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Title: Energy transition, economic efficiency, and resource use: Evidence on energy efficiency in APEC economies

Author(s): Liu, ZL (Liu, Zhile); Lu, SX (Lu, Shixiang); Zhong, YL (Zhong, Yilin); Zhang, JJ (Zhang, Jinjun)

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Abstract: Energy inefficiency remains a key challenge for Asia-Pacific Economic Cooperation (APEC) economies despite progress in renewable-energy deployment, industrial modernization, and regional energy-policy cooperation. This study examines the effects of energy transition, economic-energy productivity, industrial structure, population density, and freshwater withdrawals on energy-efficiency performance in 21 APEC economies from 1999 to 2023. Energy efficiency is proxied by energy intensity, where lower energy intensity indicates stronger efficiency performance. The study applies principal component analysis, cross-sectional dependence testing, Westerlund panel cointegration, Driscoll-Kraay fixed-effects estimation, and panel-corrected standard errors. The results show that GDP per unit of energy use is consistently associated with lower energy intensity, while industrial value added is consistently associated with higher energy intensity. Energy transition is negatively associated with energy intensity, although its statistical strength differs across estimators. Population density and freshwater withdrawals show model-sensitive effects and should be interpreted cautiously. The negative coefficient of freshwater withdrawals differs from the initial theoretical expectation, suggesting that the water--energy relationship may depend on sectoral productivity, infrastructure quality, and water-use efficiency. The study contributes by integrating energy transition, economic productivity, industrial structure, urban density, and water-resource pressure into a unified APEC-specific framework. The findings support region-specific energy-efficiency strategies aligned with Sustainable Development Goal 7.

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纪录 1 of 1

标题： 能源转型、经济效率与资源利用：APEC经济体能源效率的证据

作者： 刘，ZL（刘，直乐）;陆，SX（陆，世香）;钟，YL（钟，依林）;张，JJ（张，金俊）

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摘要： 尽管在可再生能源部署、工业现代化和区域能源政策合作方面取得了进展，能源效率低下仍是亚太经合组织（APEC）经济体面临的主要挑战。本研究考察了1999年至2023年间21个APEC经济体中能源转型、经济-能源生产率、产业结构、人口密度和淡水取用对能源效率表现的影响。能量效率由能量强度代行，能量强度越低表示效率性能越强。研究采用了主成分分析、横断面依赖性检验、Westerlund面板协整、Driscoll-Kraay固定效应估计以及面板修正标准误。结果显示，单位能源使用GDP始终与较低的能量强度相关，而工业增加值则始终与更高的能量强度相关。能量跃迁与能量强度呈负相关，尽管不同估计量的统计强度有所不同。种群密度和淡水取用量具有模型敏感性影响，应谨慎解读。淡水取用的负系数与最初理论预期不同，表明水与能源的关系可能取决于部门生产力、基础设施质量和用水效率。本研究通过整合能源转型、经济生产力、产业结构、城市密度和水资源压力，形成统一的APEC特定框架。研究结果支持与可持续发展目标7相符的区域特定能源效率策略。

