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# Digital Governance and Carbon Impact: Threshold Dynamics in Emission Reductions for High-Income Economies

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Understanding the carbon impact of e-government is essential for addressing climate change in the digital age. This study investigates the nonlinear effects of e-government and its core components on carbon emissions over the period 2003–2020 for a panel of 54 high-income countries. Using the Panel Smooth Transition Regression (PSTR) approach, the results identify statistically significant threshold effects, indicating that the environmental impact of digital governance varies across regimes. Specifically, e-government exerts a positive effect on carbon emissions below the estimated threshold, while beyond the threshold level, further improvements lead to a measurable reduction in emissions, confirming a nonlinear adjustment process. The estimated thresholds are systematically lower in major oil-producing countries, implying that relatively modest improvements in digital governance generate larger marginal emission-reduction effects in these economies. Robustness checks using GMM and fixed-effects estimations confirm the magnitude, direction, and statistical significance of the main results. These findings suggest that surpassing identified digital governance thresholds is critical for policymakers seeking to leverage e-government as an effective tool for environmental sustainability in developed economies.

**Keywords:** Carbon emission, E-government, High-income countries, PSTR, Top oil-producing countries

## Introduction

The increasing intensity of global warming has positioned climate change among the most critical global issues requiring immediate and coordinated action. The Intergovernmental Panel on Climate Change reports that average global temperatures have increased since pre-industrial times.[1] This temperature rise has led to numerous adverse effects, including more frequent and severe heat waves, melting glaciers and ice caps, rising sea levels, and disruptions within ecosystems. These global impacts, primarily driven by substantial increases in carbon emissions, transcend borders and affect ecosystems, weather patterns, and overall planetary health. Around the world, governments, policymakers, and researchers are increasingly prioritizing climate change, particularly in resource-rich nations where the issue has become especially pressing.

In this context, recognizing the vital role of governments in tackling this global challenge is essential. The relationship between Electronic Government (e-government) and carbon emissions has become a significant topic in environmental research.[2] E-government refers to the integration of Information and Communication Technologies (ICTs) into public sector administration to improve operational efficiency, strengthen transparency, and enhance the quality of public service delivery.[3] Existing evidence suggests that the continued development of e-government has considerable potential to mitigate carbon emissions by facilitating digital service provision, supporting remote working arrangements, improving resource utilization, and decreasing reliance on physical travel. Furthermore, e-government can stimulate green technological innovation by advancing digital transformation, increasing resource efficiency, and fostering collaborative digital ecosystems that enable effective interaction among diverse stakeholders. Increasingly, studies highlight e-government's potential to foster green technology innovation. However, scholars have noted that in low- and middle-income countries, green technology innovations are often limited by policies that prioritize living standards over environmental concerns and a lack of supporting innovations.[4,5] In essence, e-government supports green technology innovation, though its effectiveness in enabling green

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technology may be influenced by various policy and innovation factors.[1,6,7]

Recent research highlights the negative environmental impacts of e-government adoption. Some scholars argue that e-government may inadvertently increase carbon emissions by encouraging energy-intensive infrastructure, including extensive data storage and processing needs for public sector digitalization, which increases the demand for electricity.[8] Furthermore, the rapid turnover of electronic devices in e-government operations contributes to electronic waste, which poses environmental and health hazards, particularly in developing countries where e-waste management systems may be inadequate. The continuous upgrading of digital infrastructure can also result in a significant carbon footprint, as producing and disposing of ICT equipment generate greenhouse gases.[7] Therefore, the complex effects of e-government on environmental outcomes underscore the need for sustainable digital strategies.[6,7]

Against this backdrop, the present study addresses the existing gap in the literature by examining the multifaceted relationship between e-government and environmental performance. Using a comprehensive sample of developed economies, it provides new insights into the intricate association between digital governance and carbon emissions, thereby enhancing the understanding of the mechanisms through which e-government supports sustainable development in high-income countries.

The primary objective of this research is to investigate the nonlinear effects of e-government on carbon emissions in developed economies, offering several contributions to the existing body of knowledge. First, the analysis is exclusively focused on high-income countries, which are characterized by substantial economic resources, relatively high levels of carbon emissions, large populations, and well-established e-government systems. Second, it examines the varied relationship between government actions and environmental quality to understand the nonlinear effects of e-government on carbon emissions. This approach addresses a gap in prior research, as this topic remains underexplored. Third, the study analyzes the nonlinear relationship among the different facets of e-government, specifically the Online Service Index, Telecommunication Infrastructure Index, and Human Capital Index. Finally, it employs the Panel Smooth Transition Regression Model (PSTR) to analyze the asymmetric effects of the various components of digital government on carbon emissions. The PSTR model's ability to identify threshold levels of transition variables and reveal distinct regimes and ideal e-government levels (i.e., thresholds beyond which the relationship may shift) brings a unique insight to this area of study. Additionally, the PSTR model's design allows for flexible shifts across groups and time based on changes in the threshold variable. This approach provides a nuanced solution to cross-country variations and time-based fluctuations in the e-government–carbon emissions relationship, with parameters that adjust smoothly according to the threshold variable, unlike traditional dynamic or static panel models or interaction effect approaches.[9,10]

