A. (2023). Road use contributions to energy consumption and greenhouse gas emissions for two flexible pavement maintenance strategies. *Journal of Testing and Evaluation, 51*(4), 2210–2229. https://doi.org/10.1520/JTE20220272

Saidi, K., & Omri, A. (2020). Reducing CO2 emissions in OECD countries: Do renewable and nuclear energy matter? *Progress in Nuclear Energy, 126*, Article 103425. https://doi.org/10.1016/j.pnucene.2020.103425

Selden, T. M., & Song, D. (1994). Environmental quality and development: Is there a Kuznets curve for air pollution emissions? *Journal of Environmental Economics and Management, 27*(2), 147–162. https://doi.org/10.1006/jeem.1994.1031

Shafik, N. (1994). Economic development and environmental quality: An econometric analysis. *Oxford Economic Papers, 46*(0), 757–773.

Sun, Y. (2023). Income inequality, carbon emissions, and green development efficiency. *Environmental Science and Pollution Research, 30*, 21081–21091. https://doi.org/10.1007/s11356-022-23583-8

Tokpah, J.-T., Seraj, M., & Ozdeser, H. (2023). Panel examination of the impact of economic growth on carbon emissions: Case of 15 emerging and advanced economies. *Universal Journal of Carbon Research, 1*(2), 1–13. https://doi.org/10.37256/1220233322

Vo, D. H., Ho, C. M., Le, Q. T. T., & Nguyen, H. M. (2022). Revisiting the energy-growth-environment nexus in the OECD countries: An application of the CS-ARDL approach. *Energy, Sustainability and Society, 12*, Article 47. https://doi.org/10.1186/s13705-022-00375-z

Wahab, S., Imran, M., Ahmed, B., Rahim, S., & Hassan, T. (2024). Navigating environmental concerns: Unveiling the role of economic growth, trade, resources and institutional quality on greenhouse gas emissions in OECD countries. *Journal of Cleaner Production, 434*, Article 139851. https://doi.org/10.1016/j.jclepro.2023.139851

Wijerathna, W. A. I. D., & Dharmarathna, D. G. (2023). Effect of the financial development on carbon emission: An empirical investigation from a global perspective. *Journal of Accountancy and Finance, 10*(1). https://doi.org/10.57075/jaf1012301

Zarco-Periñán, P. J., Zarco-Soto, I. M., & Zarco-Soto, F. J. (2021). Influence of population density on CO2 emissions eliminating the influence of climate. *Atmosphere, 12*(9), Article 1193. https://doi.org/10.3390/atmos12091193

Zheng, H., Wood, R., Moran, D., Feng, K., Tisserant, A., Jiang, M., & Hertwich, E. G. (2023). Rising carbon inequality and its driving factors from 2005 to 2015. *Global Environmental Change, 82*, Article 102704. https://doi.org/10.1016/j.gloenvcha.2023.102704

Zivot, E., & Andrews, D. W. K. (1992). Further evidence on the great crash, the oil-price shock, and the unit-root hypothesis. *Journal of Business & Economic Statistics, 10*(3), 251–270. https://doi.org/10.1080/07350015.1992.10509904

APPENDIX

Table A1. FMOLS with Slope Breaks (Post-2015 Regime Shift)

Variable	Baseline	+ Slope Break (2015)
LnGDP	0.184* (0.049)	0.181* (0.050)
LnPOP	0.431* (0.076)	0.428* (0.077)
LnENJ	0.365* (0.053)	0.359* (0.054)
LnRNE	-0.170** (0.069)	-0.174** (0.070)
LnFD	-0.107* (0.019)	-0.106* (0.020)
LnGINI	0.250* (0.065)	0.252* (0.066)
LnTRD	0.116* (0.016)	0.112* (0.017)
D2015 × LnENJ	—	-0.018 (0.022)
D2015 × LnRNE	—	-0.012 (0.019)
D2015 × LnTRD	—	-0.009 (0.014)
D2015 (intercept)	—	-0.011 (0.013)

Notes: D2015 = 1 for $t \geq 2015$, 0 otherwise. All slope interaction terms are statistically insignificant at conventional levels ($p > 0.10$). This suggests that the post-2015 period (Paris Agreement) did not significantly alter the responsiveness of emissions to energy consumption, renewable energy, or trade openness.