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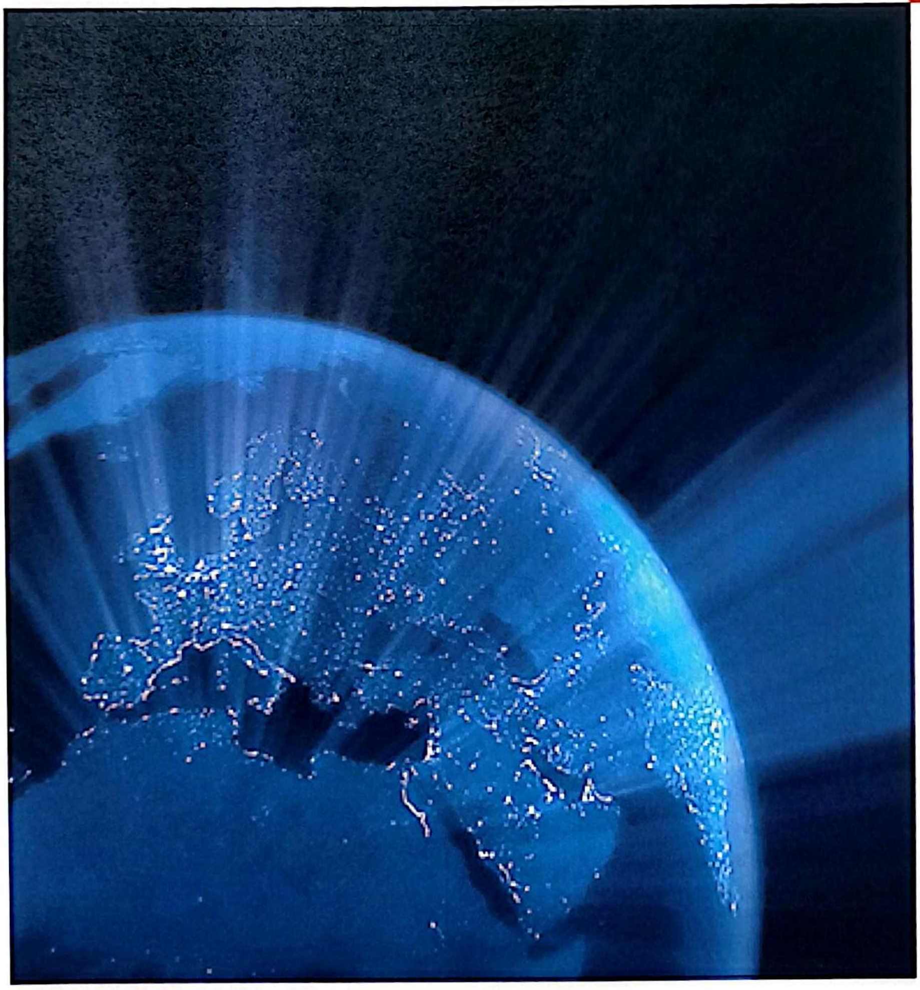

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Energy transition, economic efficiency, and resource use: Evidence on energy efficiency in APEC economies

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ABSTRACT

Energy inefficiency remains a key challenge for Asia-Pacific Economic Cooperation (APEC) economies despite progress in renewable-energy deployment, industrial modernization, and regional energy-policy cooperation. This study examines the effects of energy transition, economic-energy productivity, industrial structure, population density, and freshwater withdrawals on energy-efficiency performance in 21 APEC economies from 1999 to 2023. Energy efficiency is proxied by energy intensity, where lower energy intensity indicates stronger efficiency performance. The study applies principal component analysis, cross-sectional dependence testing, Westerlund panel cointegration, Driscoll–Kraay fixed-effects estimation, and panel-corrected standard errors. The results show that GDP per unit of energy use is consistently associated with lower energy intensity, while industrial value added is consistently associated with higher energy intensity. Energy transition is negatively associated with energy intensity, although its statistical strength differs across estimators. Population density and freshwater withdrawals show model-sensitive effects and should be interpreted cautiously. The negative coefficient of freshwater withdrawals differs from the initial theoretical expectation, suggesting that the water–energy relationship may depend on sectoral productivity, infrastructure quality, and water-use efficiency. The study contributes by integrating energy transition, economic productivity, industrial structure, urban density, and water-resource pressure into a unified APEC-specific framework. The findings support region-specific energy-efficiency strategies aligned with Sustainable Development Goal 7.

1. Introduction

Energy efficiency is a critical pillar of sustainable development, linking economic growth, resource management, and environmental protection. It is commonly measured by energy intensity, which reflects the energy required to produce one unit of economic output. Lower energy intensity indicates higher energy-efficiency performance. Improving energy efficiency reduces greenhouse gas emissions, conserves resources, and strengthens economic competitiveness. Despite rapid deployment of renewable energy technologies, global improvements in energy efficiency remain insufficient to achieve the targets of Sustainable Development Goal 7, underscoring the need for region-specific empirical studies [1] (see Tables 1 and 3, Figs. 1–8).

The Asia-Pacific Economic Cooperation (APEC) region provides a particularly suitable context for studying energy-efficiency performance [9,10]. APEC economies are heterogeneous in industrialization, urbanization, energy structure, and resource use. While service-based economies have advanced renewable systems and efficient infrastructure, emerging and resource-intensive economies continue to rely heavily on fossil fuels and energy-intensive industrial production [11]. Consequently, energy-intensity outcomes in APEC cannot be attributed solely to renewable-energy expansion but also depend on industrial value added, economic-energy productivity, urban density, and freshwater withdrawals [12].

