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SMART URBANIZATION, CLEAN ENERGY TRANSITION, AND CO_2 EMISSIONS: DYNAMIC EVIDENCE FROM OECD ECONOMIES

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Abstract
Rapid urban transformation and digital intensification are reshaping environmental outcomes in advanced economies. This study examines the environmental implications of smart urbanization by analysing the roles of Information and Communication Technologies (ICT), clean energy transition, and forest cover in shaping carbon emissions across OECD economies over the period 1995-2024. Guided by an extended STIRPAT framework, the analysis employs Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) models to capture dynamic relationships while accounting for cross-sectional dependence and heterogeneity. Robustness is assessed using Fixed-Effects regressions with Driscoll-Kraay (FE-DK) standard errors. The results indicate that economic growth is decoupled from carbon emissions in OECD countries and that urbanization does not exert a uniform direct effect on emissions. Instead, its environmental impact is conditional on accompanying energy systems. Clean energy transition significantly moderates the emissions pressures associated with urban expansion, highlighting the importance of integrating renewable energy deployment within urban environments. In contrast, ICT development and forest cover exhibit weak and heterogeneous macro-level effects. Overall, the findings underscore the importance of coordinated urban and energy policies for advancing climate-compatible urban development in advanced economies.

INTRODUCTION

Urbanization is one of the most transformative forces shaping the twenty-first century. Scholars such as Chen et al. (2021) observe that densely populated cities increasingly serve as hubs of economic innovation, technological development, and social opportunity. However, cities also consume more than 70 percent of global energy and generate the majority of greenhouse gas emissions, a pattern highlighted by Rockström et al. (2009) and reinforced by the United Nations (2015). This dual role, engine of prosperity and source of ecological strain, has intensified global interest in identifying pathways through which urban development can be reconciled with environmental sustainability.

Smart urbanization represents a major shift in how economies attempt to manage this tension. Bibri and Krogstie (2017) describe smart urbanization as the integration of ICT systems, data-driven processes, and intelligent infrastructure into the urban fabric to enhance environmental performance. Empirical evidence from Qian et al. (2023) demonstrates that smart-city pilot programs reduce carbon emissions by improving transportation efficiency and enabling energy-saving technologies. Likewise, Guo et al. (2022) show that smart-city technologies can support emission reductions by improving urban energy management.

Yet the extent to which smart urbanization mitigates environmental pressure depends on underlying structural conditions. ICT systems can reduce carbon intensity through optimized industrial processes and digital efficiency gains (Huang et al., 2024; Chang et al., 2023). However, ICT expansion may also increase emissions in economies reliant on fossil-fuel-based electricity, as data centres and communication networks require substantial energy inputs (Yan et al., 2022; Magazzino et al., 2021). These mixed effects suggest that the environmental impact of ICT is conditional on technological maturity and energy structure.Clean energy transition emerges as a crucial enabling factor within smart-urbanization pathways. Hou et al. (2023) and Mirziyoyeva and Salahodjaev (2022) highlight renewable energy as a central determinant of long-run emission trajectories. Evidence from OECD economies indicates that clean energy deployment is particularly effective in reducing emissions when supported by advanced regulatory frameworks and institutional capacity (Petruška et al., 2022; Hou et al., 2023b). Cities that rely on renewable energy systems are therefore better positioned to realize the environmental benefits of ICT and digitalization.

Ecological capacity, particularly forest cover, plays an equally vital role in environmental sustainability. Forests serve as natural carbon sinks and contribute to climate regulation and air quality improvement. Anwar et al. (2021) find that forest cover significantly reduces emissions, while Yuan et al. (2022) and Li and Su (2017) emphasize that forest ecosystems help counterbalance the environmental pressures associated with economic and urban growth. Nevertheless, forest cover has rarely been examined as a moderating factor within the urbanization–emissions relationship in cross-country settings, especially among advanced economies.

Despite growing interest in smart urbanization and sustainability, several gaps remain. First, many studies rely on narrow definitions of urbanization and do not integrate ICT development, clean energy transition, and ecological capacity into a unified analytical framework. Second, interaction effects, such as how clean energy and forest cover condition the environmental impact of urbanization, remain underexplored. Third, empirical evidence focusing specifically on OECD economies is relatively limited, despite their technological advancement and policy relevance. Finally, mean-based estimators may obscure important distributional differences across emission levels (Voumik and Sultana, 2022; Raihan, 2023; Khrais and Alghamdi, 2025).

