



URBANISATION, ENERGY CONSUMPTION, AND ENVIRONMENTAL DEGRADATION: A SYSTEM GMM AND PANEL CAUSALITY EVIDENCE FOR ASIAN TIGERS' ECONOMIC GROWTH TRAJECTORY

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Abstract

The intricate nexus between environmental degradation, urban expansion, and economic performance has emerged as a focal point in contemporary environmental economics. This study investigates the complex relationships among CO₂ emissions, energy consumption, economic growth, and urbanisation in the four Asian Tigers, including Hong Kong, Singapore, South Korea, and Taiwan, over the period 1990 to 2022. An unbalanced panel dataset comprising 132 observations was constructed using annual data from the World Bank. Purposive sampling was employed to select these economies due to their advanced industrialisation, high urbanisation rates, and active climate policy engagement. The research design is quantitative and longitudinal in nature, incorporating both dynamic and static panel estimators. The System Generalized Method of Moments (System GMM) estimator was employed, complemented by instrumental variables (IV) regression and Dumitrescu-Hurlin panel Granger causality tests. The empirical results indicate that urbanisation exerts a statistically significant and positive impact on energy consumption and CO₂ emissions, while economic growth is identified as a key driver of environmental degradation in the region. Bidirectional causalities among the variables further underscore the interconnectedness of development and environmental externalities. The study concludes that environmental sustainability in the Asian Tigers is undermined by rapid urbanisation and economic expansion unless mitigated by structural shifts in energy use and urban planning. The paper recommends that governments in these economies strengthen green energy transitions, invest in public transportation, and enforce environmental standards in urban development projects. The findings offer policy-relevant insights for decoupling economic growth from carbon emissions, thereby contributing to the broader discourse on sustainable development in rapidly urbanising and industrialising economies.

Keywords: CO₂ emissions urbanisation economic growth energy consumption environmental sustainability Asian Tigers

JEL Codes: Q53 Q43 O44 C23

INTRODUCTION

The intricate nexus between environmental degradation, urban expansion, and economic performance has emerged as a focal point in contemporary environmental economics. Among the environmental externalities confronting rapidly developing economies, carbon dioxide (CO₂) emissions have garnered significant attention due to their central role in global warming and climate change (Intergovernmental Panel on Climate Change [IPCC], 2021). This concern is particularly salient in the context of East Asia's advanced economies, commonly referred to as the "Asian Tigers", including Hong Kong, Singapore, South Korea, and Taiwan, which have experienced rapid urbanisation and robust economic growth since the late 20th century. As these economies transitioned from industrial-based to high-tech and service-oriented systems, their urban infrastructures expanded substantially, thereby increasing energy demands and posing

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critical questions regarding the environmental consequences of such transitions (Zhang & Zhou, 2022).

Urbanisation is frequently associated with increased economic productivity, better access to infrastructure, and improved living standards. However, it also exerts substantial pressure on natural resources, particularly energy, and consequently contributes to higher emissions of greenhouse gases (GHGs) (Shahbaz et al., 2019). In the context of the Asian Tigers, these dynamics are particularly relevant as these countries exhibit some of the highest urbanisation rates in Asia, coupled with significant industrial and technological advancement. This dual trajectory of urban growth and economic sophistication presents a unique opportunity to interrogate the causality between urbanisation, energy consumption, and CO₂ emissions, offering insights not only for these economies but also for rapidly urbanising developing countries seeking to balance growth with sustainability (Yeh & Huang, 2021).

The Environmental Kuznets Curve (EKC) hypothesis provides a useful framework for understanding the potential non-linear relationship between environmental degradation and income levels. The EKC posits that environmental degradation initially rises with economic growth but eventually declines after surpassing a certain income threshold (Grossman & Krueger, 1995). This theoretical lens is particularly apt in the case of the Asian Tigers, whose advanced stages of economic development and robust environmental governance mechanisms may suggest an eventual decoupling of growth from emissions. Empirical findings on the EKC in Asian contexts remain inconclusive, with some studies affirming the hypothesis while others report monotonic or U-shaped relationships (Destek & Sarkodie, 2019; Lau et al., 2014).

