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Urbanization as a Tipping Point: Threshold Effects on Carbon Emissions in EU Countries

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ABSTRACT:
This study explores how the impact of structural drivers on CO_2 emissions varies at different levels of urbanisation in EU countries, reflecting the broader implications for sustainable economic development. To this end, we apply a threshold panel regression model. Using urbanisation as the threshold variable, the model identifies a statistically significant threshold of 92.572% urban share, dividing the sample into less and highly urbanised countries. The results show that the effect of energy use on emissions is significant in less urbanised areas, but becomes insignificant above the threshold. This suggests that energy efficiency and decarbonisation are enhanced in more urbanised settings. Renewable energy consistently reduces emissions in both regimes, with a notably stronger effect in highly urbanised areas. Land use and forestry (LULUCF) only exhibit a mitigating effect in less urbanised countries. Interestingly, the effect of urbanisation itself is nonlinear: while moderate urbanisation reduces emissions, further urban growth beyond the threshold increases them, likely due to infrastructure saturation and lifestyle changes. These findings provide empirical evidence of a tipping point in the urbanisation-emissions relationship and emphasise the need for decarbonisation strategies that are tailored to the level of urbanisation and aligned with long-term sustainability goals.

Keywords: Urbanization, CO_2 emissions, Threshold regression, Bootstraping, Renewable energy, LULUCF, Energy use, EU countries

1. Introduction

Urbanisation and climate change are intertwined phenomena that form a complex, mutually influential relationship. On the one hand, urban areas contribute significantly to climate change due to their population density, infrastructure and economic activity, which drive greenhouse gas emissions, particularly CO_2. Conversely, cities are highly vulnerable to the impacts of climate change, such as heatwaves, flooding and droughts, which threaten human health, infrastructure and the economy. This feedback loop is particularly pronounced in Europe, where more than 74% of the population currently resides in urban areas — a figure projected to exceed 83% by 2050. Intensifying urban sprawl amplifies emissions and complicates climate adaptation efforts, demanding more integrated, evidence-based policy responses. EU policies such as the New Leipzig Charter (EC, 2020), the Covenant of Mayors for Climate and Energy (EU, 2008), and the EU's Sustainable Cities Initiative (EC, 2024) aim to promote integrated planning, green infrastructure and

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citizen participation as the pillars of sustainable urban development. International frameworks such as the UN's Agenda 2030, particularly Sustainable Development Goal 11, also encourage cities to become more inclusive, safe, resilient and sustainable.

The dynamic relationship between urbanisation and carbon emissions has attracted increasing scholarly attention. Some studies argue that urbanisation exacerbates CO_2 emissions due to the increased energy demand required for transport, heating, cooling and industrial activity (Ali et al., 2019; Chen et al., 2023; Raheem & Ogebe, 2017; Wang, Zeng, et al., 2018; Huttmanová & Mikča, 2024). This view aligns with traditional environmental concerns regarding dense urban growth and resource consumption. However, other research highlights the efficiency gains of urban agglomeration, suggesting that compact cities can reduce per capita emissions through economies of scale, advanced infrastructure and cleaner technologies (Cheng & Hu, 2023; Poumanyvong & Kaneko, 2010; Xu et al., 2023). These diverging perspectives imply that the relationship between urbanisation and emissions may be non-linear or context-dependent.

Despite the growing body of work on urbanisation and CO_2 emissions, the evidence remains inconclusive, especially in highly urbanised regions such as Europe. Most empirical studies rely on linear models or focus on developing countries, failing to capture nonlinear tipping points or structural changes that occur at advanced stages of urban development. Furthermore, the complex interplay between urbanisation, economic development, energy use, land management and renewable energy integration has rarely been examined within a unified econometric framework. This creates a gap in our understanding of how emissions dynamics shift at different stages of urbanisation and how such shifts interact with broader decarbonisation efforts.

This paper aims to explore whether the impact of structural drivers on CO_2 emissions differs at different levels of urbanisation in EU countries. Specifically, we use a threshold panel regression model to identify and analyse regime-dependent effects, with urbanisation acting as the threshold variable. Through this analysis, we aim to determine whether a tipping point exists beyond which the relationship between energy use and CO_2 emissions changes.