This study addresses these gaps by examining how ICT development, clean energy transition, and forest cover jointly shape the environmental impacts of urbanization in OECD economies. Employing the CS-ARDL framework, the analysis captures both short-run dynamics and long-run equilibrium relationships while accounting for cross-sectional dependence and country heterogeneity. Distributional analysis is further used to explore heterogeneity across emission levels. By focusing on interaction mechanisms within advanced economies, the study provides robust insights into how technological and ecological factors influence CO_2 emissions. The remainder of the paper is organized as follows. Section 2 reviews the relevant literature and theoretical foundations; Section 3 outlines the data and methodology; Section 4 presents the empirical results; Section 5 discusses the findings and policy implications; and Section 6 concludes.

Literature Review

Smart urbanization has emerged as a key response to the environmental pressures associated with rapid urban growth. Bibri and Krogstie (2017) conceptualize smart urbanization as the integration of digital technologies, intelligent infrastructure, and data-driven systems into the urban environment to enhance sustainability performance. Scholars such as Neirotti et al. (2014) and Lim et al. (2018) argue that smart-city initiatives can improve energy efficiency, optimize transportation systems, and reduce unnecessary resource consumption. Recent empirical studies reinforce these arguments. Qian et al. (2023) find that China's smart-city pilot program significantly reduces carbon emissions by improving mobility efficiency and enabling real-time energy management. Similarly, Ozarslan Doğan et al. (2024) provide cross-country evidence that smart-city interventions can foster better environmental performance through automation and improved energy use. Szpilko et al. (2024) emphasize that smart energy systems—such as real-time load monitoring and digital energy grids—are becoming essential components of sustainable urban development.

Nonetheless, the environmental benefits of smart urbanization depend critically on technological maturity and governance capacity. Kim (2022) highlights the role of institutional readiness, noting that weak governance structures can limit the effectiveness of smart-city technologies. Evidence from emerging economies suggests that despite rapid digitalization, the environmental benefits of smart urbanization may be constrained when energy systems remain fossil-fuel dependent (Cui and Cao, 2024). This contrast underscores the importance of institutional quality and energy-system maturity, particularly relevant for OECD economies.

The role of **information and communication technology (ICT)** in shaping environmental outcomes remains widely debated. Chen et al. (2021) show that ICT adoption enhances energy efficiency by automating industrial processes and enabling digital monitoring. Yi et al. (2025) similarly argue that ICT-driven innovation fosters cleaner production methods. Conversely, Charfeddine and Kahia (2021) find that ICT expansion may increase emissions in regions heavily dependent on fossil fuels, reflecting the substantial energy requirements of data centers and communication infrastructure. Ebaidalla (2022) further demonstrates that ICT initially raises emissions before efficiency gains begin to dominate, highlighting the presence of rebound effects.

The transition toward clean and renewable energy is central to reducing carbon emissions. Perone (2024) provides robust evidence that renewable energy contributes significantly to long-term emission reductions. Şanlı et al. (2023) document particularly strong mitigation effects in OECD countries, where established regulatory frameworks and technological readiness enhance the effectiveness of clean energy deployment. Mehta (2024) further highlights that renewable energy becomes increasingly important during periods of structural economic transformation.

Forest cover also plays a critical role in environmental sustainability by acting as a natural carbon sink and regulating local climates. Anwar et al. (2021) show that forest cover significantly reduces emissions across diverse panel economies, while Bhuiyan et al. (2023) demonstrate that maintaining forest ecosystems helps counterbalance the environmental pressures generated by industrial and urban activities. Despite its importance, forest cover has rarely been examined as a moderating factor within the smart-urbanization framework, particularly in advanced economies.

Several gaps in the literature remain. First, most studies examine urbanization in isolation, without integrating ICT, clean energy transition, and ecological capacity into a unified analytical framework. Second, interaction effects, such as how clean energy or forest cover conditions the environmental impact of urbanization, have received limited empirical attention. Third, empirical evidence focusing specifically on OECD economies remains relatively scarce, despite their advanced technological infrastructure and policy relevance. Finally, distributional heterogeneity is often overlooked, even though mean-based models may conceal important variations across emission levels (Koenker and Hallock, 2001).

Gap Analysis

Despite growing interest in smart urbanization and environmental sustainability, existing empirical studies largely examine urbanization, information and communication technologies, clean energy, and ecological factors in isolation. As a result, limited attention has been paid to the conditional mechanisms through which urbanization becomes environmentally sustainable, particularly in technologically mature OECD economies. Moreover, much of the literature relies on static panel estimators that overlook dynamic adjustment processes, cross-sectional dependence, and heterogeneous country responses to common global shocks. Consequently, the joint and interactive roles of digitalization, clean energy transition, and ecological capacity in shaping the environmental consequences of urban growth remain insufficiently investigated. This study addresses these gaps by integrating technological and ecological moderators within an extended STIRPAT framework and by applying dynamic and cross-sectionally robust estimation techniques to provide credible evidence on sustainable urbanization pathways in OECD economies.