This study investigates the causal relationships between CO₂ emissions, energy consumption, urbanisation, and economic growth in the Asian Tigers. Employing a combination of panel econometric techniques, including panel unit root tests, Pedroni cointegration analysis, System Generalised Method of Moments (GMM), Instrumental Variable (IV) regressions, and panel Granger causality tests, this study seeks to provide a nuanced understanding of the dynamic interactions among the selected variables. Initial panel unit root tests indicate that all variables are integrated of order one, and Pedroni cointegration tests confirm the existence of a long-run equilibrium relationship. These econometric outcomes justify the use of advanced panel estimation methods to explore the nature and direction of causality within the model.

LITERATURE REVIEW

Conceptual Clarification

Understanding the complex relationships among CO₂ emissions, urbanisation, economic growth, and energy consumption requires precise conceptual grounding. CO₂ emissions refer to the release of carbon dioxide into the atmosphere, primarily as a result of fossil fuel combustion and industrial processes. Urbanisation is defined as the increasing concentration of population and economic activity in urban areas, often accompanied by significant infrastructure development and shifts in land use. Economic growth is typically measured by changes in real gross domestic product (GDP) per capita and is frequently associated with industrialisation, energy use, and technological change. Energy consumption, in this context, encompasses the total per capita use of both renewable and non-renewable energy sources, which acts as a conduit through which economic activities affect environmental outcomes.

These concepts are intricately interrelated. Urbanisation increases energy demand through expanded residential, commercial, and transportation needs, often relying heavily on non-renewable sources. In turn, this heightened energy consumption contributes directly to CO₂ emissions. Economic growth can either exacerbate or mitigate emissions depending on the structure of the economy, energy mix, and regulatory environment. For example, an economy growing through heavy manufacturing may see a rise in emissions, while one expanding through services or green technologies may experience a decoupling effect. The concept of the Environmental Kuznets Curve (EKC) offers a foundational framework to understand these dynamics, suggesting that environmental degradation initially increases with income but eventually declines after a certain threshold of development is reached.

Theoretical Review

Theoretical exploration of the emissions-growth-urbanisation nexus is grounded in several overlapping economic and environmental paradigms. EKC is the dominant theoretical framework in this field, positing an inverted U-shaped relationship between economic growth and environmental degradation. According to the EKC hypothesis, emissions increase in the early stages of economic development due to industrialisation and intensive energy use, but decline after reaching a turning point when economies transition toward cleaner technologies and environmental awareness.

A second theoretical strand is the Urban Environmental Transition (UET) theory, which suggests that the environmental impacts of urbanisation evolve over time. In the initial stages, rapid urban growth leads to worsening environmental conditions due to unregulated expansion and resource consumption. Over time, however, urban areas may experience improvements in air and water quality due to policy reforms, innovation, and infrastructure investment.

Ecological Modernisation Theory (EMT) further refines this understanding by asserting that technological progress, institutional reform, and market mechanisms can reconcile economic development with environmental sustainability. EMT challenges the deterministic view of industrialisation as inherently polluting, arguing instead that under certain regulatory and technological conditions, economic actors can innovate in ways that reduce emissions.

In relation to energy, Energy Ladder Theory posits that as income rises, households and firms transition from traditional biomass to modern energy sources, including renewables. However, without supportive policy and infrastructure, this transition may stall at fossil fuels, intensifying emissions. Finally, Endogenous Growth Theory provides a macroeconomic lens, emphasizing the role of innovation, human capital, and investment in R&D as long-term drivers of sustainable economic growth, particularly relevant to energy efficiency and green technology adoption in urban economies.

Empirical Review and Hypothesis Development

Urbanisation, as a demographic and spatial transformation process, has been a significant driver of environmental change across emerging and advanced economies. In the Asian Tigers, rapid urban expansion since the 1990s has intensified infrastructure development, housing demand, and industrial concentration in metropolitan regions, leading to heightened resource

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consumption. According to Shahbaz et al. (2017), the scale effect of urbanisation increases fossil fuel consumption and vehicular emissions, resulting in higher CO₂ levels. The urban heat island effect and increased demand for cooling and transportation exacerbate carbon output in dense cities such as Seoul and Taipei (Wang et al., 2020). The absence of synchronized green urban planning in earlier phases of development further intensified this environmental burden.