This study makes several key contributions. Firstly, it provides novel empirical evidence of a non-linear relationship between urbanisation and CO_2 emissions in a European context, which is an area that is underrepresented in existing literature. Secondly, by incorporating multiple explanatory variables (energy use, the share of renewable energy, land use, land use change and forestry, and GDP) within a threshold regression framework, the study captures the heterogeneity and interdependence of emission drivers across development stages. The findings have economic and policy relevance as they emphasise the importance of tailoring decarbonisation strategies to both national economies and specific levels of urban development.

The remainder of the paper is structured as follows. Section 2 reviews the theoretical background and key empirical studies on urbanisation and emissions. Section 3 describes the data sources and presents the methodology, focusing on the threshold panel regression approach. Section 4 presents and discusses the empirical results. Section 5 concludes with evidence-based policy implications and suggestions for future research.

2. Literature review

The relationship between urbanisation and CO_2 emissions is a key topic in discussions about climate change and sustainable development. A growing body of literature has examined whether urban growth exacerbates environmental degradation or enables greater efficiency and reduced emissions. These studies often reflect two contrasting perspectives shaped by regional contexts, stages of urban development and methodological approaches.

On one side of the debate, numerous empirical studies conclude that urbanisation significantly contributes to rising CO_2 emissions, particularly in the early and middle stages of development. For example, (Ali et al., 2019) examining Pakistan, found that urbanisation enhances carbon emissions in both the short and long term, with causality running from urban growth to emissions. Similarly, (Ponce De Leon Barido & Marshall, 2014) analyse 80 countries and estimate an average urbanisation–emission elasticity of 0.95, suggesting nearly proportional increases in emissions as urbanisation rises, particularly in lower-income countries lacking strong environmental policies. In the African context, (Raheem & Ogebe, 2017) demonstrate that urbanisation directly increases emissions, outweighing any indirect effects via improvements in per capita income. These findings are echoed by (Wang, Zeng, et al., 2018), who identify the positive effects of economic and land urbanisation on emissions in China's Pearl River Delta.

However, a contrasting body of research argues that urbanisation may lead to efficiency gains, particularly in highly urbanised, infrastructure-rich environments. (Cheng & Hu, 2023) support this view, emphasising that compact urban forms can reduce per capita emissions through better energy efficiency and cleaner technologies. (Xu et al., 2023) employed high-resolution spatial data and concluded that many Chinese cities had reached a point where urbanisation was contributing to carbon reduction, with urban spillover effects sometimes lowering emissions in suburb areas. These results are consistent with urban environmental transition theory, which posits that environmental burdens from urbanisation may eventually diminish as cities become more advanced, integrated and policy-driven.

A growing body of literature highlights the nonlinear nature of the urbanisation–emissions relationship. (Ahmed et al., 2019; Chen et al., 2023; Chovancová et al., 2023, Martínez-Zarzoso & Maruotti, 2011; Shahbaz et al., 2016) all find evidence for an inverted U-shaped curve. This indicates that urbanisation initially raises CO_2 emissions, but eventually mitigates them beyond a certain threshold. For example, (Chen et al., 2023) indicate the existence of a spatial threshold effect, showing that urbanisation has only surpassed the emission-reducing turning point in eastern China, whereas in the central and western regions, it continues to contribute to CO_2 increases.

The heterogeneity of these findings underlines the importance of context, including economic development, institutional capacity, and energy structure. While some studies attribute emission reductions to the compactness and efficiency of urban agglomerations, others emphasise the emissions-intensive nature of sprawling or poorly managed urban growth. Moreover, methodological differences — ranging from cointegration and causality tests to spatial econometric models and threshold regressions — may partly explain the variation in conclusions.

Overall, the literature suggests that the environmental impact of urbanisation is not universal. Rather, it is shaped by the stage of urban development, the policy environment and the nature of urban expansion itself. However, the European context, where urbanisation is well advanced and urban sprawl is a key concern, has rarely been analysed using a non-linear or threshold approach. This study addresses this gap by applying a threshold panel regression model to European countries. It identifies a critical urbanisation tipping point and analyses how the effects of energy use, the share of renewable energy, land-use emissions and urbanisation itself vary across this divide.

