Toward Carbon Neutrality in Japan: The Synergistic Role of E-Governance, Green Innovation, and Institutional Quality

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Abstract: *This study investigates the combined impact of e-governance, green technology innovation, and institutional quality on Japan's progress toward achieving net-zero emissions from 2001 to 2023. By constructing a composite Net-Zero Emissions Index (NZEI) using principal component analysis, the study employs both Autoregressive Distributed Lag models and machine learning techniques—including Random Forest and Support Vector Machines —to capture linear and nonlinear relationships among the key variables. The econometric results reveal that e-governance and institutional quality significantly enhance carbon neutrality in both the short and long run, while green innovation shows a strong long-term effect. Machine learning models confirm these findings, with high predictive accuracy (R2 > 0.92) and variable importance analysis indicating that e-governance is the most influential predictor of NZEI. These results underscore the critical role of digital governance, innovation, and institutional strength in shaping effective climate policy. The study offers actionable insights for policymakers aiming to integrate governance reforms and technological innovation into Japan's carbon-neutral transition.*

Keywords: carbon neutrality; e-governance; green innovation; institutional quality; net-zero emission

1. INTRODUCTION

The purpose of achieving net-zero greenhouse gas emissions is central to global efforts in combating climate change and mitigating its far-reaching consequences. For a highly industrialized nation like Japan, reaching carbon neutrality by 2050 is not only a national commitment under the Paris Agreement but also a vital step toward safeguarding ecological systems and ensuring long-term socio-economic resilience [1–5]. Transitioning to a net-zero emission society is associated with numerous co-benefits, including reduced atmospheric concentrations of greenhouse gases, improved public health due to lower pollution, and the creation of new green jobs that can drive sustainable economic growth [6–10]. However, achieving this transition requires an integrated, multi-dimensional strategy encompassing technological innovation, societal transformation, and robust institutional support [11,12].

Among the technological drivers, green innovation—in the form of clean energy systems, energy-efficient technologies, and carbon capture solutions—plays a pivotal role in reducing emissions across key sectors such as energy, transportation, and industry [13–17] Yet, innovation alone is insufficient without complementary governance mechanisms that can enable its widespread diffusion and practical application. In this regard, e-governance—defined as the digitalization of public services, improved administrative efficiency, and enhanced citizen participation—has emerged as a promising tool for fostering environmental policy effectiveness and facilitating green technology deployment [12,18–20].

Simultaneously, institutional quality—reflecting the effectiveness of legal, regulatory, and political systems—plays a critical role in shaping environmental outcomes. High-quality institutions incentivize compliance with environmental regulations, encourage investment in clean technologies, and reduce corruption that can undermine sustainability efforts [21,22]. However, the empirical evidence linking institutional quality to carbon emissions remains inconclusive, with existing studies producing mixed findings and often treating institutional variables as mere controls or simplistic interaction terms [23–25].

Despite growing recognition of the individual importance of green innovation, e-governance, and institutional strength, the synergistic relationships among these three domains have received limited empirical attention, particularly in advanced economies like Japan. Most existing literature tends to evaluate these factors in isolation, overlooking how they might interact to create mutually reinforcing effects on carbon emissions reduction. For example, while e-governance can facilitate digital transparency and policy enforcement, its effectiveness may depend on the presence of strong institutions. Similarly, green innovation may thrive more effectively in an environment characterized by robust governance and institutional support. As Du and Li [26] and Milindi and Inglesi-Lotz [27] suggest, green innovation's success in reducing emissions often hinges on the enabling ecosystem in which it is embedded.

This study addresses the critical research gap by investigating the interactive and synergistic effects of e-governance, green innovation, and institutional quality on Japan's path toward carbon neutrality. It makes several important contributions to the literature. First, it conceptualizes and empirically tests the roles of these three dimensions within a unified analytical framework. Second, it focuses on Japan as a high-income yet resource-constrained economy with complex energy and environmental challenges, offering valuable insights for similarly structured nations. Third, the study leverages advanced econometric and machine learning techniques to uncover policy pathways through which institutional and governance mechanisms influence environmental performance. By integrating these elements, the research not only deepens the understanding of the governance–innovation–environment nexus but also provides evidence-based guidance for policymakers aiming to align institutional reforms and digital governance with green innovation strategies in the pursuit of net-zero emissions.