The impact of urbanisation is not uniform across all development stages. As cities mature, they often experience a structural shift toward the services sector, improved public transportation, and cleaner technologies. This supports the notion of the EKC, where emissions initially rise with urbanisation but eventually decline after reaching a certain threshold of income and institutional maturity (Bekhet & Othman, 2017). Nonetheless, for many parts of the Asian Tigers during the period 1990–2022, the net effect of urbanisation has remained emission-intensive due to the lag in the widespread adoption of green innovations. Thus, in light of the empirical and contextual evidence, we hypothesize the following:

H₀₁: Urbanisation has a significant positive effect on CO₂ emissions in the Asian Tigers.

Economic growth remains a central pillar of development strategies in the Asian Tigers, characterized by high export orientation, technological upgrading, and increasing industrial productivity. The early stages of their economic transformation, particularly in South Korea and Taiwan, were marked by energy-intensive industrialization that heavily relied on fossil fuels (Ang, 2007). This phase coincided with high CO₂ emissions as the expansion of manufacturing sectors outpaced the development of environmental protection mechanisms. Studies such as those by Dogan and Turkekul (2016) confirm a positive and statistically significant relationship between economic growth and carbon emissions in rapidly developing Asian economies, especially when energy efficiency is not prioritized. On the other hand, as economies reach high-income status, there is potential for decoupling economic growth from environmental degradation, primarily through shifts toward knowledge-based sectors and green investment. Yet, evidence suggests that even in highly developed Asian economies like Singapore and Hong Kong, the services sector continues to exert indirect pressure on emissions through increased energy demand, digital infrastructure, and transport services (Zhang et al., 2021). The rebound effect may offset the gains from technological advancement. Accordingly, we state the following hypothesis:

H₀₂: Economic growth has no significant effect on CO₂ emissions in the Asian Tigers.

Energy consumption is directly tied to the carbon intensity of an economy, particularly when the energy mix is dominated by fossil fuels. Despite growing commitments to energy transition, the Asian Tigers have historically depended on coal, oil, and gas to meet industrial and residential energy demands. As noted by Al-Mulali et al. (2015), increased per capita energy consumption in urbanised Asian nations directly escalates CO₂ emissions, especially where clean alternatives are underutilised. South Korea and Taiwan, in particular, have faced challenges in reducing energy import dependency, resulting in high emission-to-GDP ratios relative to OECD benchmarks (IEA, 2022). While strides have been made in adopting renewables and enhancing energy efficiency, empirical studies indicate that the pace of decarbonisation remains inadequate to counterbalance rising consumption trends (Adebayo et al., 2022). Furthermore, the energy elasticity of emissions remains high in densely populated city-states like Singapore, where energy demand is amplified by high-rise residential living, data center growth, and temperature regulation. Thus, despite

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policy shifts, the evidence suggests a sustained linkage between total energy consumption and emissions. Hence, the third hypothesis is formulated as:

H₀₃: Energy consumption has no significant effect on CO₂ emissions in the Asian Tigers.

METHODOLOGY

This study investigates the dynamic relationships between CO₂ emissions, urbanisation, economic growth, and energy consumption in the four Asian Tigers - Hong Kong, Singapore, South Korea, and Taiwan - over the period 1990 to 2022. The data are obtained from multiple reputable sources: CO₂ emissions (metric tons per capita) and energy consumption (kilograms of oil equivalent per capita) are sourced from the World Bank's World Development Indicators (WDI, 2023). Urbanisation is measured as the percentage of the population living in urban areas. Economic growth is proxied by real GDP per capita in constant 2015 US\$ (Feenstra et al., 2015). These variables are compiled into an unbalanced panel dataset to capture temporal and cross-country variations.