## Literature Review

E-government refers to the adoption of information and communication technologies within public administration to improve efficiency, transparency, and service quality.[11,12] Digital governance has now become deeply integrated into various aspects of social life. Broadly, e-government—also termed digital government—involves the use of ICT alongside organizational shifts to optimize the structure and functioning of government.[13] Scholars identified nine core elements that define effective digital governance, including online management of utilities, centralized IT procurement, electronic service delivery, direct engagement with citizens, and efforts to foster a balanced distribution of power.[8,10] The academic community has increasingly focused on examining how e-government, and ICT can help reduce energy use and carbon emissions.[2,14,15] While many researchers highlight e-government's positive contributions to environmental quality, findings on the digital transformation's effects on carbon emissions remain varied. These controversies are further illuminated by several theoretical perspectives. On one hand, the Environmental Kuznets Curve theory[16] posits that environmental degradation initially rises with economic and technological development but declines once a certain level of income and institutional maturity is reached. Applied to digital governance, this suggests that e-government adoption may initially increase energy use and carbon emissions due to the expansion of ICT infrastructure and associated power demand. However, as digitalization advances, it can enhance resource efficiency and reduce emissions, producing an inverted-U relationship consistent with the EKC framework.

On the other hand, rebound effect theory[17], emphasizes that efficiency gains from technological improvements may be partially or wholly offset by increased energy consumption resulting from broader use or expansion of services. In the context of digital technologies and e-government, this implies that ICT-driven efficiency improvements can paradoxically lead to higher overall energy use or emissions as digital economic activity grows. Consequently, even when e-government initially enhances efficiency, the net environmental impact may be non-linear and contingent on the scale and intensity of digital adoption.

Numerous studies suggest that e-government supports environmental sustainability. For instance, the integration of e-government solutions supports the transition toward remote work models and facilitates the provision of online public services, reducing energy consumption in offices and minimizing physical travel. By offering digital options like e-tax filings and online consultations, e-government significantly cuts transportation-related emissions.[7] Additionally, optimized administrative processes and improved data management promote resource efficiency, lowering the potential for waste and carbon emissions. Previous research highlights that digital technology development may contribute to lowering carbon emissions through dematerialization and substitution effects.[18] Scholars, for example, demonstrated that the digital economy could address resource misallocation, particularly regarding labor and capital, leading to more efficient carbon use in China, based on empirical analysis across 30 regions from 2011 to 2019.[(19)] Similarly, other authors found that ICT contributes to carbon reduction by replacing fossil fuels with renewable energy sources. As public institutions implement e-governance strategies, research shows that these efforts can make a significant contribution toward achieving the Sustainable Development Goals.[20] For instance, digital communication methods facilitate interactions between local governments and stakeholders, which supports sustainability by reducing vehicle usage and optimizing logistics.[2]

E-government is widely recognized as a tool for enhancing environmental sustainability by reducing energy consumption and carbon emissions. Digital public services support remote work and online transactions, lowering office energy use and transportation-related emissions.[7] Improved administrative efficiency and data management further promote resource optimization and emission reduction. Digitalization also contributes to carbon mitigation through dematerialization and substitution effects.[18] Moreover, ICT development can accelerate the adoption of renewable energy solutions and facilitate the realization of the Sustainable Development Goals by strengthening coordination, minimizing transportation-related activities, and enabling more efficient management of supply chains and logistics.[2,20] Digital technologies also enable government bodies to better assess energy market dynamics and price shifts, aiding the regulation of energy supply through tools like subsidies, taxes, and pricing models. By incorporating digital tools in carbon trading markets, governments can adjust market mechanisms and regulatory frameworks.[21] Such integration enhances overall energy consumption management and thus reduces carbon emissions.[22,23] Furthermore, e-government initiatives aimed at sustainable development use ICT to improve public services and administration, promoting interactions between the government and citizens. These efforts encourage public participation in decision-making, foster social equity and economic growth, and work toward conserving natural resources for future generations.[24] The advancement of e-government can serve as a powerful catalyst for green technology innovation.[25] Beyond improving government efficiency, e-government fuels digital economic growth, which fosters innovation and supports the innovation and diffusion of green technologies, which can enhance environmental performance and contribute to better ecological outcomes.[26] Additionally, e-government plays a critical role in refining resource allocation, which is essential for driving innovation, reducing inefficiencies, and channeling investments into green technology initiatives.

On the other hand, several studies have highlighted an adverse relationship between e-government development and environmental sustainability. Some research suggested that while the development of digital infrastructure can drive energy-intensive production processes, it may also lead to a greater reliance on energy sources that are more expensive or environmentally damaging, thereby negatively impacting environmental quality.[27] Authors pointed out that, although ICT has contributed significantly to global growth, it has also increased social costs that could have severe environmental repercussions.[28] Numerous studies supported the view that governments have not adequately prioritized environmental sustainability within their e-government strategies.[28–30] The findings of these studies reveal important factors influencing the effectiveness of e-government programs, which may help clarify why such initiatives could be associated with negative environmental sustainability outcomes. In the same vein, other researchers have raised concerns about the environmental effects of digitalization, such as electricity consumption and electronic waste, which result from the manufacturing, operation, and disposal of ICT devices.[31,32] While the use of digital technologies in economic activities can enhance efficiency, it also leads to higher energy consumption, particularly in the form of increased electricity demand, which consequently raises carbon emissions.[33] Other researchers have emphasized that the ICT sector cannot be considered entirely environmentally sustainable, as its embodied carbon footprint associated with production, infrastructure, and supply chains significantly exceeds its direct operational emissions.[34] This is primarily due to the ICT sector's reliance on carbon-intensive inputs from non-ICT industries.