2. DATA SOURCES

This study examines the impact of e-governance, green innovation, and institutional quality on Japan's progress toward achieving net-zero emissions over the period 2001–2023. To construct the empirical framework, a range of indicators relevant to the Net-Zero Emissions Index (NZEI)—including CO_2 emissions, combustible renewables and waste, total primary energy supply, CO_2 intensity, and electricity generation from oil-based sources—are sourced from the World Development Indicators (WDI) database [28].

Data on institutional quality (IQ) are sourced from the Worldwide Governance Indicators (WGI) [29], which encompass six dimensions of governance: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption. The E-Government Index (EGI)—used to measure the development of digital governance—is extracted from the United Nations E-Government Knowledgebase. This index captures three critical dimensions: the Online Service Index, the Telecommunication Infrastructure Index, and the Human Capital Index. To quantify green technology innovation (GTI), data are drawn from the Organization for Economic Co-operation and Development (OECD) database, which reflects patent applications and technological outputs related to environmentally sustainable innovations. Additionally, to control for the economic influence of natural endowments, data on natural resource rents (NRR) as a percentage of GDP are also obtained from the WDI.

Together, these diverse data sources provide a comprehensive and reliable foundation for assessing the synergistic effects of governance, innovation, and institutional capacity on Japan's carbon neutrality transition.

2.1 Net-zero emissions index (NZEI)

The Net-Zero Emissions Index serves as the dependent variable in this study, capturing Japan's overall progress toward achieving carbon neutrality. It integrates five critical environmental and energy-related indicators: CO_2 emissions, combustible renewables and waste, total primary energy supply, CO_2 intensity, and electricity generation from oil-based sources.

To construct a comprehensive and unified measure of carbon neutrality performance, this study employs Principal Component Analysis (PCA)—a widely accepted statistical technique used to reduce dimensionality and synthesize multiple correlated variables into a single composite index. Following methodologies established in prior empirical research, the resulting NZEI values range from 0 to 1, where higher scores indicate stronger progress toward net-zero emissions [30].

2.2 Institutional quality (IQ)

Institutional quality plays a critical role in shaping a country's development trajectory by promoting economic growth, strengthening human capital, and fostering social cohesion and policy effectiveness [31]. In this study, institutional quality is assessed using six key governance dimensions: voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption—as reported by the Worldwide Governance Indicators (WGI).

To synthesize these dimensions into a single, robust measure, this study employs Principal Component Analysis (PCA)—a well-established statistical technique that reduces dimensionality and captures the common variance across the governance indicators. Following prior literature [31], the first principal component is extracted to construct a composite Institutional Quality Index, where higher values reflect stronger institutional capacity and governance effectiveness.

3. METHODS

3.1 Unit root test

The Augmented Dickey-Fuller (ADF) test is employed to assess the presence of a unit root in a time series, thereby determining whether the series is stationary or non-stationary. It enhances the standard Dickey-Fuller test by incorporating lagged differences of the dependent variable to address potential higher-order serial correlation.

The general form of the ADF regression is:

$$\Delta y_t = \gamma y_{t-1} + \sum_{i=1}^{p} \delta_i \Delta y_{t-i} + \epsilon_t \quad (1)$$

where, γ is the coefficient of interest, testing whether the series has a unit root, δ_i are the coefficients on the lagged differences, ensuring white noise residuals, p is the number of lagged differences included, ϵ_t is the error term.

3.2 Autoregressive distributed lag (ARDL)

This study employs the ARDL modeling framework developed by Pesaran and Shin [32] to examine the short-run and long-run relationships between net-zero progress (NZEI) and its potential determinants: e-government index (EGI), green technological innovation (GTI), natural resource rent (NRR), and institutional quality (IG). The ARDL approach is particularly suitable for small sample sizes and allows for a mixture of integration orders—i.e., I(0) and I(1)—as long as none of the variables is integrated of order two, I(2). The ARDL model can be specified in its error correction form as follows:

$$\begin{aligned}\Delta NZEI_t = \phi(NZEI_{t-1} - \lambda_1 EGI_{t-1} \\ - \lambda_2 GTI_{t-1} - \lambda_3 NRR_{t-1} \\ - \lambda_4 IQ_{t-1}) + \psi_1 \Delta EGI_t \\ + \psi_2 \Delta GTI_t + \psi_3 \Delta NRR_t \\ + \psi_4 \Delta IQ_t + \epsilon_t\end{aligned} \quad (2)$$

In this equation, ϕ represents the coefficient of the error correction term (ECT), indicating the speed at which deviations from the long-run equilibrium are corrected. The λ_i coefficients capture the long-run relationships between NZEI and its explanatory variables, while the ψ_i coefficients account for the short-run dynamics through first-differenced terms. A significantly negative coefficient of the ECT provides evidence of a stable long-run equilibrium relationship among the variables and quantifies the proportion of disequilibrium corrected in each time period.