APEC has promoted regional cooperation on energy efficiency, renewable-energy deployment, and energy-intensity reduction through policy dialogue, capacity building, and technology-focused initiatives [13]. These policy efforts interact with structural conditions such as

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industrial composition, urbanization, and resource use. Economies with stronger policy coordination and infrastructure capacity may translate energy transition into lower energy intensity more effectively than economies with energy-intensive industrial structures or weaker institutional capacity [14]. This study therefore examines energy efficiency as the outcome of combined structural, policy, and economic dynamics rather than renewable-energy deployment alone [15,16].

The central debate addressed in this study is whether energy transition alone enhances energy-efficiency performance or whether its effect is moderated by industrial structure, urban density, economic productivity, and water-resource pressure [17]. Renewable-energy expansion may reduce energy intensity through cleaner production, grid modernization, and structural adjustment. At the same time, industrial expansion, inefficient urban growth, and high resource consumption may limit these gains. Understanding the interplay of these structural, economic, and environmental factors is essential for designing effective energy-efficiency policies [18].

Although previous studies have examined energy transition, industrialization, urbanization, economic productivity, and water use as separate determinants of energy performance, the literature provides limited evidence on how these factors jointly shape energy-intensity outcomes in APEC economies [19]. This limitation reflects three major research gaps. First, from a theoretical perspective, existing studies have rarely integrated energy transition, industrial structure, urban density, and water-resource pressure within a unified analytical framework. Second, from an empirical perspective, multi-country and region-specific investigations focusing on APEC economies remain scarce, despite the region's substantial contribution to global energy consumption, industrial output, and climate-policy commitments. Third, from a methodological perspective, many conventional panel-data approaches do not adequately account for cross-sectional dependence, long-run cointegration, heteroskedasticity, autocorrelation, and panel-specific errors, which may lead to biased or inconsistent empirical inferences.

To address these gaps, this study develops an integrated empirical framework that links energy transition (ET), GDP per unit of energy use (GDPE), industrial value added (IND), population density (PD), and annual freshwater withdrawals (ANF) with energy-intensity outcomes across 21 APEC economies over the period 1999–2023. By jointly incorporating these variables, the study conceptualizes energy intensity as a multidimensional outcome influenced not only by the transition toward cleaner energy sources, but also by economic productivity, industrial structural change, urban concentration, and water-resource use. This approach allows for a more comprehensive assessment of the interconnected drivers of energy intensity within economies characterized by diverse development trajectories and policy environments.

The study contributes to the literature in three important ways. First, it advances a comprehensive framework that explains energy-intensity dynamics through the combined effects of renewable-energy transition, economic-energy productivity, industrial structure, population density, and freshwater withdrawals. Second, it provides APEC-specific empirical evidence, thereby addressing the lack of integrated regional analysis for a group of economies with heterogeneous levels of industrialization, urbanization, resource use, and energy-policy commitments. Third, it applies a robust panel econometric strategy, including principal component analysis (PCA), cross-sectional dependence testing, Westerlund cointegration, Driscoll–Kraay estimation, and panel-corrected standard errors (PCSE). These methods enhance the reliability of the findings by accounting for common shocks, long-run relationships, heteroskedasticity, autocorrelation, and panel-specific disturbances.

2. Literature review

The literature on energy efficiency has evolved from single-factor explanations to integrated approaches considering multiple structural, economic, and resource dimensions. Renewable-energy adoption can reduce energy intensity by replacing fossil fuels, improving power-generation efficiency, and promoting cleaner production technologies [20,21]. Recent studies highlight innovations such as nanomaterials for hydrogen production and sustainable energy strategies, emphasizing environmental benefits and cost efficiency (e.g., *Nanomaterials and Hydrogen Production*). However, many studies examine renewable energy in isolation without considering its interaction with urbanization, industrial structure, and water use.

Economic-energy productivity: GDP per unit of energy use reflects the effectiveness of converting energy into economic output [22,23]. Higher productivity generally reduces energy intensity, though the effect depends on the sectoral composition and industrial structure of the economy (see Table 2).

Industrial value added: Industrialization can increase energy intensity, particularly in energy-intensive industries. Cleaner technologies and Industry 4.0 practices may reduce energy use, but empirical evidence is mixed across regions [22,23].

Population density: Dense urban areas can improve energy efficiency via shared infrastructure, district heating, and public transport, while poorly planned growth may increase congestion and energy demand [24,25].