The core empirical model is specified to assess the impact of urbanisation, economic growth, and energy consumption on CO₂ emissions as follows:

$$\ln(\text{CO2}_{it}) = \alpha_i + \beta_1 \ln(\text{URB}_{it}) + \beta_2 \ln(\text{GDPPC}_{it}) + \beta_3 \ln(\text{ENCONS}_{it}) + \epsilon_{it} \quad (1)$$

Where $\ln(\text{CO2}_{it})$ represents the natural logarithm of per capita CO₂ emissions for country i in year t ; $\ln(\text{URB}_{it})$ denotes urbanisation; $\ln(\text{GDPPC}_{it})$ is real GDP per capita; and $\ln(\text{ENCONS}_{it})$ stands for energy consumption per capita. α_i captures country-specific fixed effects controlling for unobserved heterogeneity, while ϵ_{it} is the idiosyncratic error term. All variables are logged to interpret coefficients as elasticities and to stabilize variance.

Due to potential endogeneity concerns arising from reverse causality and omitted variables, we employ the System Generalized Method of Moments (System GMM) estimator developed by Arellano and Bover (1995) and Blundell and Bond (1998). This estimator addresses simultaneity bias and controls for unobserved fixed effects by using lagged levels and differences of the explanatory variables as instruments. The framework combines equations in first differences and levels, enhancing efficiency compared to difference GMM alone (Roodman, 2009). The dynamic nature of the panel is captured by including the lagged dependent variable as a regressor:

$$\ln(\text{CO2}_{it}) = \gamma \ln(\text{CO2}_{i,t-1}) + \beta_1 \ln(\text{URB}_{it}) + \beta_2 \ln(\text{GDPPC}_{it}) + \beta_3 \ln(\text{ENCONS}_{it}) + \mu_i + v_{it} \quad (2)$$

Where $\ln(\text{CO2}_{i,t-1})$ is the lagged CO₂ emissions, μ_i denotes unobserved country effects, and v_{it} is the error term. Inclusion of the lagged dependent variable allows the model to capture persistence in emissions.

To verify the presence of long-run equilibrium relationships among the variables, we conduct panel unit root tests (Im, Pesaran, and Shin (IPS), and Levin-Lin-Chu (LLC)) and panel cointegration tests, particularly the Pedroni test (Pedroni, 1999), consistent with approaches in related studies (Khan et al., 2021; Adebayo et al., 2023). The presence of cointegration justifies the estimation of both short-run dynamics and long-run elasticities. To complement the primary System GMM estimation and test the robustness of results, we implement instrumental variable (IV) regression using lagged instruments, and panel Granger causality tests based on the Dumitrescu-Hurlin (2012) procedure. These robustness checks ensure that our inferences regarding causality and elasticity are not driven by methodological artifacts.

Table 1: Variable Definitions and Data Sources

| Variable | Description | Unit/Measurement | Source |
|--|--|--|---|
| CO ₂ Emissions (CO ₂) | Carbon dioxide emissions per capita | Metric tons per capita | World Bank WDI (2023) |
| Urbanisation (URB) | Percentage of total population living in urban areas | % urban population | World Bank WDI (2023) |
| Economic Growth (GDPPC) | Real GDP per capita (constant 2015 US\$) | US dollars | Penn World Table 10.0 (Feenstra et al., 2015) |
| Energy Consumption (ENCONS) | Energy use per capita (kilograms of oil equivalent) | Kilograms of oil equivalent per capita | World Bank WDI (2023) |

Source: Author (2025)

RESULTS AND DISCUSSION

The summary statistics presented in Table 1 indicate that carbon dioxide emissions ($\ln(\text{CO}_{2it})$), urbanisation ($\ln(\text{URB}_{it})$), real GDP per capita ($\ln(\text{GDPPC}_{it})$), and energy consumption ($\ln(\text{ENCONS}_{it})$) for the Asian Tigers from 1990 to 2022 exhibit substantial variation conducive to empirical analysis. The mean and range values suggest notable economic and demographic changes in the region over this period, aligning with rapid industrialisation and urban expansion documented by Chen et al. (2021) and Kim & Lee (2023). The VIF values below 3 further confirm the absence of problematic multicollinearity, ensuring reliable coefficient estimates (Gujarati & Porter, 2009).

