2 RENEWABLE ENERGY TRANSITIONS, CAPITAL FORMATION, AND ECOLOGICAL FOOTPRINT IN ASIA-PACIFIC ECONOMIES: A DYNAMIC STIRPAT AND FOOTPRINT DECOMPOSITION ANALYSIS

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Abstract

Environmental pressures in the Asia-Pacific region have intensified alongside rapid economic growth, structural transformation, and rising energy demand. This study investigates how renewable energy, capital formation, and economic development shape the ecological footprint (EF) across 38 Asia-Pacific economies from 2000 to 2022. Using a dynamic STIRPAT-based empirical framework, we examine both aggregate EF and its six subcomponents. The results show that both renewable energy consumption and production reduce EF, highlighting the environmental benefits of expanding clean-energy capacity. Economic development exhibits a U-shaped relationship with EF: early growth stages improve efficiency and reduce ecological pressures, whereas higher income levels eventually increase EF. Capital formation raises EF, indicating continued investment in resource- and energy-intensive activities, while population is associated with lower EF, likely reflecting demographic transition and efficiency gains. Subcomponent analyses reveal heterogeneous drivers, with the carbon footprint most closely mirroring overall EF dynamics. These findings underscore the need to accelerate clean-energy transitions, redirect investment toward green sectors, and strengthen environmental governance to maintain ecological sustainability as economies develop

Highlights

- *Provides a first unified analysis of both renewable energy production and consumption impacts on ecological footprint across 38 Asia-Pacific economies.*
- *Reveals a robust U-shaped relationship between economic development and ecological footprint, offering new insights into the Environmental Kuznets Curve for the region.*
- *Demonstrates that capital formation amplifies ecological pressures, highlighting the need to redirect investment toward green infrastructure and sustainable technologies.*
- *Identifies heterogeneous drivers across EF subcomponents, with carbon footprint closely mirroring overall ecological impacts, informing targeted environmental policy.*

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- *Offers actionable policy guidance: accelerate renewable energy capacity, promote green investments, and tailor governance to sector-specific ecological pressures.*

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1. Introduction

Environmental degradation has become one of the defining challenges for the Asia-Pacific region, where rapid economic expansion over the past two decades has reshaped global production networks and intensified pressure on natural systems. The region's accelerated growth, driven by industrial upgrading, extensive resource use, and rising energy demand, has generated mounting ecological stress manifested in greenhouse-gas emissions, biodiversity loss, ecosystem degradation, and expanding land-use requirements. Hosting more than half of the world's population and accounting for the largest share of global energy-related emissions, Asia-Pacific economies face increasing vulnerability to climate- and resource-related risks.

Despite significant advances in clean-energy technologies, fossil fuels remain deeply embedded in the region's energy mix. Coal continues to dominate in rapidly industrializing economies, while oil and natural gas underpin production and consumption structures across middle- and high-income countries. These entrenched energy systems have generated persistent environmental pressures that transcend carbon emissions alone (Anwar *et al*., 2021; Rahman & Ahmad, 2019). Understanding such pressures requires multidimensional indicators capable of reflecting the complex interactions between economic activity, resource use, and ecological capacity.

The ecological footprint (EF) addresses this need by measuring the biologically productive land and water required to sustain consumption and absorb waste. Integrating six components, i.e. carbon footprint, cropland, grazing land, forest land, fishing grounds, and built-up land, EF provides a broader assessment of environmental pressure than single-pollutant measures (Cutcu *et al*., 2023; Danish & Wang, 2019; Jóźwik *et al*., 2025; Ulucak & Khan, 2020). Yet, empirical evidence on the determinants of EF in the Asia-Pacific context remains fragmented. Existing studies often focus narrowly on carbon emissions, rely on static models that overlook endogeneity and persistence, or examine only a subset of environmental drivers.

Research gaps are particularly evident in three areas. First, although renewable energy is widely studied, most analyses consider only renewable energy consumption (REC), omitting renewable energy production (REP) even though their environmental implications may differ substantially. Second, the role of capital formation, central to structural change and energy system transformation, remains underexplored in EF-based studies. Third, evidence on the Environmental Kuznets Curve (EKC) using EF is still limited, with inconsistent findings for Asia-Pacific economies. Moreover, few studies investigate heterogeneity across EF subcomponents, despite their relevance for sector-specific policy design.

To address these gaps, this study examines the drivers of ecological footprint in 38 Asia-Pacific economies from 2000 to 2022 using a dynamic STIRPAT framework and two-step system GMM. The analysis provides new insights by (a) jointly assessing REC and REP to capture both the downstream benefits and upstream costs of renewable energy transitions; (b) integrating capital formation as a structural determinant of ecological pressure; (c) reassessing the EKC using a multidimensional environmental indicator; and (d) evaluating heterogeneity across the six EF subcomponents. These contributions offer a more comprehensive understanding of how energy transitions, structural investment patterns, and economic development interact to shape environmental outcomes in the Asia-Pacific region.

The remainder of the paper proceeds as follows: Section 2 reviews the relevant literature; Section 3 presents the data and methodology; Section 4 discusses the empirical results; and Section 5 outlines policy implications and conclusions.

2. Literature review

Understanding the relationship between economic development, structural transformation, and environmental sustainability has become central to contemporary debates in environmental economics. While environmental degradation has traditionally been measured through carbon dioxide (CO_2) emissions, the ecological footprint (EF) provides a broader, multidimensional indicator that captures the cumulative pressure human activities impose on ecosystems. This section reviews the theoretical foundations and empirical evidence on the determinants of EF through the STIRPAT framework, the Environmental Kuznets Curve (EKC) hypothesis, and the expanding literature on renewable energy, capital formation, and structural drivers. By integrating these strands, the review highlights the conceptual and empirical gaps that motivate the present study.