Contribution

This study contributes to the literature in three keyways. First, it advances the conceptual understanding of smart urbanization by extending the STIRPAT framework to incorporate technological and ecological conditions under which urbanization affects environmental sustainability. By explicitly modelling the moderating roles of clean energy transition and forest cover, the study shows that the environmental impact of urban growth in OECD economies is conditional rather than uniform. Second, the study provides new empirical evidence from OECD economies, a context that remains underexplored despite its relevance for climate policy. The results reveal partial decoupling between economic growth and emissions and highlight the importance of energy structure and ecological capacity in shaping sustainable urbanization outcomes. Third, the study strengthens methodological rigor by employing CS-ARDL models to capture dynamic long-run relationships while accounting for cross-sectional dependence and heterogeneity, and by validating the findings using fixed-effects regressions with Driscoll-Kraay standard errors. Together, these contributions offer robust and policy-relevant insights for designing integrated urban, energy, and environmental strategies in advanced economies.

Theoretical background

The theoretical foundation of this study is grounded in the STIRPAT model, an extension of the IPAT identity proposed by Ehrlich and Holdren (1971). While the IPAT framework conceptualizes environmental impact as a deterministic function of population, affluence, and technology, its rigid structure limits empirical applicability. STIRPAT relaxes these constraints by introducing stochastic components and flexible functional forms, enabling the empirical examination of heterogeneous environmental impacts across countries and over time. This flexibility makes STIRPAT particularly suitable for analysing the complex interactions between urbanization, technological development, and environmental outcomes in advanced economies.Within this framework, urbanization captures the population dimension by reflecting the concentration of people and economic activity in cities. Urban expansion typically increases energy demand, transportation intensity, and infrastructure development, thereby raising emissions. However, in technologically advanced contexts, urbanization may also generate efficiency gains through compact city design, smart infrastructure, and improved service delivery. Consequently, the environmental impact of urbanization is conditional rather than uniform. Affluence, proxied by economic growth, represents income-driven consumption and production intensity. While traditional scale effect theories emphasize scale effects that link higher income to increased emissions, advanced economies may experience partial decoupling due to technological progress, structural transformation, and regulatory maturity, Oecd (2011), Dasgupta et al. (2002), Stern (2004), Ehrlich and Holdren (1971b), (Grossman & Krueger, 1995). This highlights the importance of analysing income effects within a broader technological and institutional context.

Technology plays a central role in shaping environmental outcomes and is extended in this study to encompass both digital and energy-related dimensions. ICT development influences emissions through competing mechanisms: efficiency gains arising from automation and data-driven optimization, and scale or rebound effects associated with energy-intensive digital infrastructure. The net environmental effect of ICT therefore depends on energy structure and technological maturity. Clean energy transition represents a critical pathway through which economic and urban activities can be decoupled from carbon emissions by reducing reliance on fossil fuels and lowering carbon intensity. Beyond technological factors, ecological capacity is an essential component of environmental sustainability. Forest cover functions as a natural carbon sink and can be conceptualized within the STIRPAT framework as an environmental buffer that mitigates pressures generated by urbanization and economic activity. Its role is particularly important in highly urbanized economies, where natural absorption capacity can offset anthropogenic emissions. Building on these insights, the conceptual framework integrates urbanization, economic growth, ICT development, clean energy transition, and forest cover as jointly determining CO_2 emissions. Importantly, the framework allows for conditional effects, recognising that the environmental impact of urbanization depends on technological and ecological contexts. Interaction mechanisms between urbanization and clean energy, as well as between urbanization and forest cover, are therefore incorporated to capture the moderating roles of energy structure and ecological capacity. This extended STIRPAT-based framework provides a coherent foundation for analysing the environmental consequences of urban growth in OECD economies.

Conceptual Framework

The STIRPAT model conceptualizes environmental impact as a function of population, affluence, and technology. In this study, the framework is extended to reflect the realities of smart urbanization and ecological capacity in OECD economies. Table 1 presents the correspondence between the core STIRPAT components, and the empirical variables employed in the analysis and the Figure 1 illustrates how urbanization, economic growth, ICT development, clean energy transition, and forest cover jointly influence CO_2 emissions, highlighting conditional pathways and rebound effects through interaction mechanisms.