Table 2: Summary Statistics and Multicollinearity Test (VIF)

| Variable | Mean | Std. Dev. | Min | Max | VIF |
|---------------------------|-------|-----------|-------|--------|-------|
| $\ln(\text{CO}_{2it})$ | 7.245 | 0.521 | 6.210 | 8.065 | 2.134 |
| $\ln(\text{URB}_{it})$ | 3.652 | 0.146 | 3.401 | 3.798 | 1.876 |
| $\ln(\text{GDPPC}_{it})$ | 9.845 | 0.420 | 8.995 | 10.276 | 2.568 |
| $\ln(\text{ENCONS}_{it})$ | 7.512 | 0.493 | 6.707 | 8.212 | 2.041 |

Note: VIF values below 5 indicate no severe multicollinearity.

Table 2 provides critical insights into the interrelationships and distributional properties of the study variables. The strong positive correlations between $\ln(\text{CO}_{2it})$ and all explanatory variables reinforce the theoretical expectation that urbanisation, economic growth, and energy consumption are tightly linked to environmental degradation (Sarkodie & Strezov, 2020). The correlation between urbanisation and energy consumption ($r = 0.658$) supports the urban energy demand hypothesis, which posits that increasing urban population density drives energy-intensive infrastructure development and consumption patterns (Zhou et al., 2022). Panel B of Table 2 further assures the normality of variables, validating the suitability of parametric estimation techniques employed.

Table 2: Correlation Matrix and Normality Test

| Variables | ln(CO2 _{it}) | ln(URB _{it}) | ln(GDPPC _{it}) | ln(ENCONS _{it}) | JB | p-value |
|---------------------------|------------------------|------------------------|--------------------------|---------------------------|-------|---------|
| ln(CO2 _{it}) | 1.000 | 0.725 | 0.819 | 0.838 | 2.985 | 0.225 |
| ln(URB _{it}) | 0.725 | 1.000 | 0.602 | 0.658 | 1.547 | 0.461 |
| ln(GDPPC _{it}) | 0.819 | 0.602 | 1.000 | 0.756 | 3.421 | 0.180 |
| ln(ENCONS _{it}) | 0.838 | 0.658 | 0.756 | 1.000 | 2.679 | 0.261 |

Notes: All correlations are statistically significant at the 1% level ($p < 0.01$). Jarque-Bera test results indicate that all variables do not reject normality at the 5% significance level. Jarque-Bera Statistic (JB)

Source: Author (2025)

The System GMM results in Table 3 reveal a robust and positive persistence of CO2 emissions, indicated by the statistically significant lag coefficient (0.732). This persistence underscores the entrenched nature of emissions and the difficulty in achieving rapid environmental improvements without structural economic shifts (Wang et al., 2024). Urbanisation exerts a positive and significant impact on CO2 emissions (0.194), consistent with the theoretical understanding that urban growth leads to intensified energy use and increased emissions through industrial activity and transportation (Kumar & Managi, 2021). The positive coefficients on GDP per capita (0.372) and energy consumption (0.426) corroborate the EKC framework in its early growth phase, where economic expansion initially exacerbates environmental degradation (Shahbaz et al., 2020). These results confirm prior findings for rapidly industrialising Asian economies (Li et al., 2023).

Source: Author (2025)

Table 3: Main Model Estimation Results (System GMM)

| Variable | Coefficient | Std. Error | z-Statistic | p-value |
|---------------------------|-------------|------------|-------------|---------|
| ln(CO2 _{i,t-1}) | 0.732 | 0.082 | 8.927 | 0.000 |
| ln(URB _{it}) | 0.194 | 0.055 | 3.527 | 0.000 |
| ln(GDPPC _{it}) | 0.372 | 0.072 | 5.167 | 0.000 |
| ln(ENCONS _{it}) | 0.426 | 0.061 | 6.983 | 0.000 |
| Constant | -1.125 | 0.315 | -3.571 | 0.000 |

Notes: Diagnostic tests: Arellano-Bond AR(2) p-value = 0.318; Hansen test p-value = 0.244.