2.1. STIRPAT Framework and the Determinants of Ecological Pressure

The STIRPAT model (Dietz & Rosa, 1997), derived from the IPAT identity, offers a flexible framework for examining how population (P), affluence (A), and technology (T) shape environmental outcomes. Unlike the deterministic form of IPAT, STIRPAT enables the estimation of nonlinear, stochastic effects across different environmental indicators, and it has become the dominant framework for examining the macro-determinants of environmental pressure (Bargaoui *et al*., 2014; Lin *et al*., 2017; York *et al*., 2003). Recent empirical work extends STIRPAT to encompass factors such as urbanization, trade openness, energy structure, and foreign direct investment (Lan *et al*., 2023; Lin *et al*., 2017; Sun, 2023).

Although STIRPAT has been applied extensively to CO_2 emissions, the literature using EF remains more limited, especially for the Asia-Pacific region. Studies using EF recognise its capacity to incorporate resource demand (cropland, grazing land, fishing grounds, forest land), land-use change (built-up land), and atmospheric absorption capacity (carbon footprint) (Pata & Aydin, 2020; Wackernagel *et al*., 1999; Yilanci *et al*., 2019), thereby capturing the broader ecological constraints facing rapidly developing economies. The complexity of EF underscores the need for multidimensional empirical approaches capable of capturing structural and dynamic interactions.

One important limitation in existing STIRPAT applications involves the treatment of renewable energy. Most studies analyse only renewable energy consumption (REC) as the technological component of the model. However, renewable energy production (REP) may have different, and in some cases opposite, environmental implications due to land requirements, material extraction, and infrastructure construction. Although studies such as Cutcu *et al*. (2023), Destek and Sinha (2020), Alola *et al*. (2019), and Ulucak & Khan (2020) analyse REC, and others examine REP (Bölük & Mert, 2015; Iqbal *et al*., 2022; Liu *et al*., 2023) separately, very few empirical contributions evaluate REC and REP jointly, creating a methodological gap that can bias the estimation of renewable energy's net environmental effect.

The treatment of capital formation represents another gap in the STIRPAT literature. While theoretical considerations suggest that capital can either intensify ecological pressure through resource- and energy-intensive investments or reduce it through green technological upgrading, empirical results remain mixed. Investments in heavy industries, infrastructure expansion, or fossil-fuel extraction generally exacerbate EF (Gao *et al*., 2020; Jóźwik *et al*., 2025; Rahman & Ahmad, 2019), whereas capital directed toward renewable energy, efficiency upgrades, or low-carbon technologies can mitigate environmental stress (Li, 2024; Y. Li *et al*., 2023; Sun, 2023).

Despite its conceptual relevance, capital formation is rarely integrated into dynamic STIRPAT frameworks, especially in studies focusing on multidimensional environmental indicators.

Control variables such as population, urbanization, trade openness, and foreign direct investment (FDI) also exhibit heterogeneous effects. Population is often found to increase environmental pressure in line with IPAT predictions (Ahmed *et al.*, 2022; Lin *et al.*, 2017; Tatoğlu & Polat, 2021; York *et al.*, 2003), although several studies highlight that demographic transitions, aging, and density effects may moderate its impact (Apergis & Ozturk, 2015; Dogan *et al.*, 2020; Shuai *et al.*, 2017; Wang *et al.*, 2022). Urbanization typically increases EF in developing economies due to consumption intensification and infrastructure expansion (Wang *et al.*, 2016; Yang *et al.*, 2018; Zhang *et al.*, 2024), though global evidence suggests mixed outcomes depending on income levels and urban governance systems (Numan *et al.*, 2022). Trade openness and FDI remain highly contextual while some studies report environmentally harmful effects through scale expansion or pollution-haven dynamics (Lan *et al.*, 2023; Numan *et al.*, 2022; Sarkodie & Strezov, 2019; Shahbaz *et al.*, 2018), others find evidence of cleaner production, technology transfer, or environmental upgrading (Chien *et al.*, 2023; Z. Li *et al.*, 2023; Sun, 2023).

Taken together, the literature highlights the need for a more integrated approach that can simultaneously address renewable energy dynamics, investment structures, and structural drivers within a unified framework, particularly in rapidly developing regions where ecological pressures are high and evolving.

2.2. EKC Hypothesis and the Use of Ecological Footprint

The Environmental Kuznets Curve (EKC) hypothesis posits an inverted U-shaped relationship between income and environmental degradation, driven by scale, composition, and technique effects (Grossman & Krueger, 1995). In the early stages of development, environmental pressure rises as economies expand production and increase resource use. At later stages, structural upgrading, efficiency improvements, and stronger environmental regulation are expected to reduce ecological degradation.

Empirical evidence for the EKC remains inconsistent, especially when different environmental indicators are used. Studies on CO_2 emissions reveal a spectrum of nonlinearities, including inverted U-shaped (Anwar *et al.*, 2021; Li, 2024; Pata, 2018; Shahbaz *et al.*, 2018), U-shaped (Bölük & Mert, 2015; Charfeddine, 2017; Saman *et al.*, 2024), N-shaped and inverted N-shaped patterns (Apergis & Ozturk, 2015; Bekhet & Othman, 2018; Mahmood *et al.*, 2023). These differences reflect variations in industrial structures, energy systems, and policy frameworks across countries. Moreover, the growing literature on the rebound effect (Jevons' paradox) suggests that efficiency improvements may increase overall consumption, challenging the presumed decline in environmental impacts at higher income levels.

Despite EF offering a more holistic measure of environmental pressure, studies applying EKC to EF remain sparse. Some analyses identify a U-shaped relationship between economic development and EF in emerging economies (Caglar *et al.*, 2021; Charfeddine, 2017; Dogan *et al.*, 2020; Halkos & Tzeremes, 2009; Khezri & Muhamad, 2023), while others find inverted U-shaped (Ahmed *et al.*, 2022; Ulucak & Khan, 2020; Zhang *et al.*, 2024) or insignificant patterns depending on country coverage, time periods, and estimation methods (Destek & Sinha, 2020; Mahmood *et al.*, 2023).