3. Data and methods

The analysis is based on a panel dataset covering 27 member states of the European Union (EU) over the period 2000 to 2022. Variables used in analysis are as follows:

- CO_2 – Annual CO_2 emissions per capita, measured in tons per person;
- GDP – Gross Domestic Product per capita, measured in current USD (thousands) per person;
- EnUse – Primary energy consumption per capita, measured in megawatt-hours (MWh) per person;
- LULUCF – Net greenhouse gas emissions from Land Use, Land-Use Change, and Forestry (LULUCF), measured in tons per person;
- RESshare – Share of renewable energy in total energy consumption, expressed as a percentage of total final energy use;
- Urban – Share of population living in urban areas, expressed as a percentage of the total population.

Descriptive statistics providing an overview of the distribution and variability of data, including the number of observations (Obs), mean values, standard deviations (Std. Dev.), and minimum (Min) and maximum (Max) values is captured in table 1.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std.Dev.	Min	Max
CO2	621	7.7694	3.5081	2.8998	25.9849
GDP	621	30.3171	22.2034	1.6212	133.7118
EnUse	621	42.2948	17.5443	15.7799	113.1062
LULUCF	621	-0.9893	1.4977	-6.4	2.6
RESshare	594	17.4787	11.9406	0	57.9
Urban	621	72.1695	12.6344	50.754	98.153

Source: Own processing in Stata

To account for potential non-linear relationships between CO_2 emissions and their explanatory variables across different structural or policy regimes, we apply a threshold panel regression model originally introduced by Hansen (1999) and later extended to dynamic panels by Seo and Shin (2016). This approach allows the estimated coefficients to vary depending on whether the threshold variable exceeds a certain endogenously determined value, thereby capturing regime-dependent effects.

The model is specified as follows:

$$CO_{2it} = \begin{cases} \beta_1 X_{it} + \mu_i + \varepsilon_{it} \ if \ q_{it} \leq \gamma \\ \beta_2 X_{it} + \mu_i + \varepsilon_{it} \ if \ q_{it} > \gamma \end{cases}$$

Where:
CO_{2it} is the dependent variable representing per capita CO_2 emissions,
X_{it} is a vector of explanatory variables,
q_{it} is the threshold variable (e.g., GDP per capita, share of renewables, urbanization),
γ is the estimated threshold value,
μ_i captures unobserved individual effects,
ε_{it} is the idiosyncratic error term.

The threshold value γ is estimated by minimizing the sum of squared residuals (SSR) over a grid of possible values. Statistical inference on the presence of a threshold effect is conducted using bootstrap procedures as proposed by (Hansen, 1999), which provide valid confidence intervals and significance tests for the estimated threshold.

This model enables the estimation of regime-specific marginal effects and offers greater flexibility in assessing how structural characteristics—such as the level of renewable energy use or urbanization—affect the sensitivity of emissions to economic and policy factors. This is particularly useful in heterogeneous panels such as EU member states, where national contexts and policy frameworks vary considerably.

To ensure robustness, we report:

- Estimated threshold values along with their confidence intervals,
- Bootstrap F-statistics and p-values testing the null hypothesis of no threshold effect,
- Regime-specific coefficients with confidence intervals, allowing assessment of differences between regimes.

The method is implemented following the procedures described by (Seo & Shin, 2016).

4. Results and discussion

To examine whether the impact of structural factors on CO_2 emissions differs across different levels of urbanization, a threshold panel regression model was estimated using urbanization (Urban) as the threshold variable. The estimation procedure identified a statistically significant threshold value of 92.572%—as shown in Table 2—which divided the sample into:

- Mode 1: Countries with Urban ≤ 92.572% (lower level of urbanization)
- Mode 2: Countries with Urban > 92.572% (higher level of urbanization)

Table 2 Estimated threshold value for Urban

Model	Threshold	Lower	Upper
Th- 1	92.5720	91.8760	92.9050

Source: Own processing in Stata

The Bootstrap test of the threshold effect (Table 3) confirms the presence of a statistically significant threshold effect ($F = 673.90$; $p = 0.0000$), which confirms the use of a dual-mode specification.