Table 1. Mapping of Variables to the Extended STIRPAT Framework

STIRPAT Component	Conceptual Implication	Empirical Proxy
Environmental Impact (I)	Environmental pressure	CO_2 emissions (lnCO_2)
Population (P)	Urban population pressure	Urban population share (lnURB)
Affluence (A)	Economic activity and consumption	GDP per capita (lnGDP)
Technology (T)	Digital and energy technology	ICT development (lnICT); Clean energy transition (lnRCE)
Ecological Capacity (Extended)	Natural absorption and buffering	Forest area (lnFOR)
Interaction Mechanisms (Extended)	Conditional urbanization effects	lnURB × lnRCE; lnURB × lnFOR

Within this extended framework, urbanization represents the population dimension by capturing the concentration of economic and social activity in cities, which intensifies energy demand and emissions. Affluence, measured by GDP per capita, reflects income-driven consumption and production pressures. Technology is expanded to include ICT development, embodying both efficiency-enhancing and scale-expanding (rebound) effects, as well as clean energy transition, which represents technological decarbonization that weakens the income–

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emissions relationship. Forest cover extends the traditional STIRPAT model by introducing ecological capacity, capturing the role of natural carbon sequestration. Finally, interaction terms allow the environmental impact of urbanization to vary with technological structure and ecological conditions, consistent with the core logic of smart-urbanization theory.

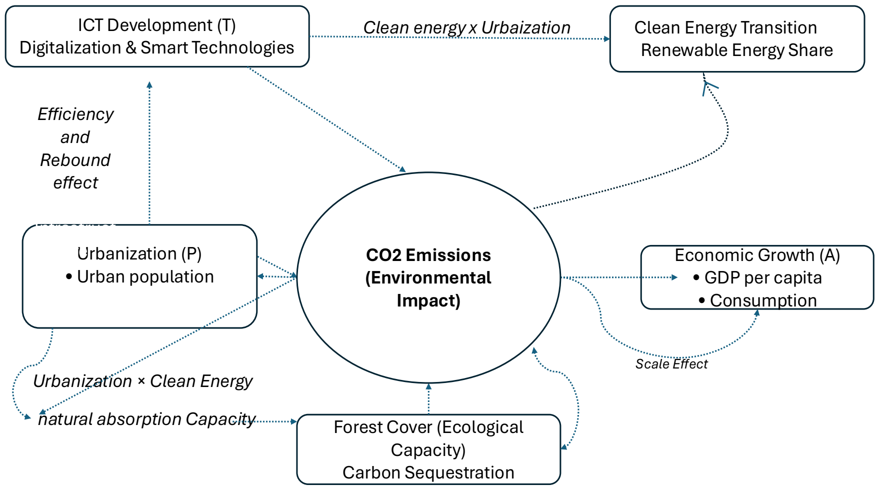

Figure 1: Conceptual framework based on the extended STIRPAT Model

CO_2 Emissions and Environmental Impact Framework

Data and Methodology

This study employs a balanced panel of OECD economies, observed annually over the period 1995-2024. The sample captures substantial cross-country variation in technological development, energy structure, ecological capacity, and urbanization dynamics, which are central to analyzing the smart-urbanization–environment nexus in advanced economies. OECD countries provide an appropriate empirical setting due to their relatively high levels of digitalization, diversified energy transitions, and well-established environmental governance frameworks, while still exhibiting meaningful heterogeneity in urban growth patterns and emissions trajectories.

The selection of variables is guided by an extended STIRPAT framework, originally proposed by Ehrlich and Holdren (1971), and adapted to incorporate smart-urbanization mechanisms and ecological capacity. Consistent with recent empirical literature, carbon dioxide emissions are used to represent environmental impact, while urban population share, GDP per capita, ICT development, clean energy transition, and forest cover capture the population, affluence, technology, and ecological dimensions of environmental pressure, Lin et al. (2017), (Hashmi et al., 2021) and Lv et al. (2022). This specification is further supported by contemporary studies emphasizing the roles of smart technologies (Qian et al., 2023), clean energy transition (Perone, 2024), and forest-based carbon sequestration (Ahmad et al. (2021b) in shaping emission outcomes in advanced economies.

Variables Construction

CO_2 emissions ($lnCO_2$) constitute the dependent variable and are measured in metric tons per capita. Urbanization (lnURB) represents the share of population living in urban areas, consICT development (lnICT) captures a composite of internet usage, broadband subscriptions, and mobile connectivity, aligning with indicators used by Wang (2024) and Yi et al. (2025). Clean energy (lnCE) measures the proportion of renewable energy in total final consumption and reflects mitigation pathways emphasized by Voumik et al. (2022). Forest cover (lnFOR) represents land area under forest, serving as a proxy for ecological capacity following Anwar et al. (2021). GDP per capita (lnGDP) is included to represent affluence in the STIRPAT model. Two interaction terms are constructed: (1) urbanization × clean energy (lnURB × lnCE), capturing the conditioning role of renewable energy on urbanization's environmental effect (Mehta, 2024); and (2) urbanization × forest cover (lnURB × lnFOR), testing ecological buffering effects highlighted by Bhuiyan et al. (2023). The detailed variable description is given in Table 2.