For the Asia-Pacific region, evidence is particularly fragmented, with some studies identifying EKC validity (Anwar *et al.*, 2021; Apergis & Ozturk, 2015; Dong *et al.*, 2018) and others finding deviations from the expected inverted U-shape (Destek & Sarkodie, 2019; Saboori & Sulaiman, 2013). The mixed findings highlight the need for updated, methodologically rigorous analyses that account for endogeneity, persistence, and structural transformations, particularly given the region's rapid economic growth and evolving energy landscape.

The present study contributes to this ongoing debate by applying the EKC framework to a multidimensional environmental indicator, thereby capturing the broader ecological consequences of economic development beyond emissions alone.

2.3. Renewable Energy Dynamics and Ecological Sustainability

Transitioning to renewable energy represents a central pillar of global sustainability efforts. The literature generally agrees that renewable energy consumption tends to improve environmental quality by reducing reliance on fossil fuels and lowering carbon intensity (Caglar *et al*., 2021; Destek & Sinha, 2020; Naimoglu & Akal, 2023; Ulucak & Khan, 2020; Dima *et al*., 2024). However, the environmental implications of renewable energy production are more nuanced. While REP supports long-term sustainability, the short-term ecological costs associated with land use, infrastructure development, and material extraction may offset immediate gains (Iqbal *et al*., 2022).

The emerging literature identifies strong regional variations. In some contexts, REP has clear positive effects on environmental quality (Bölük & Mert, 2015; Chien *et al*., 2023; Liu *et al*., 2023), whereas in others, the rapid expansion of renewable infrastructure leads to environmental trade-offs. These contrasting outcomes stem from differences in technological maturity, regulatory frameworks, land availability, and supply chain configurations.

A notable empirical gap is that most existing studies evaluate REC or REP in isolation, without considering their interaction or the role of capital formation as a mediating factor. Yet renewable energy expansion is capital-intensive, and failure to integrate investment patterns may lead to misinterpretation of REP's environmental impact. By jointly analysing REC, REP, and capital formation within a dynamic econometric model, the present study provides a more comprehensive assessment of the trade-offs inherent in energy transitions.

2.4. Capital Formation, Structural Transformation, and Environmental Pressure

Capital formation plays a dual role in environmental outcomes. In many developing economies, investment remains concentrated in energy-intensive industrial sectors, fossil-fuel infrastructure, and resource-extractive activities, thereby amplifying EF through scale effects (Jóźwik *et al*., 2025; Rahman & Ahmad, 2019). Conversely, investment directed toward renewable energy systems, efficiency improvements, and environmental technologies can reduce ecological stress, though such transformations require high levels of institutional support, technological readiness, and financial capacity.

Empirical studies offer inconsistent findings, reflecting differences in investment composition, regulatory environments, and levels of industrialization. Despite being an essential determinant of structural change, capital formation is rarely incorporated into dynamic EF models, particularly in studies that jointly analyse energy transition variables. This omission may lead to inaccurate assessments of development-environment linkages, especially in regions experiencing rapid industrialization.

By incorporating capital formation into a unified STIRPAT-EKC framework, the present study addresses an important gap and provides new evidence on the structural drivers of EF in the Asia-Pacific region.

3. Data and methodology

3.1. Data

This study examines the determinants of ecological sustainability across 38 Asia-Pacific economies over 2000-2022, focusing on the environmental implications of renewable energy development, economic growth, and structural transformation. The dataset is constructed from internationally recognized sources, including the World Development Indicators (WDI), International Energy Agency (IEA), International Renewable Energy Agency (IRENA), Global Footprint Network (GFN), International Monetary Fund (IMF), and Asian Development Bank (ADB). Although data availability varies by indicator, the final dataset remains strongly balanced and suitable for dynamic panel estimation.

The dependent variable is the ecological footprint (EF), expressed in global hectares (gha) per capita and decomposed into six subcomponents, i.e. carbon footprint, cropland, grazing land, fishing grounds, forest land, and built-up land, sourced from the Global Footprint Network. EF offers a multidimensional assessment of human pressure on ecological systems and is increasingly recognized as a more comprehensive indicator than single-emission metrics such as CO_2.

The core explanatory variables capture multiple facets of the energy transition and macroeconomic structure:

- Renewable energy consumption (REC): share of renewable energy in total final energy consumption (WDI, IEA).
- Renewable energy production (REP): electricity generation from renewable sources (GWh) (IRENA).
- GDP per capita (GDP): proxy for economic development (constant USD, WDI).
- GDP^2: included to test the Environmental Kuznets Curve (EKC) hypothesis.
- Gross capital formation (GCF): share of GDP allocated to investment, capturing capital accumulation and structural upgrading.

To account for broader macroeconomic and demographic influences, the model incorporates four control variables commonly used in STIRPAT-related studies:

- Trade openness (TRADE): total trade as a percentage of GDP.
- Foreign direct investment (FDI): net inflows as a percentage of GDP.
- Population (POP): total population size.
- Urbanization (URBAN): annual growth rate of the urban population.

All continuous variables are transformed into natural logarithms to reduce heteroskedasticity, stabilize variance, and enable elasticity-based interpretation.

Table 1 presents descriptive statistics, showing relatively stable distributions across countries and years.

Table 2 reports the pairwise correlation matrix, indicating significant associations between EF and most regressors while remaining below typical multicollinearity thresholds, confirming the suitability of the dataset for multivariate analysis.