Table 3 Test of Threshold Effect Significance for Urban (bootstrap 300)

Threshold	RSS	MSE	F stat	pvalue
Single	131.8719	0.2305	673.90	0.0000

Source: Own processing in Stata

To examine how the relationship between key explanatory variables and CO_2 emissions changes at different levels of urbanization, Table 4 presents the estimated coefficients from a threshold panel regression model based on an identified urbanization threshold of 92.572%. Within this model, we distinguish between countries with lower and higher levels of urbanization, which allows us to analyze the impact of individual variables in a nonlinear and context-dependent framework of economic-energy-emission relationships:

- Although recent study by Ziemblińska et al. (2025) reports that economic growth decouples from CO_2 emissions, when we consider urbanization as a threshold variable, the GDP per capita coefficient is statistically insignificant in both regimes and the confidence intervals overlap significantly, indicating that the relationship between GDP and emissions does not differ significantly between different levels of urbanization.
- In the case of EnUse in regime 1 (less urbanized countries), the coefficient is positive and highly statistically significant (0.2150***), indicating a strong correlation between energy consumption and emissions. In mode 2 (highly urbanized countries), the coefficient becomes insignificant and close to zero (0.0013). This stark contrast suggests that in more urbanized environments, energy systems may be more efficient or decarbonized, mitigating the direct relationship between consumption and emissions. Conversely, in less urbanized areas, energy consumption is likely to reflect greater dependence on fossil fuels or inefficient energy infrastructure. The diminishing impact of energy use on CO_2 emissions in highly urbanised countries may reflect underlying differences in the energy mix composition, with a higher share of renewable and low-carbon energy sources being integrated into urban energy systems. Additionally, urban centres often benefit from more efficient energy infrastructure, grid optimization, and

localized renewable energy projects, which reduce the marginal emissions impact of additional energy consumption.

- LULUCF has a strong and negative impact in less urbanized countries (-0.1078***), but in highly urbanized countries this effect is statistically insignificant and accompanied by a very wide confidence interval, reflecting a high degree of uncertainty. As the confidence intervals overlap here too, it is not possible to confirm a robust threshold effect for this variable. The weak significance of LULUCF in highly urbanised countries likely reflects the limited role of traditional forestry in dense urban settings and the aggregation of national-level data, which may overlook urban green infrastructure such as parks, green roofs, and urban forests. While land-based mitigation remains important, its urban contributions require more spatially disaggregated data to be fully assessed.
- The RESshare coefficient is statistically significant and negative in both regimes, with its effect being much stronger in highly urbanized countries (–0.4103***) compared to less urbanized ones (–0.0697***). This suggests that the development of renewable energy sources in urbanized environments leads to greater emissions reductions, likely due to higher demand concentration, better integration into the electricity grid, and more targeted decarbonization policies. These findings highlight the reinforcing role of sustainable urban infrastructure in maximizing the effectiveness of the transition to clean energy sources.
- Urbanization itself shows an interesting double effect: In mode 1, the coefficient is negative and statistically significant (-0.0640***), suggesting that moderate urbanization can contribute to reducing emissions, probably due to population density or more efficient land use planning. In mode 2, however, the effect reverses and becomes positive and significant (0.0520***), indicating that beyond a certain level of urbanization, urban expansion may lead to additional emissions – probably due to infrastructure saturation, traffic congestion or lifestyle changes in highly urbanized environments. These results provide empirical support for a nonlinear, threshold-dependent impact of urbanization on CO_2 emissions.

Table 4 Estimated coefficients from threshold panel regression with Urban as the threshold variable

CO2	Mode	Urban	Coef	95% Conf. Interval	
GDP	1	Urban < 92.572	-0.0018	-0.0076	0.0039
	2	Urban > 92.572	-0.0200	-0.0532	0.0131
EnUse	1	Urban < 92.572	0.2150***	0.2031	0.2269
	2	Urban > 92.572	0.0013	-0.0228	0.0255
LULUCF	1	Urban < 92.572	-0.1078***	-0.1590	-0.0567
	2	Urban > 92.572	0.8201	-2.5189	4.1591
RESshare	1	Urban < 92.572	-0.0697***	-0.0827	-0.0567
	2	Urban > 92.572	-0.4103***	-0.4805	-0.3402
Urban	1	Urban < 92.572	-0.0640***	-0.0924	-0.0357
	2	Urban > 92.572	0.0520***	0.0172	0.08694
constant			4.8641***	2.7638	6.9644