Freshwater withdrawals: Energy is required for water extraction, treatment, and distribution. Excessive use can increase energy intensity, highlighting the need for integrated water-energy planning [26]. Recent advances in smart wastewater management and green innovation (e.g., *Nanobioremediation for Sustainable Wastewater Management*; *Green innovation insights from ISO 14001-certified manufacturers*) provide additional opportunities for reducing energy use in urban and industrial systems.

Energy-efficiency performance is influenced by interactions among

Table 1
Key determinants of energy intensity in APEC economies: Literature gaps and study contributions.

Research stream	Key evidence	Remaining gap	How this study addresses it
Energy transition	Reduces energy intensity via cleaner technologies [2,3]; nanomaterials and hydrogen production offer clean energy solutions	Most studies analyze ET separately, ignoring interactions with structural and resource factors	Tests ET while controlling for GDPE, IND, PD, ANF
Economic-energy productivity	Higher output per energy unit reduces intensity [4,5]	Effects vary by sector and industrialization	Includes GDPE to capture cross-country variation
Industrial value added	Can increase energy intensity unless modernized [6]	Interaction with other factors often untested	Includes IND in joint framework
Population density	Dense areas reduce energy intensity; poor planning increases it [7]	Context-dependent, limited cross-country studies	Includes PD to capture urban structure effects
Freshwater withdrawals	Energy-intensive; excessive use increases energy intensity [8]; nanobioremediation and green technologies can improve efficiency	Often excluded from models	Includes ANF to capture water-energy nexus
APEC-specific	Energy-intensity patterns vary widely	Limited integrated multi-country analysis	Provides panel evidence 1999–2023
Methodology	Cross-sectional dependence, heteroskedasticity, autocorrelation	Conventional panels may bias inference	Applies PCA, CD tests, Westerlund cointegration, Driscoll–Kraay, PCSE

energy transition, economic productivity, industrial structure, urban density, and water-resource use. Few studies have combined all these dimensions in APEC economies [27,28]. This study addresses this gap by providing a robust, region-specific analysis that integrates multiple structural, economic, and environmental determinants, offering insights for energy-policy design and planning.

2.1. Hypothesis

The hypothesis are derived from the two-theory framework. Ecological Modernization Theory supports the expectation that energy transition and economic-energy productivity improve energy-efficiency performance, while industrial value added may either improve or weaken efficiency depending on the degree of industrial modernization [29–31]. Urban Metabolism Theory supports the expectation that population density and freshwater withdrawals influence energy intensity through infrastructure use, transport systems, water-resource flows, and energy demand. Since the dependent variable is energy intensity, lower energy intensity indicates stronger energy-efficiency performance.

H1. Energy transition is significantly associated with lower energy intensity in APEC economies.

H2. GDP per unit of energy use is significantly associated with lower energy intensity in APEC economies.

H3. Population density has a significant, context-dependent association with energy intensity in APEC economies.

H4. Freshwater withdrawals have a significant, context-dependent association with energy intensity in APEC economies.

H5. Industrial value added has a significant, context-dependent association with energy intensity in APEC economies.

3. Research methodology

This study applies a reproducible empirical panel-data methodology to examine the determinants of energy-efficiency performance in APEC economies from 1999 to 2023. Because the analysis is based on macroeconomic and energy data rather than laboratory experiments, reproducibility depends on a transparent description of the sample, data sources, variable construction, data preparation, econometric sequence, statistical tests, robustness checks, and error treatment. The empirical strategy is restricted to the techniques reported in the Results section, including principal component analysis, descriptive statistics, partial and semi-partial correlations, cross-sectional dependence testing, Westerlund panel cointegration, Driscoll–Kraay fixed-effects estimation, and panel-corrected standard errors. This ensures consistency between the stated methodology and the reported empirical evidence.

The final sample includes 21 APEC economies: Australia, Brunei Darussalam, Canada, Chile, China, Hong Kong, Indonesia, Japan, Malaysia, Mexico, New Zealand, Papua New Guinea, Peru, the Philippines, Russia, Singapore, Korea, Chinese Taipei, Thailand, the United States, and Viet Nam. The study period covers 25 annual observations for each economy, resulting in a maximum balanced panel structure of 525 economy-year observations.