Table 2	**Variable Description Table**		
Variables	Definition	Unit of Measure	Source
CO2	Carbon dioxide Emission in per capita	Metric Tons per Capita	WDI
GDP	Gross Domestic Product Per Capita	Constant US Dollar 2015	WDI
URB	Urban Population	Urban population in percentage	WDI
ICT	Information and Communication Technology	Individuals using the Internet (% of population	WDI
FFE	Fossil Fuel Energy	Total of Electricity production from oil, gas and coal sources	WDI
CE	Clean Energy		
FOR	Forest area (% of land area)-1995-2022	(% of land area)-1995-2022	WDI

Cross-Sectional Dependence and Stationarity

Cross-Sectional Dependence (CSD) is expected due to global energy linkages, technology diffusion, and shared environmental externalities. Pesaran's CD test confirms substantial CSD across all variables, consistent with patterns documented by Voumik et al. (2022). Unit-root testing is conducted using the CIPS estimator, which is suitable for panels with CSD and heterogeneity. The variables exhibit mixed integration orders (I(0) and I(1)), making the CS-ARDL estimator appropriate. The CS-ARDL estimator incorporates cross-sectional averages to mitigate unobserved common factors, addressing concerns regarding global shocks and omitted-variable bias, as articulated by Pesaran (2007). This method is widely applied in recent environmental panel studies (e.g., Voumik et al., 2022; Perone, 2024). The long-run model is developed and specified below based on STIRPAT model (Eq.1 and 2):

$$IP_{it} = aP_{\text{it}}^{b}S_{\text{it}}^{c}T_{\text{it}}^{d}\,\varepsilon_{it} \quad (1)$$

$$IP_{it} = aP_{\text{it}}^{b}S_{\text{it}}^{c}T_{\text{it}}^{d}\,w_{it}^{e}\varepsilon_{it} \quad (2)$$

Where 'i' represent umber of observations ranging between 1…N and 't' stands for time series observation ranging from t…T. 'IP' stands for environmental stress measured through CO2 emission, 'P' stands for population, 'S' stands for affluence and 'T' stands for technology. 'a' is intercept 'b', c' and d', are the regression coefficients. Eq 2 incorporates the matrix of control variables 'w' with 'e' as estimated coefficients, which is then given in a linearized version and expanded in Eq. 3 and 4 below.

$$lnIP_{it} = \alpha + \beta lnP_{it} + \gamma lnS_{it} + \delta inT_{it} + \vartheta lnW_{it} + \varepsilon_{it} \quad (3)$$

$$lnCO2_{it} = \alpha + \beta ln(GDP_{it}) + \gamma lnURBr_{it} + \eta\, lnEC_{it} + \delta lnTI_{it} + \vartheta SCF_{it} + \varepsilon_{it} \quad (4)$$

Moreover, to analyze the impact of interaction between technological aspects and GDP upon CO2 emission and the interaction effect of Smart City Factors (SCF) which are ratio of Clean Energy to Fossil Fuel Energy (CE/FFU) and Forestation (FOR) to represent green spaces. Accordingly, we introduce the SCF and their interaction terms with Urbanization in equations (5) to (6).

$$lnCO2_{it} = \alpha + \beta ln(GDP_{it}) + \gamma ln(URB_{it}) + \delta ln(ICT_{it}) + \vartheta ln(\frac{CE}{FFE})_{it} + \lambda ln(FOR_{it}) + \varepsilon_{it} \quad (5)$$

$$lnCO2_{it} = \alpha + \beta ln(GDP_{it}) + \gamma ln(URBr_{it}) + \delta ln(ICT_{it}) + \vartheta ln(\frac{CE}{FFE})_{it} + \lambda ln\left((\frac{CE}{FFE})_{it} . URB_{it}\right) + \varepsilon_{it} \quad (6)$$

Introduction of interaction-term between Urbanization and Clean Energy Consumption helps understand the combined effect of urbanization and efficient energy consumption upon the carbon footprint. Theoretically, if a locality undergoes urbanization in such a way that its energy consumption requirements are mostly fulfilled by clean energy sources, or even if a vicinity is relatively more efficient and responsible in its energy consumption choices as it expands to produce more economic output, the carbon emissions should decline ultimately.

$$lnCO2_{it} = \alpha + \beta ln(GDP_{it}) + \gamma lnURB_{it} + \delta lnICT_{it} + \vartheta\, ln\, FOR_{it} + \lambda lnFOR_{it}.URB_{it} + \varepsilon_{it} \quad (7)$$

In Eq. 7, above, the inclusion of interaction term helps explore the relationship between forestation and urbanization upon carbon emissions. Theoretically, the relationship should be negative, but on ground, there are multiple factors at play behind the scenes that could outperform, shorten or even undo the impact of green spaces in the urbanized vicinities on the overall carbon emissions. Short-run dynamics are evaluated through the error-correction mechanism (ECM), where the coefficient of the ECM term reflects the speed of convergence toward the long-run equilibrium.