Empirical evidence on the relationship between e-governance and sustainability remains mixed. Studies covering 153 countries indicate that e-governance contributes to sustainable natural resource management and energy efficiency, particularly in resource-dependent economies.[35] Cross-country analyses of 103 nations over the period 2003–2018 further show that e-governance enhances sustainability outcomes, especially in developing and transitional contexts.[36] These findings are reinforced by logit-based evidence demonstrating that e-governance increases the probability of achieving sustainability as measured by adjusted net savings.[37] Additionally, cross-sectional evidence from 147 countries confirms that e-governance adoption positively affects economic sustainability.[38] In contrast, several studies document adverse sustainability effects associated with e-governance and digitalization. Evidence from 15 MENA countries over the period 2003–2018 indicates that although e-government improves governance quality, including corruption control and government effectiveness, it exerts a negative influence on multiple dimensions of

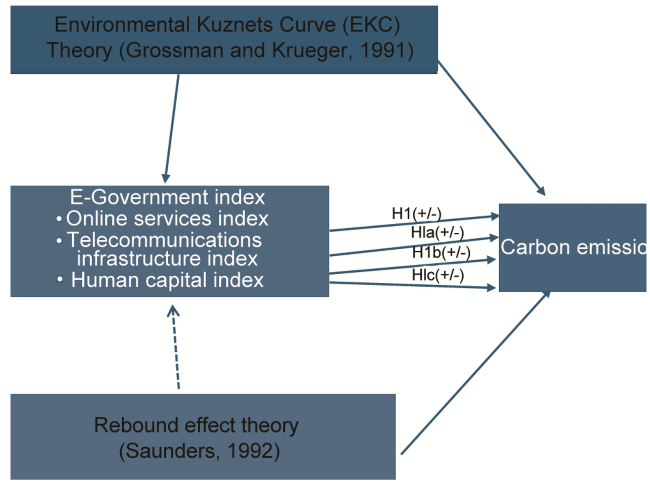


Fig. 1 — Conceptual framework, source: author

sustainable development.[39] Further empirical analysis reveals a U-shaped relationship between digitalization and carbon emissions, where initial emission reductions in the logistics sector weaken as digitalization intensifies.[40] Consistent with this, city-level spatial econometric evidence from 285 Chinese cities shows that ICT adoption aggravates environmental pollution, largely due to rebound effects associated with expanded digital activity.[27]

Building on the existing literature, we develop the conceptual framework in Fig. 1 and propose the following hypothesis:

*H1: E-government exerts a nonlinear effect on carbon emissions in high-income countries.*

*H1.a: Online Services Index exerts a nonlinear effect on carbon emissions in high-income countries.*

*H1.b: Telecommunications Infrastructure Index exerts a nonlinear effect on carbon emissions in high-income countries.*

*H1.c: Human capital index exerts a nonlinear effect on carbon emissions in high-income countries.*

**Data and Variables**

The data for this study were sourced from the World Development Indicators and the E-Government Development Index, provided by the World Bank and the United Nations E-Government Survey. The study spans from 2003 to 2020, as e-government data became available in 2003, and carbon emission data from the World Development Indicators is available until 2020. The study focuses on 54 high-income countries, chosen according to the availability of e-government index data and classified based on the World Bank's income categories for 2020. This year was chosen as a reference because high-income status

Table 1 — List of countries

| Countries | |
|---|---|
| Ireland | Barbados |
| Italy | Belgium |
| Japan | Brunei Darussalam |
| Kuwait | Canada |
| Latvia | Cyprus |
| Liechtenstein | Czech Republic |
| Lithuania | Denmark |
| Luxembourg | Finland |
| Malta | Spain |
| Monaco | France |
| Andorra | Germany |
| Antigua and Barbuda | Greece |
| Estonia | Hungary |
| Netherlands | Iceland |
| New Zealand | Slovenia |
| Norway | Sweden |
| Oman | Switzerland |
| Palau | Trinidad and Tobago |
| Poland | United Arab Emirates |
| Portugal | United Kingdom of Great Britain and Northern Ireland |
| Qatar | United States of America |
| Republic of Korea | Uruguay |
| Australia | Saint Kitts and Nevis |
| Austria | San Marino |
| Bahamas | Saudi Arabia |
| Chile | Singapore |
| Bahrain | Slovakia |

is relatively stable over time, and the classification reflects the economic context of the countries for the majority of the 2003–2020 study period. Counties are reported in Table 1.