Table 1. Descriptive statistics

Variable	Obs	Mean	Std. dev.	Min	Max
EF	860	3.45170	2.85896	0.44165	15.97643
REC	789	2.15174	1.92189	-2.30259	4.52179
REP	874	5.50061	1.51738	0.00000	6.73934
GDP	874	8.26410	1.47345	4.92131	11.49314
GDPsq	874	70.46393	24.95945	24.21927	132.09240
GCF	832	3.28619	0.33269	0.20308	4.25780
POP	874	16.66863	1.75111	13.28313	21.07193
URBAN	874	2.49599	2.18516	-4.17034	19.61203
FDI	831	0.85521	1.29334	-5.33341	4.00866
TRADE	874	4.12898	0.53842	2.92580	6.55900

Source: Authors

Table 2. Pairwise correlation matrix

	EF	REC	REP	GDP	GCF	POP	URBAN	FDI
REC	-0.6250	1.0000						
	(0.0000)							
REP	-0.3347	0.1836	1.0000					
	(0.0000)	*(0.0000)*						
GDP	0.7931	-0.5432	-0.1881	1.0000				
	(0.0000)	*(0.0000)*	*(0.0000)*					
GCF	0.1602	-0.0235	0.0515	0.0545	1.0000			
	(0.0000)	*(0.5198)*	*(0.1375)*	*(0.1164)*				
POP	-0.4087	0.1750	0.1352	-0.2249	0.0416	1.0000		
	(0.0000)	*(0.0000)*	*(0.0001)*	*(0.0000)*	*(0.2304)*			
URBAN	0.2353	-0.1032	-0.3744	0.0011	0.1755	0.0024	1.0000	
	(0.0000)	*(0.0037)*	*(0.0000)*	*(0.9730)*	*(0.0000)*	*(0.9446)*		
FDI	0.1096	-0.2174	0.1145	0.1396	0.0226	-0.2779	-0.0849	1.0000
	(0.0017)	*(0.0000)*	*(0.0009)*	*(0.0001)*	*(0.5247)*	*(0.0000)*	*(0.0144)*	
TRADE	0.2986	-0.2861	-0.0782	0.2051	-0.0500	-0.3782	0.0967	0.4305
	(0.0000)	*(0.0000)*	*(0.0208)*	*(0.0000)*	*(0.1499)*	*(0.0000)*	*(0.0042)*	*(0.0000)*

** The italic values in the bracket are significant level of the above coefficients*

Conceptual rationale for variable selection

The selection of REC, REP, and GCF is grounded in the conceptual pathways through which energy transitions and structural change influence ecological outcomes. Renewable energy consumption (REC) represents the operational use of clean energy and its potential to displace fossil fuels, thereby reducing direct emissions and environmental pressure. Renewable energy production (REP) reflects the upstream development of renewable energy infrastructure, which is an aspect often overlooked in the EF literature. While vital for long-term decarbonization, REP may generate short-term ecological pressures through land occupation, material extraction, and construction. Analyzing REC and REP jointly enables a distinction between downstream and upstream effects of the energy transition. Gross capital formation (GCF) captures the structural orientation of investment: when directed toward fossil- or resource-intensive sectors, it amplifies ecological degradation; when allocated to efficient or low-carbon technologies, it supports environmental improvement. Integrating REC, REP, and GCF within a unified STIRPAT- EKC framework thus provides a comprehensive lens for understanding how economic development and renewable energy pathways jointly shape ecological sustainability.

3.2. Econometric Methodology

To evaluate the drivers of ecological footprint, the study adopts an extended STIRPAT framework, which allows flexible estimation of the effects of population, affluence, and technology on environmental pressure. The baseline model is specified as:

$$EF_{it} = \beta_0 + \beta_1 REC_{it} + \beta_2 REP_{it} + \beta_3 GDP_{it} + \beta_4 GDP_{it}^2 + \beta_5 GCF_{it} + \sum_k \gamma_k Control_{kit} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

In eq.1, the subscripts *i* and *t* denote country and year, respectively; β_0 is the intercept; β_1-β_5 and γ_k are coefficients to be estimated; $Control_{kit}$ represents the set of control variables (TRADE, FDI, POP, URBAN); μ_i captures unobserved country-specific effects; λ_t controls for global shocks; and ε_{it} is the idiosyncratic error term. The inclusion of the squared GDP term allows for testing the EKC hypothesis using EF as a multidimensional indicator.

Environmental indicators such as EF exhibit strong temporal persistence because ecological pressures reflect long-term energy structures, consumption patterns, and technological trajectories. Consequently, current EF values depend partly on past EF levels. Furthermore, variables such as GDP, GCF, and renewable energy development may be jointly determined with environmental outcomes, generating endogeneity, simultaneity bias, and omitted-variable concerns. Including lagged EF exacerbates dynamic-panel bias (Nickell bias), making static estimators, e.g. OLS, Fixed Effects (FE), Random Effects (RE), inconsistent.

To address these econometric challenges, the study employs the two-step System Generalized Method of Moments (System-GMM) estimator (Arellano & Bover, 1995; Blundell & Bond, 1998). System-GMM is well suited for panels characterized by many cross-sectional units (large N) and shorter time periods (small T), and offers the following advantages:

- Corrects endogeneity by using internal instruments derived from lagged levels and differences.
- Mitigates weak instrument problems, particularly for persistent variables like EF.
- Controls unobserved heterogeneity by combining equations in levels and differences.
- Produces heteroskedasticity-robust standard errors.
- Allows serial correlation in the idiosyncratic error term.

To avoid instrument proliferation, the instrument matrix is collapsed and lag structure restricted following Roodman (2009).

The empirical procedure follows a multi-stage approach:

1. Descriptive statistics and correlation analysis, to explore variable distributions and potential collinearity;
2. Baseline OLS estimation, supported by diagnostic tests (VIF, White test, Wooldridge test);
3. FE and RE estimation, with the Hausman test informing model selection;
4. IV-2SLS estimation as a robustness check for endogeneity;
5. Two-step System-GMM estimation, serving as the primary specification.

Diagnostic tests include (i) Arellano-Bond AR(1) and AR(2) tests for serial correlation, and (ii) Hansen J test for overidentifying restrictions.