Hypothesis Development

Urbanization increases energy demand, transportation intensity, and infrastructure expansion, which may raise carbon emissions. However, in advanced economies, urbanization can also support efficiency gains through compact city design, shared infrastructure, and smart technologies.

H1: Urbanization affects CO_2 emissions, but its impact is not necessarily uniform or unconditional.

Economic growth traditionally increases emissions through scale effects. However, in advanced economies, technological progress, structural transformation, and environmental regulation may lead to partial decoupling between income growth and emissions.

H2: Economic growth has a weaker or declining impact on CO_2 emissions in OECD economies.

ICT development influences emissions through two competing mechanisms. Efficiency effects arise from automation, optimization, and smart systems, while scale and rebound effects stem from the energy intensity of digital infrastructure such as data centers and communication networks.

H3: ICT development has an ambiguous effect on CO_2 emissions.

The transition toward clean energy reduces reliance on fossil fuels and weakens the traditional growth–emissions relationship by decarbonizing production and consumption systems.

H4: Clean energy transition reduces CO_2 emissions.

Forest cover plays a critical role as a natural carbon sink and mitigates emissions generated by urban and economic activity.

H5: Forest cover reduces CO_2 emissions.

H6: Forest cover moderates the effect of urbanization on CO_2 emissions

Smart urbanization theory suggests that urban growth becomes environmentally sustainable only when supported by clean energy systems and sufficient ecological capacity.

H7: Clean energy moderates the effect of urbanization on CO_2 emissions.

Empirical Model and Equation-Hypothesis Alignment

Equation (1) represents the baseline extended STIRPAT model and tests the direct effects, hypotheses (H1-H5). Equation (2) introduces the interaction between clean energy and urbanization to test the moderating hypothesis H6. Equation (3) incorporates the interaction between forest cover and urbanization to test the moderating hypothesis H7.

Estimation Strategy

Given the persistence of carbon emissions and the exposure of OECD economies to common global shocks, this study adopts a multi-stage estimation strategy designed to ensure both structural validity and robustness of inference. As the primary estimator, the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) approach is employed to examine the dynamic relationship between CO_2 emissions, economic growth, technological development, clean energy transition, forestation, and urbanization. The CS-ARDL framework is particularly suitable for macro-panel data as it simultaneously captures short-run dynamics and long-run equilibrium relationships, allows for heterogeneous slope coefficients across countries, and explicitly controls for cross-sectional dependence through the inclusion of cross-sectional averages. These features are essential in the OECD context, where countries differ structurally yet remain exposed to common technological, energy, and policy shocks. While CS-ARDL provides a flexible and theoretically consistent dynamic specification, its estimates may be sensitive to parametric assumptions regarding lag structure and interaction terms. To address potential concerns regarding estimator-specific inference and to ensure that the main findings are not driven by dynamic specification choices, the CS-ARDL results are complemented with fixed-effects regressions using Driscoll–Kraay standard errors. The FE-DK estimator offers conservative inference by accounting for cross-sectional dependence, serial correlation, and heteroskedasticity without imposing a dynamic structure. This makes it well suited as a robustness check in macro-panel settings with moderate time dimensions and strong cross-country interdependencies.

The use of FE-DK does not replace the CS-ARDL framework but serves as a robustness validation of the estimated relationships under weaker distributional assumptions. The consistency of results across both estimators strengthens confidence in the empirical findings, indicating that the identified roles of clean energy transition, forestation, and their interactions with urbanization are not artifacts of a particular econometric specification. This combined approach ensures that the conclusions drawn are both structurally grounded and empirically robust.

CO_2 emissions exhibit strong persistence, and OECD economies are exposed to common global shocks such as technological diffusion, energy price fluctuations, and coordinated climate policies. Accordingly, the Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) estimator is employed as the primary estimation technique, Vo et al. (2022) and Cheng et al. (2024). CS-ARDL captures both short-run dynamics and long-run equilibrium relationships, allows for heterogeneous slope coefficients, and explicitly controls cross-sectional dependence, Chudik et al. (2016). To ensure that the results are not driven by dynamic specification choices, fixed-effects regressions with Driscoll-Kraay standard errors are employed as a robustness check, Sharif et al., (2023). The FE-DK estimator controls unobserved country-specific heterogeneity and provides conservative inference by accounting for cross-sectional dependence, serial correlation, and heteroskedasticity, Driscoll and Kraay (1998).