E-government variable is measured by the E-Government Development Index (EGDI), which reflects the online availability of government services and web connectivity. The EGDI is a composite index that averages three sub-indices: the Online Services Index (OSI), the Telecommunications Infrastructure Index (TII), and the Human Capital Index (HCI), reflecting web connectivity, telecom infrastructure, and skilled workforce. Each component is weighted equally at 0.33. The index takes values between 0 and 1, with lower values denoting limited e-government advancement and higher values indicating a more developed e-government environment. Carbon emission data, the dependent variable in this study, is sourced from the World Development Indicators. Consistent with previous research, carbon emissions are measured as per capita $CO_2$ emissions in metric tons.[41,42]

Drawing from existing literature on the factors influencing carbon emissions, we incorporate several control variables.[41,42] These include financial system development (FD), represented by private sector credit as a percentage of GDP, foreign direct investment (FDI), measured by net inflows as a percentage of GDP, GDP growth (GDP), measured by GDP per capita in constant 2015 US dollars, trade openness (TO), population (POP), and institutional factors such as control of corruption (CORR) and the rule of law (RL), since better governance is often associated with improved environmental outcomes. Data for these control variables is also obtained from the World Development Indicators.

**Empirical Model**

The Panel Smooth Transition Regression (PSTR) model is used to investigate the potential nonlinear relationship between e-government and carbon emissions in high-income countries. This model offers several advantages for our analysis. It divides the panel data into distinct homogeneous groups, each with its own set of coefficients.[43,10] In this study, these groups are defined according to the level of e-government development. In addition, the PSTR model emphasizes smooth transitions between regimes, rather than abrupt changes. Unlike PTR model, it allows the elasticity of the dependent variable to the e-government variable to vary over time and across countries, depending on the level of digital government development.[44] The PSTR model was chosen due to its flexibility in handling unknown forms of transition within the data.
The following model is used:

$$Y_{it} = \alpha_i + \beta_0 EGDI_{it} + \beta_1 EGDI_{it} \times g(q_{it};\, \gamma; c) + \beta_2 Z_{it} + e_{it} \quad \ldots (1)$$

where, $Y_{it}$ is the dependent variable measured by carbon emissions, $EGDI_{it}$ is the vector of e-government measurements for country i at time t. $Z_{it}$ is a k-dimensional vector of control variables. Standard errors at the country level are clustered to prevent heteroscedasticity concerns. According to the literature, the logistic transition function, denoted as $g(q_{it};\, \gamma; c)$ is a continuous function of the transition variable $q_{it}$.[10] $q_{it}$ is confined within the range of 0 and 1 and is defined as follows:

$$g(q_{it};\, \gamma; c) = \left[1 + \exp\left(-\gamma \prod_{j=1}^{m} (q_{it} - c_j)\right)\right]^{-1} \ldots (2)$$

where, $\gamma > 0$; $c_1 \leq c_2 \leq \ldots \leq c_m$ ; $\gamma$ is the slope of the transition function and $c = (c_1,..,c_m)$ is an m dimensional vector of threshold parameters. For m = 1 and m = 2, there are one or two levels of digital government around which the effect on environment is non-linear. This non-linear effect is represented by a parameter continuum between the extreme regimes. Equation (1) allows to see if non-linearity is connected to different levels of e-government. Indeed, depending on the values of EGDI variables, different levels may have a significant impact on carbon emissions. Whereas the linear model in Eq. (1) imposes a fixed elasticity that remains unchanged and equal to zero, the PSTR framework captures heterogeneous elasticities that evolve across firms and time periods according to the level of the transition function.

When the transition variable is equivalent to the exogenous variable (i.e., $q_{it} = EGDI_{it}$), the elasticity of carbon emissions with respect to e-government development is defined as follows:

$$\frac{\partial Y_{it}}{\partial EGDI_{it}} = \beta_0 + \beta_1 g(EGDI_{it};\ \gamma; c) + \beta_1 \frac{\partial g(EGDI_{it}; \gamma; c)}{\partial EGDI_{it}} EGDI_{it}\ , \forall i, \forall t \quad \ldots (3)$$

The elasticity of carbon emissions with respect to e-government can be expressed as a linear combination of the parameters β0 and β1. The PSTR model offers a detailed analysis of the impact of e-government on environmental quality. One key advantage of this model is that the elasticity of environmental quality relative to the level of digital governance can differ between the extreme regimes, i.e., β0 and β0 + β1. As shown in Eq. (3), these parameters do not represent the direct effect of e-government on carbon emissions. For example, β0 reflects the direct impact of e-government on carbon emissions when the transition function $g(q_{it};\ \gamma; c)$ approaches 0. Conversely, when $g(q_{it};\ \gamma; c)$ approaches 1, the elasticity of carbon emissions to e-government is the sum of β0 and β1. In between these two extremes, the elasticity of carbon emissions to e-government is a weighted average of β0 and β1, representing a continuous range of potential effects.