This methodological approach facilitates a comprehensive analysis of both the immediate (short-run) and persistent (long-run) impacts of economic and policy variables on the advancement toward net-zero emissions.

3.3 Machine learning (ML)

To complement the econometric analysis, this study employed machine learning techniques—specifically, Random Forest (RF) and Support Vector Machines (SVM)—to uncover potential nonlinear and complex relationships among the variables. Unlike traditional parametric models, ML algorithms are data-driven and do not require prior assumptions about the functional form of the relationships. This enables the detection of intricate interactions and hidden patterns that may otherwise go unnoticed.

The dataset was partitioned into training (80%) and testing (20%) subsets to evaluate the models' predictive performance. Model accuracy was assessed using standard evaluation metrics, including Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and the coefficient of determination (R^2). For the Random Forest model, variable importance was analyzed using two key indicators: the percentage increase in mean squared error (%IncMSE) and the increase in node purity (IncNodePurity). These metrics provided insights into the relative contribution of each predictor to the overall model performance.

All machine learning analyses were implemented using Stata (version 19) for preliminary data processing and R (version 4.3.1) for model training and evaluation.

4. RESULTS AND DISCUSSION

This section presents and interprets the key findings derived from both econometric and machine learning (Random Forest and SVM) analyses. It highlights the short- and long-run impacts of e-governance, green innovation, and institutional quality on Japan's progress toward net-zero emissions, offering insights into their relative importance and policy implications.

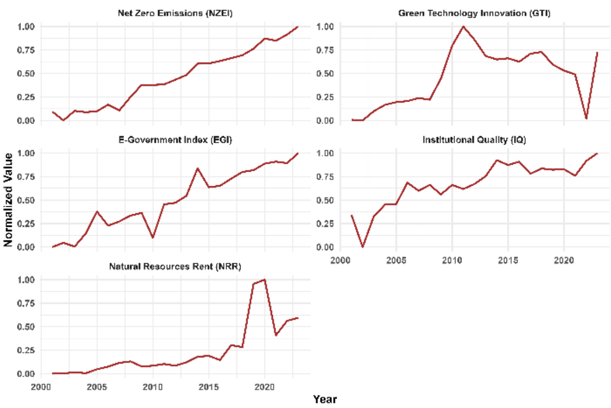

Fig. 1. Trends in NZEI, GTI, EGI, IQ, and NRR in Japan (2001–2023).

The NZEI shows a consistent upward trajectory, reflecting Japan's steady progress toward carbon neutrality—driven by diversified energy strategies, proactive climate policies, and technological advancements in renewable energy. The EGI exhibits a similar upward trend, highlighting the growing role of digital governance in supporting environmental initiatives. Likewise, IQ and GTI show gradual improvements, indicating ongoing efforts to strengthen institutional frameworks and foster green innovation. Meanwhile, NRR also demonstrates a modest rise, suggesting increasing economic returns from resource-related sectors amid sustainable management practices.

Before estimating the ARDL model, the ADF test was conducted to assess the stationarity properties of each variable.

Table 1. ADF Unit Root test results (Without Trend).

Variable	ADF test statistic	
	At level	1st difference
NZEI	0.354	-4.389***
EGI	-0.743	-5.443***
GTI	-1.959	-2.805*
NRR	-1.389	-4.767***
IQ	-3.106**	-3.200**

***p<0.01, **p<0.05, *p<0.1

The results of the ADF unit root tests indicate that, at level, most of the variables are non-stationary. Specifically, the test statistics for NZ, EGI, GTI, and NRR fail to reject the null hypothesis of a unit root at the 5% significance level, suggesting that these series are non-stationary in their levels. Only IQ is found to be stationary at level, as its ADF test statistic exceeds the 5% critical value and the corresponding p-value is below 0.05. However, after first differencing, the ADF test statistics for NZ, EGI, NR, and IQ are all significant at the 5% level, indicating that these variables become stationary after differencing. GTI shows a marginal result with a p-value slightly above 0.05, suggesting near-stationarity. Overall, the mixed order of integration — I(0) and I(1) — among the variables supports the appropriateness of applying the Autoregressive Distributed Lag (ARDL) modeling framework, which allows for a combination of stationary and first-differenced variables in the analysis.