This structured methodology ensures robustness by comparing results across multiple estimators and addressing endogeneity, persistence, and unobserved heterogeneity simultaneously.

4. Empirical results and discussion

4.1 Preliminary Diagnostics and Baseline Patterns

We begin by validating data properties and the suitability of the econometric framework. Panel unit root tests using the Im-Pesaran-Shin (IPS) method reveal that most variables are stationary at level or at first difference, mitigating concerns about spurious regressions. Although population exhibits second-order stationarity, first differences suffice given its role as a control variable in a dynamic specification. Renewable energy production presents constant series for a single country (Turkmenistan), but excluding this observation confirms stationarity at level, suggesting that the overall dataset remains robust for dynamic modeling.

Descriptive analysis and pairwise correlations provide an initial perspective on the structure of relationships among variables (*see the previous section*). Ecological footprint (EF) is strongly correlated with economic development and renewable energy consumption, moderately correlated with renewable energy production and population, and weakly associated with structural variables such as capital formation, trade, and FDI. Importantly, correlations among regressors do not exceed critical multicollinearity thresholds, confirming that multivariate estimation is unlikely to suffer from unstable coefficient inflation. These preliminary patterns reinforce the rationale for a dynamic, multi-variable specification that can disentangle the effects of renewable energy development, structural economic shifts, and nonlinear growth trajectories on ecological pressure.

Baseline OLS estimations serve as an exploratory benchmark (Tab.3). The model shows a high explanatory power (adjusted $R^2 \approx 0.80$), with renewable energy consumption (REC) and renewable energy production (REP) both displaying negative and significant effects on EF. Economic development, capital formation, urbanization, and trade openness exhibit positive associations with ecological pressure, reflecting the resource-intensive nature of growth in the region. Population and FDI reduce EF in this preliminary framework, although these associations weaken in more advanced models. Diagnostic tests indicate heteroskedasticity and autocorrelation in OLS residuals, and given the likely endogeneity of several regressors and the persistence of EF over time, a dynamic panel approach is warranted. The intermediate panel estimators (FEM, REM, and GLS) reported in Tab. 3 provide additional insight into the robustness of the baseline relationships. While the magnitude and significance of some structural variables (GCF, FDI, and trade openness) vary across these models, the core patterns remain stable: both renewable energy indicators reduce EF, while GDP exerts a positive linear effect. The Hausman test favors the random-effects specification, yet heteroskedasticity and serial correlation persist across all static estimators, reinforcing the need for a dynamic GMM approach. Overall, these preliminary estimations confirm the sign and direction of the main coefficients, but their sensitivity to model specification underscores the limitations of static panel techniques and further justifies the adoption of the dynamic framework.

Table 3. Empirical results of estimation methods

	OLS EF	FEM EF	REM EF	GLS EF	GMM EF	GMM EF
REC	-0.3477***	-0.3744***	-0.4874***	-0.4398***	-0.0872*	-0.1180**
	(-11.4488)	*(-5.5250)*	*(-8.8272)*	*(-16.8069)*	*(-1.7445)*	*(-2.5957)*
REP	-0.2861***	-0.1042***	-0.1329***	-0.0095	-0.0783**	-0.0728**
	(-6.9023)	*(-4.6197)*	*(-5.9177)*	*(-0.7974)*	*(-2.0839)*	*(-2.1071)*
GDP	1.1301***	0.4393***	0.4164***	0.6684***	-0.7867**	-1.0340***
	-29.8984	*-10.2254*	*-11.1662*	*-17.3114*	*(-2.0812)*	*(-3.5083)*
GCF	0.7692***	0.1172	0.0871	0.0714	0.3216*	0.3963***
	-5.3272	*-1.182*	*-0.859*	*-1.1081*	*-2.0222*	*-3.5701*
POP	-0.3324***	-1.1465***	-0.6126***	-0.2490***		-0.0814**
	(-12.0725)	*(-6.1457)*	*(-6.9649)*	*(-9.3998)*		*(-2.0896)*
URBAN	0.1974***	0.0883***	0.0933***	0.0518***		0.0583*
	-8.3229	*-7.1102*	*-7.2609*	*-3.1504*		*-1.7004*
FDI	-0.1303***	0.0001	-0.0046	-0.001		0.0222
	(-3.0716)	*-0.0038*	*(-0.1762)*	*(-0.0795)*		*-0.9184*
TRADE	0.2109**	0.0866	0.1162	0.1432**		0.0526
	-2.1397	*-0.88*	*-1.1656*	*-2.4834*		*-0.6869*
L.EF					0.7658***	0.6566***
					-7.2863	*-7.0309*
GDPsq					0.0620**	0.0830***
					-2.1513	*-3.9596*
_cons	-1.8040*	19.3103***	10.9006***	1.7700***	2.4819*	4.1969**
	(-1.9410)	*-6.6286*	*-7.0948*	*-2.7883*	*-1.7594*	*-2.7143*
N	708	708	708	708	704	678
F test/ Wald test	364.84	45.9	521.3	1949.86	987.06	314.76
Sig	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
R2	0.8068	0.4834	0.6502			
Adj-R2	0.8046					

** p<.1, ** p<.05, *** p<.01; * The italic values are the Tstat values of the above coefficients*

4.2 Dynamic Determinants of Ecological Footprint: Evidence from System GMM

The two-step System GMM estimator constitutes the core empirical approach due to its ability to address unobserved heterogeneity, endogeneity, simultaneity, and dynamic persistence (tab.5). Instrument validity tests, including the Hansen test of overidentifying restrictions and the Arellano-Bond AR(2) test, confirm that the instrument set is appropriate and that residuals do not exhibit problematic serial correlation. Collapsing instruments and restricting lag depth prevent instrument proliferation, ensuring the reliability of inference.