Finally, the literature outlined a procedure for conducting specification tests.[10] The first step is to test the linearity against the PSTR model, and the second is to determine the number, r, of transition functions. The linearity test in the PSTR model (Eq. (1)) involves testing $H0 : \gamma = 0$ or $H0 : \beta_1 = 0$. However, under the null hypothesis, this test becomes nonstandard, as the PSTR model includes unidentified nuisance parameters. One approach to address this issue is to replace the transition function $g(q_{it};\ \gamma; c)$ with its first-order Taylor expansion around $\gamma = 0$ and test the equivalent hypothesis in an auxiliary regression.

## Results

### Descriptive Statistics

Descriptive statistics for the relevant variables are presented in Table 2. The average carbon dioxide emissions amount to 9.93 tons per capita, with a considerable standard deviation, indicating significant variation in environmental quality across the sample. The average e-government score is 0.68, suggesting a relatively advanced level of digital governance in high-income countries. The minimum value is 0, while the maximum is 0.97, highlighting substantial heterogeneity among the countries in the sample, which justifies the use of the PSTR model. Similarly, the e-government subdimensions exhibit high mean values, except for the Telecommunications Infrastructure Index (TII), which has a lower average compared to the other dimensions.

Table 2 — Descriptive statistics

| Variable | Mean | Standard Deviation | Min | Max |
|---|---|---|---|---|
| CO2 | 9.939363 | 6.712283 | 1.355235 | 47.65696 |
| EGDI | 0.684302 | 0.176954 | 0 | 0.9758 |
| OSI | 0.615161 | 0.249831 | 0.0262 | 1 |
| TII | 0.495227 | 0.322057 | 0 | 1 |
| HCI | 0.854925 | 0.186052 | 0 | 1 |
| FD | 92.52781 | 47.71089 | 0.18617 | 304.5751 |
| FDI | 16.24117 | 98.91351 | −1303.11 | 1282.607 |
| TO | 112.0129 | 70.58938 | 21.32613 | 437.3267 |
| GDP | 1.053632 | 4.20209 | −21.7935 | 23.30469 |
| POP | 20619573 | 47088940 | 17794 | 3.32E+08 |
| CORR | 1.140008 | 0.736683 | −0.64981 | 2.459118 |
| RL | 1.129354 | 0.569978 | −0.67413 | 2.124782 |

**Correlation Matrix**

The correlation matrix reported in Table 3 illustrates the relationships among the dependent variable, the main independent variables, and the set of control variables. The findings show that EGDI and its subcomponents are negatively correlated with carbon emissions. Additionally, the table reveals a weak correlation between the explanatory variables, supporting their inclusion in the same model.

**Results of the Homogeneity Test**

Results of the homogeneity tests are presented in Table 4. It includes the p-values from the Lagrange multiplier and Fisher-type tests for the null hypothesis of linearity versus non-linearity. At the 1% significance level, the homogeneity hypothesis is rejected. The results indicate that when m = 1, the rejection of linearity is statistically significant. This suggests that for each transition variable, there is a single threshold beyond which the effects of different e-government measures on carbon emissions become non-linear, resulting in two distinct regimes. Following the previous literature, it is assumed that only one threshold exists (m = 1), so further analysis of nonlinearity was not pursued.[45] Moreover, there is no theoretical or empirical evidence to support the possibility of m equalling 2 in our context. Based on these findings, we employ the PSTR methodology to estimate the relationship, since the results reveal that the influence of e-government on $CO_2$ emissions changes according to the level of digital governance advancement.

Notes: LM and *F* refer to the Lagrange multiplier and *F* tests for assessing linearity. Under the null hypothesis (**$H_0$**), the relationship is assumed to follow a linear specification, while the alternative hypothesis (**$H_1$**) suggests a PSTR model with one transition function ($m$ = 1). EGDI, OSI, TII, and HCI correspond to the alternative measures of e-government development employed in the analysis.

**Results of the PSTR Model**

The results derived from the PSTR model are presented in Table 5. The columns provide the estimated coefficients based on the different proxies used to capture e-government development. Before starting analyzing the results, it is important to note that the estimated parameters of the PSTR model cannot be directly interpreted; we can only draw conclusions from the signs of the regression coefficients.[10] More precisely, the marginal effect of e-government on carbon emissions is obtained by combining the linear coefficient with the transition component, which varies according to the position of the transition variable relative to the estimated threshold. Findings in Table 5 indicate the presence of non-linearity and the existence of one threshold in the E-government–carbon emissions relationship. Particularly, the relationship between digital government and pollution is defined by two distinct regimes. The model incorporates a single transition function, meaning that for countries with low levels of e-government development (below the estimated threshold), the marginal effect of e-government on