Table 2. ARDL estimation results for net-zero emissions.

Variable	Estimate	Std. Error	p-value
Adjustment (ECM)			
$NZEI_{t-1}$	-0.339**	0.152	0.046
Lon-run effect			
EGI	0.908**	0.391	0.039
GTI	0.126*	0.161	0.077
NRR	0.257	0.243	0.311
IQ	0.076*	0.452	0.069
Short-run dynamics			
△EGI	0.128	0.137	0.368
△GTI	0.044	0.058	0.464
△NRR	–0.003	0.073	0.974
△IQ	0.219*	0.109	0.068

***p < 0.01; **p < 0.05; *p < 0.10

The ARDL estimation results provide important insights into both the short-run and long-run determinants of net-zero emissions in Japan. The error correction term ($NZEI_{t-1}$) is negative and statistically significant at the 5% level (–0.339, p = 0.046), confirming the presence of a long-run equilibrium relationship and indicating that approximately 34% of the disequilibrium is corrected each year.

In the long run, e-government development (EGI) exerts a positive and significant effect on the Net-Zero emissions index (0.908, p = 0.039), highlighting the crucial role of digital governance in facilitating carbon neutrality. Green technology innovation (GTI) also has a positive association (0.126), albeit weakly significant at the 10% level ($p = 0.077$), suggesting its supportive, though modest, contribution. Institutional quality (IQ) exhibits a similarly positive and marginally significant effect (0.076, $p = 0.069$), emphasizing the importance of governance structures in promoting environmental sustainability. However, the effect of natural resource rents (NRR) is positive but statistically insignificant ($p = 0.311$), indicating limited influence on long-term emission outcomes.

In the short run, changes in IQ (ΔIQ) have a positive and weakly significant impact ($p = 0.068$), suggesting that improvements in institutional quality can yield immediate environmental benefits. Other short-run changes, including those in EGI, GTI, and NRR, do not show statistically significant effects, implying that these variables primarily influence carbon neutrality through long-term channels.

Overall, the econometric findings underscore the synergistic long-run roles of e-governance, green innovation, and institutional quality in advancing Japan's net-zero emissions goals.

Fig. 2 presents the prediction accuracy of the ML models on the 20% unseen (test) dataset. Both the RF and SVM models exhibit high predictive performance, with RMSE values of 0.066 and 0.071, MAE values of 0.051 and 0.043, and R^2 scores of 0.93 and 0.92, respectively. These results indicate a strong alignment between predicted and actual NZEI values.