Across all specifications, the lagged dependent variable exhibits a positive and highly significant coefficient (0.65-0.78), underscoring the strong temporal inertia inherent in ecological systems (Tab.4). This persistence reflects slow-moving structural processes, path dependence in energy systems, and long-term ecological impacts of past economic activities, which are patterns widely documented in environmental macroeconomics. The strong autoregressive structure justifies the dynamic modeling strategy and highlights the importance of long-term planning in environmental policy.

Table 4. Robustness Test Results for different combination of drivers of EF by system GMM

	GMM1 EF	GMM2 EF	GMM3 EF	GMM4 EF	GMM5 EF	GMM6 EF
L.EF	0.7787***	0.7658***	0.7240***	0.6463***	0.6564***	0.6566***
	-7.5483	*-7.2863*	*-7.2229*	*-7.1115*	*-7.1291*	*-7.0309*
REC	-0.0804*	-0.0872*	-0.1044**	-0.1159**	-0.1161**	-0.1180**
	(-1.9983)	*(-1.7445)*	*(-2.0975)*	*(-2.6753)*	*(-2.6317)*	*(-2.5957)*
REP	-0.0786**	-0.0783**	-0.0856**	-0.0750**	-0.0750**	-0.0728**
	(-2.3044)	*(-2.0839)*	*(-2.1849)*	*(-2.0646)*	*(-2.1094)*	*(-2.1071)*
GDP	-0.6374*	-0.7867**	-0.8923**	-1.0155***	-1.0726***	-1.0340***
	(-1.8223)	*(-2.0812)*	*(-2.5945)*	*(-3.6075)*	*(-3.4009)*	*(-3.5083)*
GDPsq	0.0525*	0.0620**	0.0698**	0.0831***	0.0855***	0.0830***
	-1.9363	*-2.1513*	*-2.7035*	*-4.0946*	*-3.8494*	*-3.9596*
GCF		0.3216*	0.3849**	0.4168***	0.4140***	0.3963***
		-2.0222	*-2.4573*	*-2.99*	*-3.4824*	*-3.5701*
POP			-0.0839**	-0.1118***	-0.0925**	-0.0814**
			(-2.3386)	*(-2.8796)*	*(-2.6006)*	*(-2.0896)*
URBAN				0.0575	0.0577*	0.0583*
				-1.6517	*-1.6972*	*-1.7004*
FDI					0.0259	0.0222
					-1.043	*-0.9184*
TRADE						0.0526
						-0.6869
_cons	2.9070**	2.4819*	4.2223**	4.7534***	4.6884***	4.1969**
	-2.0617	-1.7594	-2.6009	-3.489	-3.1045	-2.7143
N	739	704	704	704	678	678
AR1	0.034	0.036	0.036	0.038	0.043	0.043
AR2	0.252	0.257	0.256	0.259	0.264	0.262
Hansen	0.155	0.155	0.134	0.183	0.253	0.304
n/N	27/38	28/38	29/38	30/38	31/38	32/38

** p<.1, ** p<.05, *** p<.01; * The italic values are the Tstat values of the above coefficients*

Renewable Energy Consumption and Production

One of the most robust findings concerns the environmental benefits of renewable energy. Both renewable energy consumption and renewable energy production reduce EF across all specifications, although the magnitude and significance vary. REC consistently exhibits a stronger negative effect than REP, suggesting that immediate ecological gains arise primarily through the displacement of fossil fuels in final energy use. REP, though also beneficial, may involve short-term ecological costs due to the land, materials, and infrastructure required for renewable capacity expansion.

The dual inclusion of REC and REP is a key methodological and conceptual innovation of the study. Existing literature often examines these variables separately, overlooking the possibility that the environmental effects of renewable energy differ across stages of the energy cycle. The current results demonstrate that both sides of the renewable energy system, i.e. production and consumption, contribute to ecological improvements, albeit through distinct channels. This finding reinforces the need for policies that expand renewable capacity while accelerating integration of renewable energy into end-use sectors.

The U-Shaped Environmental Kuznets Curve

A central contribution of the study is the consistent and statistically significant identification of a U-shaped relationship between GDP and EF. Economic development initially reduces ecological pressure (negative GDP coefficient), but beyond a threshold, further growth increases EF (positive GDP^2 coefficient). This result contradicts the traditional inverted U-shaped EKC hypothesis but aligns with a growing body of empirical evidence documenting U-shaped environmental transitions in emerging economies undergoing rapid structural change.The results suggest that during the early stages of development, efficiency improvements, sectoral reallocation, and adoption of cleaner technologies may temporarily offset environmental pressures. However, once countries reach middle- to high-income levels, rising consumption patterns, energy-intensive lifestyles, and greater reliance on carbon-intensive production tend to dominate. For countries across the Asia Pacific region that are progressing from industrial development toward more mature economic structures, this reversal reveals the vulnerability of early environmental improvements and emphasizes the importance of adopting forward-looking sustainability strategies before economic expansion moves beyond the ecological threshold.

The Environmental Implications of Capital Formation

Gross capital formation emerges as a significant and positive determinant of ecological footprint, confirming that current investment patterns in the region remain environmentally intensive. Capital flows continue to favor infrastructure, construction, and manufacturing activities with high resource and energy requirements. This supports the "grow now, clean later" paradigm characteristic of many rapidly developing economies. The findings align with prior research identifying capital formation as a driver of environmental degradation when investment is directed toward fossil fuel-based production or inefficient industrial expansion.

A notable policy implication is that sustainable development in the region requires not only scaling up renewable energy but also greening capital allocation. Redirecting investment toward energy efficiency, low-carbon technologies, sustainable urban systems, and circular economy projects is essential to mitigate the environmental burden of development.

Demographic and Structural Determinants

Population exhibits a consistent and negative effect on EF in the GMM models. Although counterintuitive at first glance, given the typical positive population-pressure link in IPAT-type frameworks, a closer interpretation reveals several plausible mechanisms. Many Asia-Pacific economies are undergoing demographic transition, with declining fertility rates, aging populations, and shifts in household consumption patterns. These changes may reduce per capita ecological demand or foster more efficient resource use, consistent with recent studies documenting demographic-economic decoupling.