Table 3 — Correlation matrix

| | CO2 | EGDI | OSI | TII | HCI | FD | FDI | TO | GDP | POP | CORR | RL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CO2 | 1 | — | — | — | — | — | — | — | — | — | — | — |
| EGDI | −0.625 | 1 | — | — | — | — | — | — | — | — | — | — |
| OSI | −0.674 | 0.511 | 1 | — | — | — | — | — | — | — | — | — |
| TII | −0.247 | 0.602 | 0.433 | 1 | — | — | — | — | — | — | — | — |
| HCI | −0.124 | 0.507 | 0.511 | 0.466 | 1 | — | — | — | — | — | — | — |
| FD | 0.324 | 0.011 | 0.012 | 0.074 | 0.103 | 1 | — | — | — | — | — | — |
| FDI | 0.101 | 0.106 | 0.214 | 0.133 | 0202 | 0.306 | 1 | — | — | — | — | — |
| TO | 0.291 | 0.224 | 0.239 | 0.187 | 0.004 | 0.401 | 0.356 | 1 | — | — | — | — |
| GDP | 0.030 | 0.027 | 0.077 | 0.156 | 0.111 | 0.202 | 0.061 | 0.128 | 1 | — | — | — |
| POP | 0.402 | 0.001 | 0.044 | 0.101 | 0.198 | 0.047 | 0.077 | 0.152 | 0.088 | 1 | — | — |
| CORR | 0.311 | 0.144 | 0.202 | 0.178 | 0.056 | 0.099 | 0.155 | 0.066 | 0.144 | 0.044 | 1 | — |
| RL | 0.143 | 0.148 | 0.012 | 0.352 | 0.233 | 0.135 | −0.072 | 0.155 | 0.093 | 0.077 | 0.233 | 1 |

Table 4 — LM and F tests of homogeneity (P-values)

| | EGDI m=1 | OSI m=1 | TII m=1 | HC m=1 |
|---|---|---|---|---|
| LM test | 0.003 | 0.001 | 0.005 | 0.002 |
| F test | 0.002 | 0.002 | 0.007 | 0.004 |

Table 5 — PSTR estimation results (all the sample)

| | Model 1 EGDI | Model 2 OSI | Model 3 TII | Model 4 HCI |
|---|---|---|---|---|
| EGDI | 0.008* (0.005) | — | — | — |
| EGDI* g (.) | −0.011** (0.002) | — | — | — |
| OSI | — | 0. (0.012) | — | — |
| OSI* g (.) | — | −0.013** (0.001) | — | — |
| TII | — | — | 0.005** (0.003) | — |
| TII*g(.) | — | — | −0.106** (0.011) | — |
| HCI | — | — | | 0.001* (0.002) |
| HCI*g(.) | — | — | — | −0.022** (0.006) |
| Control variables | | | | |
| FD | 0.011** (0.003) | 0.106* (0.056) | 0.033* (0.002) | −0.065 (0.366) |
| FDI | 0.020 (0.103) | 0.018* (0.002) | 0.032* (0.008) | 0.016** (0.009) |
| TO | 0.134*** (0.001) | 0.166* (0.003) | 0.154 (0.118) | 0.165** (0.098) |
| GDP | 0.102* (0.010) | −0.101 (0.106) | 0.128** (0.033) | 0.104 (0.111) |
| POP | 0.033* (0.022) | 0.020 (0.110) | 0.013* (0.008) | 0.014* (0.088) |
| CORR | −0.115** (0.035) | −0.107*** (0.002) | −0.101** (0.040) | −0.098*** (0.007) |
| RL | −0.020** (0.001) | −0.023 (0.110) | 0.014 (0.130) | −0.026* (0.014) |
| Transition parameters | | | | |
| EGDI($c_{1,1}$) | 0.58 (0.013) | — | — | — |
| EGDI(γ) | 25.14 (0.503) | — | — | — |
| OSI($c_{1,1}$) | — | 0.53 (0.032) | — | — |
| OSI(γ) | — | 18.44 (0.562) | — | — |
| TII($c_{1,1}$) | — | — | 0.49 (0.035) | — |
| TII(γ) | — | — | 23.26 (0.802) | — |
| HCI($c_{1,1}$) | — | — | | 0.69 (0.022) |
| HCI(γ) | — | — | | 30.11 (0.703) |
| Countries | 54 | 54 | 54 | 54 |

Note: Models 1 to 4 include EGDI, OSI, TII and HCI as transition variables. $c_{1,1}$ and γ represent the estimated location parameter and estimated slope parameter. *, **, and *** denote significance levels at 10, 5, and 1%, respectively.

$CO_2$ emissions corresponds to $\beta_0$. For countries exceeding the threshold (high-development regime), the effect is given by $\beta_0 + \beta_1$, representing the combined influence once the transition variable crosses the critical point. In this case, $\beta_0 + \beta_1$ is negative, showing that further improvements in e-government are associated with reductions in carbon emissions. Specifically, in the low regime, a 1% increase in EGDI, OSI, TII, and HCI corresponds to increases in $CO_2$ emissions of 0.008%, 0.002%, 0.005%, and 0.001%, respectively, indicating that initial stages of digital governance may slightly raise emissions. In contrast, above the threshold, the marginal effects are −0.003% (0.008 − 0.011), −0.011% (0.002 − 0.013), −0.101% (0.005 − 0.106), and −0.021% (0.001 − 0.022) for EGDI, OSI, TII, and HCI, respectively, illustrating that once e-government reaches a higher level of maturity, it contributes meaningfully to emission reductions. Thus, when the transition variable exceeds the estimated threshold, the combined marginal effect becomes negative, implying that further improvements in e-government reduce carbon emissions through efficiency gains, dematerialization of public services, and improved regulatory enforcement.