Source: Own processing in Stata

This finding of a threshold effect of urbanization on CO_2 emissions fits into the growing literature on nonlinear relationships between urbanization and emissions and confirms the existence of a critical point where the benefits of urbanization turn into environmental burdens. Our findings are consistent with several studies, mainly from Asia. The nonlinear relationship between urbanization and emissions is supported, for example, by a study of (Khan & Su, 2021), that explicitly identified the optimal level of urbanization beyond which urbanization ceases to reduce emissions. (Chen et al., 2023), in the context of China, confirm the existence of an inverse U-curve between urbanization and CO_2 emissions and also states that the average level of urbanization in the country has not yet reached the threshold, while in eastern China it has. This suggests that the threshold effect of urbanization is not universal but depends on the level of development of the region, which is also supported by (Wang, Li, et al., 2018), showing that the relationships between urbanization, growth, and emissions vary across country income groups. Furthermore, (Zhu et al., 2016) although they do not use a threshold model, their use of panel quantile regression shows that the effects of urbanization and other variables are heterogeneous across emission levels, implying a hidden nonlinearity similar to our results.

5. Conclusion and considerations for policy-makers

These findings challenge the conventional Environmental Kuznets Curve (EKC) logic as it relates to urbanisation. The EKC framework usually suggests that, once a certain threshold has been surpassed, continued development — whether in terms of income or urbanisation — leads to a decline in environmental degradation thanks to technological progress, institutional capacity and improved efficiency. However, our results reveal a more complex dynamic: while moderate urbanisation (mode 1) is associated with lower CO_2 emissions, this trend reverses beyond the identified threshold, where additional urban growth contributes to increased emissions (mode 2).

This implies that urbanisation may not lead to permanent environmental improvements beyond a certain level and may instead enter a 'post-optimal' phase characterised by diminishing or even negative returns in terms of emission mitigation. This interpretation aligns with emerging perspectives (e.g., Yao et al., 2021; Xu et al. 2023) that opens the possibility that we are not observing a simple inverted U-shape, but rather a wave-like or cyclical pattern, where emissions may rebound beyond a certain threshold due to saturation effects, infrastructure overload and lifestyle changes.

These findings have several implications for policymakers:

- Policy-makers should avoid taking a one-size-fits-all approach to urban planning and climate policy. A shift in focus is required for densely urbanised areas, moving from expansion to optimisation in order to reduce overconsumption, traffic congestion and infrastructure overload.
- Continuing urban sprawl must be carefully managed. Policies should promote smart growth principles, such as transit-oriented design and land-use zoning.
- Urban planning should be integrated with wider climate and resilience policies.

- The negative effects of renewable energy are stronger in highly urbanised areas, suggesting that urban centres offer high leverage points for decarbonisation, e.g. through rooftop solar panels and energy communities.
- Economic instruments such as carbon pricing or green investment incentives could be used to promote the decarbonisation of the urban environment.

It is important to acknowledge the limitation of our study, which is that urbanisation is a long-term structural process that evolves gradually. Given this, the use of a relatively short time series (2000–2022) may not fully capture the deeper nonlinearities or delayed effects or potential reversibility in emission outcomes associated with urban development. While our threshold model reveals a statistically significant regime shift, it is possible that additional turning points could emerge over longer periods. Therefore, future research could benefit from incorporating longer historical time spans to provide a more complex understanding of the long-term sustainability of urbanisation trajectories.

While this study focuses on EU countries, future research should assess whether the observed nonlinear threshold effects of urbanisation on CO_2 emissions hold across different economic blocs and income levels. Expanding the model to a global or multi-regional scope would enhance its generalisability and provide comparative insights into how urban development pathways influence emission dynamics.

Moreover, the selection of urbanisation as the primary threshold variable is theoretically grounded, but we acknowledge that other factors such as industrial structure or governance quality may mediate urban-emission dynamics. Future research should explore whether these policy-relevant variables offer stronger explanatory power or interact with urbanisation thresholds.

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