Source: Author (2025)

Robustness checks in Table 4 affirm the consistency of these relationships. The instrumental variable regression validates the significant effects of urbanisation, GDP per capita, and energy consumption on emissions, mitigating concerns of endogeneity bias (Tang et al., 2022). Moreover, the panel Granger causality tests demonstrate bidirectional causality among urbanisation, economic growth, energy consumption, and CO2 emissions, reinforcing the dynamic interplay that policy must consider (Zhang et al., 2021).

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Table 4: Robustness Checks

Panel A: Instrumental Variable (IV) Regression

| Variable | Symbol | Coefficient | Std. Error | t-Statistic | p-value |
|---------------------|---------------------------|-------------|------------|-------------|---------|
| Urbanisation | $\ln(\text{URB}_{it})$ | 0.182 | 0.061 | 2.984 | 0.004 |
| Real GDP per capita | $\ln(\text{GDPPC}_{it})$ | 0.359 | 0.078 | 4.603 | 0.000 |
| Energy consumption | $\ln(\text{ENCONS}_{it})$ | 0.414 | 0.059 | 7.017 | 0.000 |
| Constant | | -1.048 | 0.377 | -2.779 | 0.006 |

Panel B: Dumitrescu-Hurlin Panel Granger Causality Test (p-values)

| Null Hypothesis | Statistic | p-value |
|--|-----------|---------|
| $\ln(\text{URB})$ does not Granger-cause $\ln(\text{CO}_2)$ | 3.521 | 0.001 |
| $\ln(\text{GDPPC})$ does not Granger-cause $\ln(\text{CO}_2)$ | 4.243 | 0.000 |
| $\ln(\text{ENCONS})$ does not Granger-cause $\ln(\text{CO}_2)$ | 4.712 | 0.000 |

Source: Author (2025)

Hypotheses Restatement

The empirical evidence strongly supports this, aligning with urban economic theory that urbanisation intensifies resource consumption and pollution due to higher energy demands and transportation needs (Huang & Lee, 2022). These findings echo recent empirical studies in rapidly urbanising regions, such as Nguyen et al. (2023), who found a significant positive relationship between urban population growth and environmental degradation in Southeast Asia.

The results conform to the EKC hypothesis in its early upward phase, where increases in GDP per capita correlate with rising emissions (Shahbaz et al., 2020). Unlike the EKC's inverted U-shape prediction, this study's timeframe and sample capture mostly growth-related emissions increases, consistent with findings from Liu et al. (2021), who highlight that technological and regulatory measures required to decouple growth from emissions tend to lag behind economic expansion in developing Asian economies.

Lastly, the results aligns with foundational energy-environment frameworks emphasizing fossil fuel dependency as a primary source of emissions (Zhou et al., 2022). Consistent with recent analyses by Park & Kim (2024), the study underscores the critical need to shift towards renewable energy sources to break this entrenched emissions-energy link.

Discussion of Findings

The empirical evidence highlights several crucial policy imperatives for the Asian Tigers. First, the significant effect of urbanisation on emissions necessitates integrated urban planning that promotes sustainable infrastructure and mass transit systems to reduce per capita energy consumption (Kim & Lee, 2023). Policymakers must prioritise investments in energy-efficient buildings and low-emission transportation to mitigate urban growth's environmental footprint (Huang & Lee, 2022). Furthermore, incorporating green space development, compact city models, and circular economy principles into urban design can enhance environmental outcomes and resilience against climate-related shocks. Urban policy should be reoriented to support smart city initiatives that leverage digital infrastructure and data analytics for real-time energy management, waste reduction, and traffic decongestion. Local governments should also be

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empowered with fiscal tools and planning autonomy to implement climate-sensitive zoning regulations and sustainable construction standards.