These findings suggest that e-government has a nonlinear effect on environmental outcomes: modest improvements in countries already above the threshold can significantly decrease $CO_2$ emissions, while countries below the threshold may initially experience small increases. These results corroborate the Environmental Kuznets Curve theory[16], which predicts an initial phase of environmental deterioration followed by improvement as institutional quality and technological maturity advance.

Besides, Table 5 displays the threshold levels for each e-government measure. Below these thresholds, lower levels of digital government are associated with increased pollution, while above these thresholds, higher levels of e-government are linked to reductions in pollution. The threshold levels are 0.58 for EGDI, 0.53 for OSI, 0.49 for TII, and 0.69 for HCI. Therefore, among these e-government measures, the human capital index must be particularly well-developed to positively impact the environment.

Based on results in Table 5, the positive effect of digital government on carbon emission in the first regime imply that a low developed level of digital governance will have a detrimental effect on environmental quality. These findings support previous studies that found a positive effect between e-government and pollution.[27,39,40] Digital government initiatives often optimize resource management through real-time data on environmental indicators. In a low-digital government environment, these efficiencies are harder to achieve, leading to inefficiencies that contribute to pollution.[46] When digital government initiatives are lacking, public awareness campaigns are less effective, and citizen participation in green practices is reduced. Similarly, our findings could be explained by the fact that low digital government capabilities hinder the implementation of smart city technologies, which can significantly increase pollution.[47,48] Without a digital infrastructure, cities cannot fully leverage these technologies, leading to increased pollution. Without adequate digital infrastructure, governments cannot leverage data to make effective environmental policies, resulting in less targeted pollution reduction efforts.

The results presented in Table 5 indicate that the net negative coefficient of e-government on carbon emissions in the second regime reflects the environmental benefits associated with advanced digital government development, highlighting its potential role in improving environmental quality. Particularly, results prove that a high level of online services, a well-developed telecommunications and internet infrastructure, and a strong human capital index all contribute positively to improving environmental quality. These results support previous studies that underline the positive effects of digital governance on environmental quality.[35–38] Our findings align with previous research suggesting that e-government adoption fosters remote work and the use of digital platforms for public services and citizen engagement, which reduces the demand for traditional workplace energy use and face-to-face mobility, thereby contributing to a decline in transport-related carbon emissions.[49] In addition, improved administrative efficiency and advanced data management systems enhance resource utilization by reducing operational inefficiencies, limiting waste generation, and lowering carbon emissions. Our results reinforce the view that digital technologies contribute to carbon emission reductions through dematerialization and substitution effects.[18] Similarly, the carbon reduction impact of the EGDI and its subcomponents supports the notion that integrating digital tools in the carbon trading market allows for adjustments in market mechanisms and regulations.[21] This leads to improved management of energy consumption and a reduction in overall carbon emissions.[22,23] Moreover, e-government initiatives focused on sustainable development utilize ICT to improve public service delivery, foster government-citizen interactions, and encourage citizen involvement in decision-making. This promotes social equity, supports socioeconomic development, and helps preserve natural resources for future generations.[24]

To gain a deeper understanding of the results in Table 5, it is essential to examine the slope of the transition function, represented by ($\gamma$). This parameter indicates the speed of the transition, with higher values signifying a faster shift from one regime to the next. The slope parameters are 25.14; 18.44; 23.26 and 30.11 respectively in specifications (1), (2), (3) and (4). The consistent high values of the slope in Table 5 suggest a swift transition across all specifications. For example, in a country with a digital government development level just below the threshold of 0.58, the transition function suggests that an increase in development level will lead to a relatively rapid reduction in carbon emissions.

Furthermore, the analysis extends to examining the threshold dynamics of the previously identified variables within the context of the leading oil-producing countries—Canada, Saudi Arabia, and the USA. The selection of these countries is consistent with classifications established in the existing literature.[50] This research hypothesizes that the environmental effects of e-government are not uniform but may vary depending on the country-specific characteristics of these economies, as their natural resource abundance is likely to contribute significantly to pollution levels. The results of the PSTR estimation are presented in Table 6. Findings in