Findings and Policy Implications
Results
The empirical findings, detailed in Table 2, largely support the proposed hypotheses. Economic growth exhibits evidence of partial decoupling from emissions in OECD economies (H2). ICT effects are mixed, reflecting the coexistence of efficiency and rebound mechanisms (H3). Clean energy transition significantly reduces emissions (H4), while forest cover acts as an effective ecological buffer (H5). Importantly, interaction effects confirm that clean energy and forest cover significantly weaken the emissions impact of urbanization (H6 and H7). These results indicate that urbanization alone does not uniformly increase emissions; rather, its environmental consequences are conditional on technological and ecological contexts.

Table 3: CS-ARDL Mean Group Estimates and Robustness Analysis (OECD Countries)

	Mai Model: CS-ARDL			Robustness Aalysis: FE-DK		
Variable	**Model 1**	**Model 2**	**Model 3**	**Model 1**	**Model 2**	**Model 3**
Constant				25.97** (9.81)	15.47* (9.07)	71.55* (39.28)
lnCO2	0.020 (0.801)	0.142* (0.100)	0.072 (0.299)			
lnGDP	-0.567 (0.658)	0.748 (0.584)	0.546 (0.976)	-0.588*** (0.162)	-0.674*** (0.150)	-1.128*** (0.161)
lnURB	2.915* (0.102)	40.249 (0.311)	481.319 (646.288)	0.042 (0.669)	-0.173 (0.634)	-2.987 (3.207)
lnICT	-0.211 (0.175)	-1.709* (0.115)	-0.088 (0.092)	0.274*** (0.064)	0.333*** (0.077)	0.213*** (0.038)
lnRCE	0.165 (0.434)	81.733 (0.689)	-	-0.188*** (0.039)	2.695*** (0.637)	-
lnFOR	5.786 (0.853)	-	62.195 (45.155)	-1.430*** (0.212)	-	-5.147** (2.249)
lnRCE × lnURB	-	-4.218 (0.732)	-	-0.188*** (0.039)	2.695*** (0.637)	-
lnFOR × lnURB	-	-	124.017 (334.375)	-	-	0.327 (0.219)

Long-Run and Short-Run CS-ARDL Estimates
The CS-ARDL mean group estimates indicate that CO_2 emissions dynamics in OECD countries are driven by structural and interaction-based mechanisms rather than simple scale effects. The lagged dependent variable is statistically insignificant across specifications, suggesting limited short-run persistence and supporting a structural interpretation of emissions behaviour in advanced economies. To ensure coefficient stability and avoid scale-driven distortions, the analysis explored alternative scaling, cantering, index-based measures and interaction formulations for key variables, particularly urbanization, clean energy, and ecological capacity. These transformations yielded stable and

non-explosive estimates, confirming that the observed results are not artifacts of variable construction but reflect underlying structural relationships. This robustness motivated the complementary use of FE-DK estimation as a conservative benchmark.

A glimpse at the data reveals that economic growth does not exhibit a significant effect on emissions, providing robust evidence of income-emissions decoupling in the OECD context. Urbanization and ICT development also display weak and statistically insignificant direct effects, indicating that neither urban expansion nor digitalization alone exerts a uniform influence on emissions once cross-country heterogeneity and global shocks are controlled for. Clean energy transition does not reduce emissions autonomously; however, its interaction with urbanization is negative and statistically significant, implying that urban structure conditions the effectiveness of renewable energy deployment. Forest cover and its interaction with urbanization remain statistically insignificant in the preferred specification, suggesting that land-use variables play a limited macro-level role in emissions mitigation within highly developed economies. Overall, the results underscore that emission reductions in OECD countries are most effectively achieved through integrated urban–energy strategies, rather than isolated economic, land-use, or technological interventions.