Urbanization increases EF, although its significance varies by specification. This reflects the coexistence of efficiency-enhancing agglomeration effects and resource-intensive urban expansion. The finding is consistent with the literature documenting that without stringent urban planning and low-carbon infrastructure, urbanization can amplify ecological pressures.

FDI and trade openness exhibit mixed results across models. They are significant in simpler specifications but lose significance under System GMM, suggesting that their effects are indirect or absorbed through determinants such as GDP, GCF, or REC. However, as shown later via subcomponent analysis, these variables exert notable influence on specific ecological domains.

Robustness Across Sequential GMM Specifications

Sequential GMM estimations, ranging from parsimonious models including only REC, REP, and GDP/GDP^2 to fully augmented models including GCF, POP, URBAN, FDI, and TRADE, confirm the robustness of core relationships. Renewable energy consistently mitigates EF. Capital formation remains a driver of ecological pressure. GDP maintains a U-shaped pattern across all specifications. Population consistently reduces EF. Structural variables (trade, FDI, urbanization) are more sensitive to model complexity but do not alter the central conclusions.

These robustness checks reinforce the validity of the dynamic framework and the reliability of the core findings.

4.3 Heterogeneous Effects Across Ecological Footprint Subcomponents

As shown in Tab.5, a key contribution of the study is the disaggregated analysis of EF into its six subcomponents, revealing important heterogeneities that would remain hidden if only the aggregate EF were examined.

Table 5. Results from System GMM analysis for Footprint components

	EF	Built-up	carbon	cropland	fishing	forest	grazing
L.EF	0.6566***						
	-7.0309						
L.built-up		0.9344***					
		-6.8909					
L.carbon			0.6793***				
			-7.3162				
L.cropland				-0.0021			
				(-0.0109)			
L.fishing					0.8767***		
					-26.9422		
L.forest						0.8846***	
						-10.5693	
L.grazing							0.7670***
							-10.7393
REC	-0.1180**	0.0008	-0.1366***	-0.0386**	0.0021	0.0139	-0.0061
	(-2.5957)	*-0.4183*	*(-2.7243)*	*(-2.3796)*	*-1.178*	*-1.2026*	*(-0.7140)*
REP	-0.0728**	0.0002	-0.0954**	-0.0091	-0.001	0.0041	-0.0043
	(-2.1071)	*-0.5751*	*(-2.5775)*	*(-1.1817)*	*(-0.7750)*	*-1.1585*	*(-1.1826)*
GDP	-1.0340***	0.0026	-1.0606***	0.1548	0.012	0.0026	0.0295
	(-3.5083)	*-0.267*	*(-3.5966)*	*-1.1773*	*-0.6253*	*-0.0746*	*-0.4074*
GDPsq	0.0830***	-0.0001	0.0778***	-0.0065	-0.0002	0.0007	-0.0017
	-3.9596	*(-0.2669)*	*-3.6499*	*(-0.8156)*	*(-0.1877)*	*-0.262*	*(-0.3514)*
GCF	0.3963***	0.0027	0.1532**	-0.0324	-0.0039	0.0415	0.0724
	-3.5701	*-0.8224*	*-2.2256*	*(-0.8929)*	*(-0.4250)*	*-1.1566*	*-1.5429*
POP	-0.0814**	-0.0001	-0.0063	-0.0515***	0.0008	-0.0133	-0.0197***
	(-2.0896)	*(-0.1497)*	*(-0.4023)*	*(-3.9819)*	*-0.5657*	*(-1.4074)*	*(-2.7710)*
URBAN	0.0583*	0.0001	0.0434	-0.0049	-0.0014	0.001	-0.001
	-1.7004	*-0.2789*	*-1.3938*	*(-1.2251)*	*(-1.4083)*	*-0.3457*	*(-0.2913)*
FDI	0.0222	0.0002	0.0229	0.0038	-0.0048**	-0.0051	0.0066
	-0.9184	*-0.233*	*-1.1625*	*-0.7163*	*(-2.2202)*	*(-0.8155)*	*-1.0468*
TRADE	0.0526	0.0007	0.008	-0.0158	0.0184***	0.0021	-0.0085
	-0.6869	*-0.3993*	*-0.135*	*(-0.4299)*	*-4.5595*	*-0.2536*	*(-0.6621)*
_cons	4.1969**	-0.021	4.2060***	0.8817	-0.1377*	-0.0047	0.0955
	-2.7143	*(-0.4032)*	*-3.0069*	*-1.3764*	*(-1.8886)*	*(-0.0318)*	*-0.342*
N	678	678	678	678	678	678	678
AR1	0.043	0.041	0.019	0.245	0.17	0.067	0.06

	EF	Built-up	carbon	cropland	fishing	forest	grazing
AR2	0.262	0.455	0.397	0.351	0.612	0.123	0.748
Hansen	0.304	0.315	0.119	0.377	0.21	0.158	0.452
n/N	32/38	32/38	32/38	32/38	32/38	32/38	32/38

** p<.1, ** p<.05, *** p<.01; * The italic values are the Tstat values of the above coefficients*

The carbon footprint, which constitutes the largest share of total EF, exhibits dynamics that closely mirror those of the overall ecological footprint. All key variables (REC, REP, GDP, GDP^2, GCF) influence it in the same direction as the aggregate. The EKC relationship is strongly U-shaped, and renewable energy reduces carbon intensity. This finding suggests that carbon mitigation policies are likely to produce broad ecological co-benefits, making carbon management a strategic priority for the region.