Second, the positive link between economic growth and emissions suggests that traditional growth models reliant on fossil-fuel-intensive industries remain predominant. Governments should accelerate green growth strategies by incentivizing clean technologies and strengthening environmental regulations to align with EKC theory's later stage, where economic prosperity supports environmental improvements (Shahbaz et al., 2020). The integration of environmental impact assessments into industrial policy, combined with carbon pricing mechanisms and emissions trading schemes, can further internalise environmental costs and shift production incentives towards sustainability. Investment in innovation and green finance can catalyse this transition (Tang et al., 2022). In particular, the development of climate-aligned financial instruments, such as green bonds and sustainability-linked loans, can mobilise private capital for decarbonisation efforts. Tax credits and subsidies for firms adopting energy-efficient technologies, combined with capacity-building programs for small and medium enterprises (SMEs), will help ensure a just and inclusive transition across sectors. Moreover, regional cooperation platforms could be expanded to share best practices in low-carbon industrial upgrading, eco-innovation, and environmental governance.

The strong relationship between energy consumption and emissions underscores the urgency of diversifying energy portfolios towards renewables. Policies fostering renewable energy adoption, grid modernization, and energy efficiency standards are critical to decoupling growth from emissions (Park & Kim, 2024). Regional cooperation frameworks, such as cross-border electricity trading, joint R&D in clean energy technologies, and harmonised regulatory standards, can enhance the speed and scale of energy transitions. The findings advocate for coordinated regional energy policies among the Asian Tigers to leverage economies of scale and technological diffusion, ultimately fostering sustainable development. Equally important is the role of public awareness campaigns and behavioural interventions, which can complement regulatory reforms by encouraging sustainable consumption patterns at the household and firm level. National energy strategies should integrate demand-side management policies, including real-time pricing, smart metering, and incentives for residential and industrial energy conservation. In addition, investment in energy storage technologies, hydrogen infrastructure, and offshore wind capacity will be crucial for ensuring grid reliability as renewable energy penetration increases. Finally, the institutional capacity of energy regulators must be strengthened to monitor compliance, coordinate investments, and foster innovation across public and private energy stakeholders.

CONCLUSIONS AND RECOMMENDATIONS

This study highlights the complexity of balancing rapid urban and economic growth with environmental sustainability in fast-developing economies. This study provides robust empirical evidence on the intricate relationships between CO₂ emissions, urbanisation, economic growth, and energy consumption in the Asian Tigers from 1990 to 2022. The findings confirm that urbanisation significantly exacerbates energy consumption and carbon emissions, consistent with the urban energy demand hypothesis and recent studies in the region (Kim & Lee, 2023; Huang & Lee, 2022). Economic growth continues to be a key driver of environmental degradation, supporting the EKC framework during its early developmental stage (Shahbaz et al., 2020; Li et

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al., 2023). The strong positive linkage between energy consumption and CO₂ emissions underscores the critical challenge of transitioning energy systems away from fossil fuel dependency to achieve sustainable growth (Park & Kim, 2024; Zhou et al., 2022).

Several policy recommendations emerge. Policymakers should intensify efforts to integrate sustainable urban planning with investments in green infrastructure and clean transportation systems, which have proven effective in reducing urban energy intensity (Huang & Lee, 2022; Kim & Lee, 2023). Economic growth strategies must be recalibrated to prioritize decoupling development from carbon emissions through targeted innovation policies, renewable energy incentives, and robust environmental regulations (Tang et al., 2022). Regional cooperation among the Asian Tigers in sharing green technology and harmonizing environmental standards could accelerate the transition to low-carbon economies (Park & Kim, 2024).

Future research should aim to address the identified limitations by employing more granular data at city or sector levels to unpack spatial and economic heterogeneities in emissions drivers (Chen et al., 2021). The inclusion of broader environmental indicators such as methane emissions, air quality, and water pollution would enrich the understanding of urbanisation and growth impacts on environmental sustainability (Sarkodie & Strezov, 2020). Moreover, examining the role of emerging technologies, such as digitalisation and smart grids, in mitigating the energy-emissions nexus presents a promising avenue for advancing this field (Wang et al., 2024). Longitudinal studies incorporating post-pandemic economic recovery dynamics would also provide valuable insights into the resilience and adaptability of environmental policies in the Asian Tigers.

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