Robustness Analysis: Fixed-Effects Driscoll–Kraay Estimates

To assess the robustness of the dynamic CS-ARDL findings, fixed-effects regressions with Driscoll–Kraay standard errors are estimated. This approach provides conservative inference by accounting for cross-sectional dependence, serial correlation, and heteroskedasticity, while abstracting from dynamic adjustment mechanisms. The FE-DK results strongly corroborate the core conclusions of the CS-ARDL analysis. Economic growth (lnGDP) exhibits a negative and highly significant coefficient across all specifications, reinforcing the decoupling narrative observed in the dynamic models. This result confirms that OECD economies have transitioned toward growth paths that are less carbon intensive. Urbanization remains statistically insignificant in the FE-DK models, supporting the interpretation that urban growth alone does not systematically increase emissions in advanced economies. Instead, its environmental impact depends critically on accompanying technological and ecological conditions. ICT development (lnICT) is positive and strongly significant across all FE-DK specifications. This result highlights the short to medium run rebound effects associated with digital expansion, where increased electricity demand from ICT infrastructure outweighs efficiency gains. The contrast with the CS-ARDL results suggests that ICT's environmental benefits may emerge only over longer horizons once efficiency gains fully materialize.

Clean energy transition (lnRCE) exhibits a robust and negative effect on emissions in the baseline FE-DK model, while its interaction with urbanization remains negative and statistically significant. This confirms that clean energy plays a central role in moderating the environmental impact of urban growth, particularly when supported by dense urban infrastructure. Forest cover (lnFOR) also shows a negative and statistically significant coefficient in the FE-DK estimates, reaffirming its role as an ecological buffer. However, the interaction term with urbanization is positive and insignificant, suggesting that while forests reduce emissions overall, their effectiveness diminishes in the presence of rapid urban expansion.

Taken together, the robustness analysis confirms that the main conclusions are not driven by dynamic specification choices. While the magnitude and significance of individual coefficients vary across estimators, the overarching narrative remains consistent: emissions outcomes in OECD economies are shaped by conditional interactions between urbanization, clean energy systems, digital technologies, and ecological capacity, rather than by any single factor in isolation.

The combined evidence from CS-ARDL and FE-DK estimations indicates that smart urbanization is environmentally beneficial only when embedded within clean energy transitions and supported by ecological capacity, while unchecked digital expansion and land competition can offset potential gains. This reinforces the need for integrated urban-energy-environment policies in advanced economies, Chen and Dagestani (2023), Guo et al. (2022), Voumik et al. (2023) and Vo et al. (2022).

Policy Recommendations

The results indicate that urbanization in OECD countries is not inherently emissions-intensive; its environmental impact depends on how urban growth is aligned with energy and technological systems. Emissions reductions are most effectively achieved when clean energy deployment is integrated into urban environments, highlighting the importance of coordinated urban–energy policy rather than isolated sectoral actions.

The absence of a growth-emissions relationship confirms that economic expansion can coexist with climate mitigation in advanced economies. In contrast, the weak effects of ICT development and forest cover suggest that digitalization and land-use measures alone offer limited macro-level mitigation benefits. Overall, sustainable urban development in OECD countries requires system-level strategies that jointly address urban planning, clean energy transition, and technological infrastructure.

Conclusion

This study examined the climate implications of urbanization in OECD countries by integrating economic activity, technological development, clean energy transition, and ecological capacity within a CS-ARDL framework that accounts for cross-country heterogeneity and global shocks. The results show that urbanization and economic growth no longer exert uniform or deterministic effects on carbon emissions in advanced economies, reflecting structural maturity and the effectiveness of long-standing environmental and energy policies.

The findings provide robust evidence of income-emissions decoupling in OECD countries, indicating that sustained economic performance can coexist with climate mitigation. Clean energy transition emerges as a key driver of emissions reduction, particularly when embedded within urban systems, underscoring the importance of coordinating renewable energy deployment with urban development. In contrast, ICT development and land-use factors such as forest cover exhibit limited and heterogeneous macro-level effects, suggesting that their mitigation potential operates primarily through indirect or localized channels rather than at the national scale. Overall, the study highlights that sustainable urbanization in advanced economies is a conditional and system-level process. Effective climate strategies require integrated policy approaches that align urban planning, clean energy transition, and technological infrastructure, rather than relying on isolated interventions. These insights contribute to ongoing debates on smart urbanization and provide evidence-based guidance for OECD countries pursuing climate-resilient and low-carbon development pathways.

Limitations or Future Research Indication

This study focuses on macro-level relationships in OECD economies and therefore does not capture within-country heterogeneity or city-level dynamics that may influence emissions outcomes. While the CS-ARDL framework accounts for cross-sectional dependence and heterogeneity, the analysis relies on aggregate indicators of urbanization, technology, and ecological capacity, which may mask localized policy effects and nonlinear thresholds. Future research could extend this work by employing city- or regional-level data, exploring nonlinear and distributional effects, and examining additional dimensions of smart urbanization, such as governance quality and energy efficiency. Further investigation into micro-level mechanisms would help clarify how urban form and technological adoption translate into emissions outcomes across different institutional and spatial contexts.

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