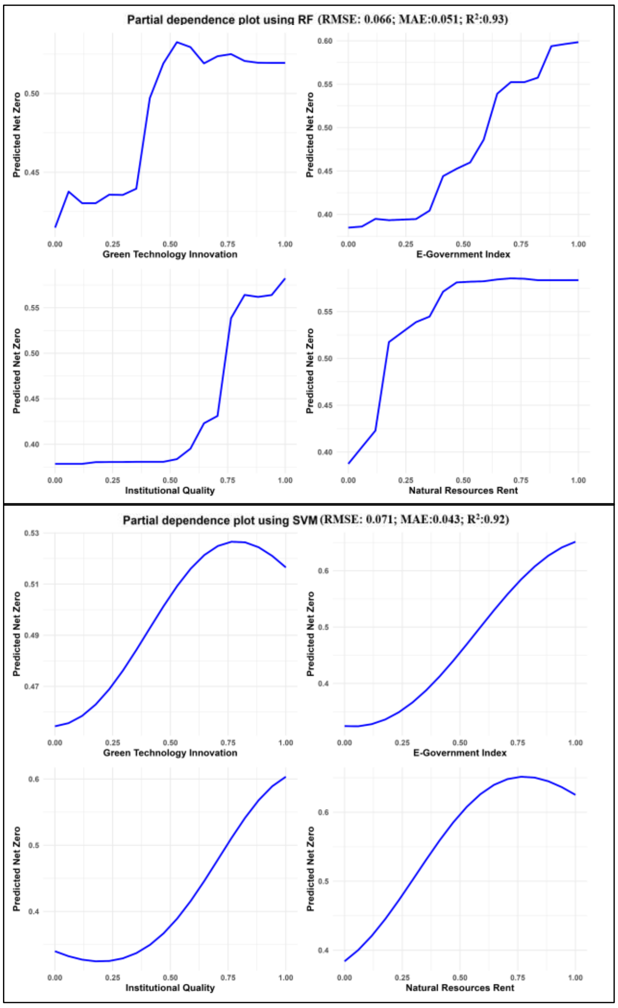

Fig. 2. Predicted NZEI based on GTI, EGI, IQ, and NRR using RF and SVM machine learning approaches.

These results indicate a strong alignment between predicted and actual NZEI values. Moreover, both models consistently identify EGI, IQ, GTI, and NRR as the most influential predictors of Japan's net-zero emissions trajectory. These machine learning findings reinforce the econometric results obtained from the ARDL model (Table 2), underscoring the robustness of the identified relationships.

Fig. 3 presents the variable importance results from the RF model, based on two key metrics: %IncMSE and IncNodePurity. The findings reveal that the E-Government Index (EGI) holds the highest importance score among all predictors, indicating its dominant role in influencing Japan's net-zero emissions performance. This underscores the critical contribution of digital governance in advancing carbon neutrality goals.

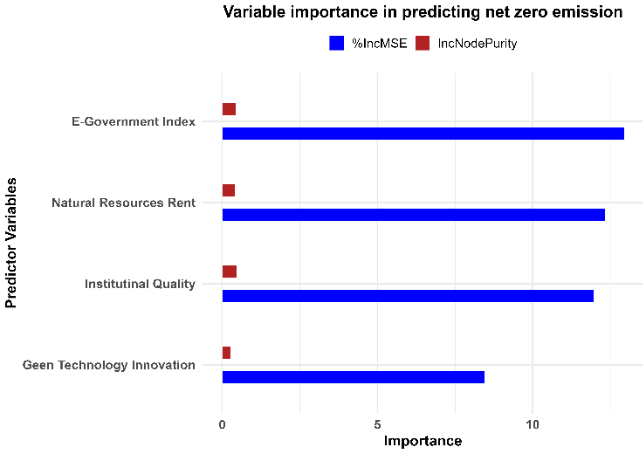

Fig. 3. Importance of predictors for NZEI estimation using the RF model.

This study investigates the synergistic impact of e-governance, green technology innovation, and institutional quality on Japan's progress toward achieving net-zero emissions over the period 2001–2023. Employing both econometric (ARDL) and machine learning (RF and SVM) techniques, the analysis reveals that all three dimensions—e-governance, green innovation, and institutional quality—play a statistically significant and complementary role in advancing carbon neutrality. Long-run estimates from the ARDL model demonstrate that improvements in the EGI, GTI, and IQ are positively associated with the Net-Zero Emissions Index (NZEI). These findings are robustly supported by the high predictive performance of machine learning models, which consistently rank EGI, NRR, IQ, and GTI as key predictors of Japan's low-carbon transition.

The consistent results across methodologies highlight the importance of an integrated governance–innovation–institutional framework for environmental sustainability. In particular, the critical role of digital governance (EGI) suggests that government digitalization efforts can effectively facilitate emission reductions through improved public service delivery, data transparency, and policy coordination. Similarly, green innovation is shown to be a key driver in decarbonizing sectors like energy, transport, and manufacturing.

The findings of this study offer several important policy implications for Japan's carbon neutrality strategy. First, the strong influence of e-governance on emission reductions highlights the need to further digitalize public administration and integrate digital platforms into climate governance. Enhancing data transparency, public participation, and inter-agency coordination through e-government tools can accelerate low-carbon transitions. Second, sustained investment in green technology innovation is essential, and policymakers should strengthen support for clean R&D, incentivize eco-patents, and foster collaboration between academia, industry, and government. Third, improving institutional quality—through stronger rule of law, regulatory efficiency, and anti-corruption measures—is critical for ensuring effective enforcement of environmental regulations and long-term policy stability. Finally, the study suggests that resource rents should be better managed and redirected toward green initiatives, ensuring that natural wealth contributes to sustainable development. Together, these policy actions can create a synergistic environment that aligns innovation, governance, and institutional strength with Japan's ambitious net-zero emissions goals.

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