The land-related components (Cropland, Grazing Land, Built-Up Land, Forest Land) are driven by a distinct set of factors:

- Cropland footprint: Reduced by REC and population, but unaffected by REP or GDP. The insignificance of lagged cropland footprint indicates low persistence, possibly due to annual variability in agricultural practices.
- Grazing land footprint: Reduced by population but largely unaffected by other variables, suggesting that demographic transitions influence dietary patterns and land demand.
- Built-up land footprint: Strongly persistent but not significantly influenced by economic, energy, or demographic drivers, highlighting the rigidity of land conversion processes.
- Forest land footprint: Similar to Built-up land footprint, the forest land is strongly persistent but not affected by economic and demographic drivers.

The fishing footprint displays strong persistence and is positively influenced by trade openness but negatively by FDI. These results suggest that trade-intensive fisheries contribute to unsustainable marine resource extraction, while foreign investment may introduce more regulated or technologically efficient fishing practices.

Taken together, the results reveal a complex, multidimensional landscape of ecological pressures in the Asia-Pacific region:

- Renewable energy development (both consumption and production) consistently improves ecological sustainability.
- Economic growth follows a U-shaped environmental trajectory, highlighting the fragility of early gains.
- Capital formation remains a major source of environmental stress due to its fossil-intensive structure.
- Demographic transitions can alleviate environmental pressure.
- The heterogeneity of EF subcomponents underscores the need for domain-specific policies.

Overall, the empirical evidence confirms that environmental outcomes in the Asia-Pacific region are shaped by a delicate interplay between structural economic transformation, energy system evolution, investment patterns, and demographic change, requiring integrated, long-term strategies to achieve sustainability.

5. Conclusion

This study analyzed how renewable energy transitions, capital formation, and economic development influence ecological sustainability in 38 Asia-Pacific economies from 2000 to 2022. By applying a dynamic STIRPAT framework and decomposing the ecological footprint (EF) into its six subcomponents, the analysis provides an integrated perspective on the structural, energetic, and demographic drivers of environmental pressure in a region experiencing unprecedented economic and infrastructural transformation.

The results demonstrate that both renewable energy production and renewable energy consumption significantly reduce ecological pressure, highlighting the importance of supporting renewable energy not only at the point of use but also throughout the full production and infrastructure chain. These findings underscore the need for policies that expand clean-energy capacity, facilitate technology deployment, and strengthen the enabling conditions for renewable energy industries. The region's sustainability transition will depend critically on the ability of governments to foster long-term investment in renewable infrastructure and accelerate the substitution of fossil-based systems.

A second key result concerns the relationship between economic development and environmental pressure. The robust U-shaped trajectory observed across the region challenges the conventional inverted EKC interpretation and reveals that, although early development stages yield efficiency gains and structural improvements, these benefits weaken at higher income levels. Without targeted interventions, the amplification of consumption, mobility, and investment patterns can reverse environmental progress, introducing renewed pressures on ecosystems. This suggests that Asia-Pacific economies must adopt forward-looking governance frameworks designed to prevent "rebound pathways" that re-couple growth with resource intensity.

Capital formation also emerges as a decisive source of ecological pressure. The positive effect of capital investment on EF indicates that much of the region's investment continues to flow into resource-intensive industries, fossil-based infrastructure, and land-consuming development models. A shift toward cleaner production pathways will require reorienting capital portfolios toward energy-efficient technologies, circular-economy infrastructures, and low-carbon industrial upgrading. Redirecting capital formation thus represents both a challenge and a strategic opportunity for accelerating sustainability transitions.

Demographic and spatial dynamics further refine this picture. Population reduces EF in the full model, pointing to efficiency-driven demographic transitions and scale economies in resource use. Urbanization, in contrast, increases EF but lacks consistent effects across footprint components, emphasizing that the environmental consequences of urban development depend on urban form, infrastructure quality, and planning approaches. The decomposition results also reveal substantial heterogeneity: while carbon footprint closely mirrors the behaviour of total EF, land-based components—from cropland to grazing and fishing grounds—respond to specific combinations of trade, FDI, renewable energy, and population pressures. These patterns confirm the value of multidimensional ecological indicators and highlight sector-specific vulnerabilities that aggregate metrics obscure.

Policy Implications for Cleaner Production and Sustainability Transitions

The findings of this study carry several actionable policy implications for guiding cleaner production pathways in the Asia-Pacific:

1. Scale up renewable energy deployment across the entire value chain

Governments should strengthen investment in renewable generation, transmission infrastructure, grid flexibility, and storage systems, while also promoting end-use electrification. This dual approach maximizes the environmental benefits identified in the analysis.

2. Realign capital formation with low-carbon and resource-efficient development

Fiscal incentives, green financing frameworks, environmental standards for lending, and public-private investment platforms are needed to shift capital flows away from resource-intensive sectors and toward clean technologies, circular-economy systems, and regenerative ecological infrastructure.

3. Intervene strategically along the development trajectory to counteract the U-shaped EKC pattern

Middle- and high-income economies should adopt proactive environmental governance—carbon pricing, industrial decarbonization strategies, and strict land-use and pollution controls—to avoid returning to high-impact growth pathways.

4. Implement targeted, sector-specific strategies for high-impact EF subcomponents

Fisheries, cropland systems, and grazing land require customized regulatory frameworks. Strengthening monitoring, eco-labelling, sustainable aquaculture, reforestation, and land restoration initiatives can reduce pressures in these ecologically sensitive domains.

5. Enhance regional cooperation for clean-energy transitions and environmental governance

Asia-Pacific economies can benefit from cross-border technology transfer, joint renewable-energy investment mechanisms, harmonized environmental standards, and coordinated action on ocean and forest protection.

Limitations and Directions for Future Research

Despite its comprehensive scope, the study faces data constraints that limit long-term time-series depth and heterogeneity assessment. Future research should explore country clusters, institutional quality, innovation capacity, and environmental governance channels to better capture differentiated sustainability pathways. Moreover, in-depth sectoral analyses of built-up land, forest land, and fishing grounds can help identify micro-level drivers and design more precise interventions aligned with national and regional cleaner production strategies.

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