Table 6 — PSTR estimation results in top oil producing countries

| | Model 1 EGDI | Model 2 OSI | Model 3 TII | Model 4 HCI |
|---|---|---|---|---|
| EGDI | 0.010* (0.003) | — | — | — |
| EGDI* g (.) | −0.035*** (0.001) | — | — | — |
| OSI | — | 0.012* (0.006) | — | — |
| OSI* g (.) | — | −0.026*** (0.002) | — | — |
| TII | — | | 0.014** (0.006) | — |
| TII*g(.) | — | | −0.164*** (0.007) | — |
| HCI | — | — | — | 0.033* (0.027) |
| HCI*g(.) | — | — | — | −0.096*** (0.016) |
| Control variables | | | | |
| FD | −0.012** (0.007) | −0.116** (0.066) | −0.113* (0.049) | −0.099* (0.012) |
| FDI | −0.017* (0.010) | 0.020* (0.003) | −0.044* (0.030) | −0.031** (0.009) |
| TO | 0.022* (0.016) | 0.108* (0.036) | 0.098** (0.017) | 0.047** (0.026) |
| GDP | 0.122* (0.006) | 0.107* (0.044) | 0.116* (0.028) | 0.136* (0.012) |
| POP | 0.039** (0.025) | 0.044*** (0.009) | 0.036* (0.016) | 0.055** (0.006) |
| CORR | −0.106*** (0.002) | −0.171*** (0.006) | −0.167*** (0.009) | −0.133*** (0.003) |
| RL | −0.103*** (0.025) | −0.108*** (0.004) | 0.146** (0.079) | −0.109* (0.055) |
| Transition parameters | | | | |
| EGDI($c_{1,1}$) | 0.50 (0.011) | — | — | — |
| EGDI($\gamma$) | 20.11 (0.402) | — | — | — |
| OSI($c_{1,1}$) | — | 0.51 (0.055) | — | — |
| OSI($\gamma$) | — | 17.53 (0.601) | — | — |
| TII($c_{1,1}$) | — | — | 0.47 (0.055) | — |
| TII($\gamma$) | — | — | 21.32 (0.759) | — |
| HCI($c_{1,1}$) | — | — | | 0.52 (0.012) |
| HCI($\gamma$) | — | — | | 26.02 (0.308) |
| Countries | 3 | 3 | 3 | 3 |

Note: Models 1 to 4 include EGDI, OSI, TII and HCI as transition variables; $c_{1,1}$ and $\gamma$ represent the estimated location parameter and estimated slope parameter; *, **, and *** denote significance levels at 10, 5, and 1%, respectively

Table 6 support those in Table 5. Interestingly, Table 6 indicates that the digital government variables are highly significant. This suggests that the impact of e-government on carbon emissions reduction is particularly pronounced in the leading oil-producing countries. Additionally, the threshold levels are lower than those observed previously, with thresholds of 0.50 for EGDI, 0.51 for OSI, 0.47 for TII, and 0.52 for HCI.

The lower threshold levels for digital government effectiveness in top oil-producing countries can be attributed to their heavy reliance on natural resources, which creates a dynamic where effective governance is crucial for managing pollution even at lower levels of digital development. Increased global pressure for sustainable practices and existing environmental challenges mean that even minor improvements in governance can lead to significant pollution reductions. Moreover, these countries may have established infrastructure and resources that facilitate rapid implementation of digital initiatives without requiring extensive digitalization. Economic incentives linked to oil production further motivate governments to adopt digital solutions for environmental management, resulting in a more pronounced impact on carbon emissions reduction at lower thresholds.

Finally, the institutional control variables (CORR and RL) exhibit the expected negative signs, indicating that stronger governance structures and higher regulatory effectiveness are associated with improved environmental outcomes. This result suggests that effective institutions play a critical role in limiting environmental degradation through better policy design, enforcement, and accountability mechanisms. Besides, the positive coefficient of POP variable suggests that higher population levels increase energy demand and resource consumption, which in turn intensifies environmental pressures and contributes to higher carbon emissions.

In contrast, the macroeconomic variables, including FD, FDI, GDP, and TO, show positive coefficients, implying that they contribute to higher levels of environmental pollution. These findings are in line with some previous empirical studies[51,52], which argue that greater access to financial resources and increased economic integration tend to stimulate industrial expansion and production intensity. In such contexts, economies often prioritize growth objectives over environmental protection, leading to a sustained reliance on pollution-intensive technologies.

## Robustness Tests

The robustness results are displayed in Tables (S1) and (S2) in the appendices. As part of our robustness tests, we re-estimated the model using Generalized Method of Moments (GMM) and fixed effects approaches. Furthermore, we evaluated the consistency of our findings by extending the baseline model with supplementary control variables, such as renewable energy consumption expressed as a percentage of total final energy consumption, urbanization, regulatory quality, and government effectiveness. The results in Tables (S1) and (S2) reaffirm our main estimation findings.

## Conclusions

This study investigates the nonlinear effects of e-government and its core dimensions on carbon emissions in 54 high-income countries over 2003–2020 using a Panel Smooth Transition Regression approach. The findings reveal significant threshold effects: digital governance initially increases carbon emissions but contributes to substantial reductions once critical development levels are reached. These thresholds are lower in major oil-producing economies. Robustness checks using GMM and fixed-effects models confirm the stability of the results. The findings highlight the strategic importance of advancing digital governance to support climate mitigation. Policymakers should deepen digital maturity through investments in digital infrastructure, advanced public services, data integration, cybersecurity, and capacity building. In oil-dependent economies, leveraging lower e-government thresholds can support economic diversification and environmental transition by integrating environmental policies into digital platforms and directing resource revenues toward digital and green initiatives. Future research should expand the sample of major oil-producing countries to further refine these threshold effects.

## Supplementary Matter

Supplementary data of this article is available at https://nopr.niscpr.res.in/handle/123456789/46 and https://or.niscpr.res.in/index.php/JSIR/article/view/17895.

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## Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the author used ChatGPT-3.5 solely to assist with spelling and grammatical editing. All AI-generated suggestions were carefully reviewed, revised where appropriate, and verified by the author. The author assumes full responsibility for the accuracy, integrity, and final content of the manuscript.

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