The empirical analysis uses internationally comparable annual data from the World Development Indicators and APEC-related energy-statistical sources. The dependent variable is energy efficiency, proxied by energy intensity. Lower energy intensity indicates stronger energy-efficiency performance. The explanatory variables are energy transition, population density, annual freshwater withdrawals, industrial value added, and GDP per unit of energy use. The variables were collected annually, harmonized by economy and year, checked for missing observations, and arranged into a panel dataset. Economy names were standardized before merging. Variables with different scales were transformed consistently before estimation to reduce scale effects and improve comparability across economies.

Energy prices, technological innovation, institutional quality, and environmental regulations are recognized determinants of energy intensity. Their exclusion may create omitted-variable bias if they are correlated with both the included regressors and energy intensity. For example, economies with stronger environmental regulations may also have higher renewable-energy adoption and lower energy intensity, while economies with stronger innovation capacity may simultaneously improve energy productivity and accelerate energy transition. Energy prices may influence both energy demand and investment in energy-saving technologies. Institutional quality may affect policy implementation, infrastructure investment, and industrial upgrading.

These variables were not included in the baseline specification because consistent annual data covering all 21 APEC economies over 1999–2023 are not available. To reduce the risk of omitted-variable bias, the model includes economy-specific effects to control for time-invariant differences across economies and time effects to capture common shocks such as global energy-price movements,

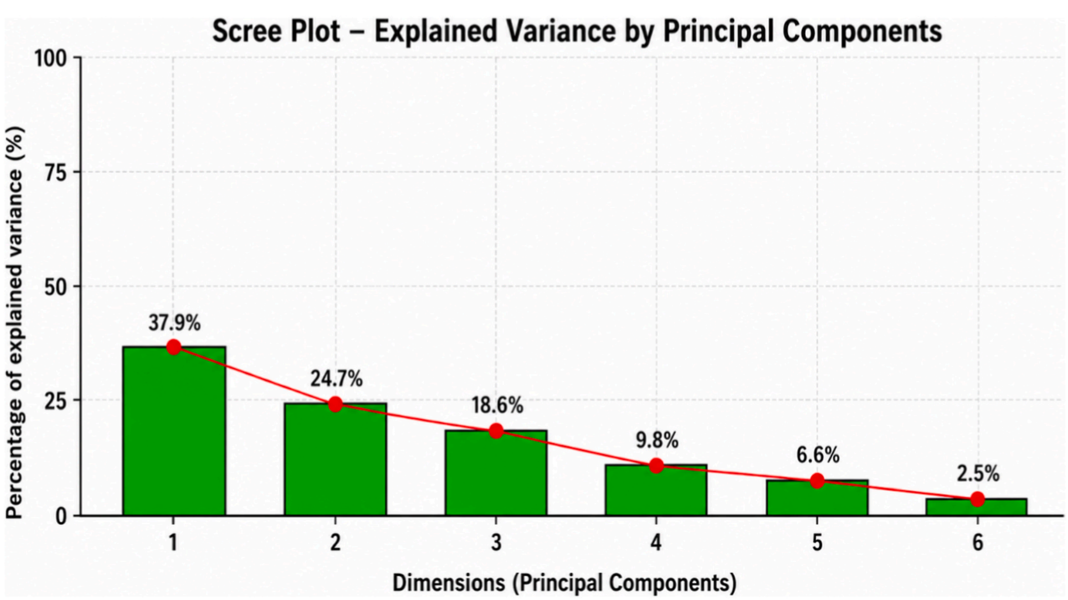

Fig. 1. Scree plot of principal components based on explained variance from PCA.

macroeconomic crises, and regional policy changes. The study also applies Driscoll–Kraay and PCSE estimators to address cross-sectional dependence, heteroskedasticity, autocorrelation, and contemporaneous correlation. Nevertheless, the possibility of omitted-variable bias cannot be completely eliminated, and the results should be interpreted as conditional associations rather than definitive causal estimates.

3.1. Theoretical framework

This study is grounded in two complementary theories: Ecological Modernization Theory and Urban Metabolism Theory. These theories were selected because they directly correspond to the two main dimensions of the study: technological-economic transformation and resource-urban system dynamics. Ecological Modernization Theory explains how cleaner technologies, renewable-energy adoption, industrial upgrading, and efficiency-oriented investment can allow economies to reduce environmental pressure while maintaining economic development. Urban Metabolism Theory explains how economies and cities consume energy, water, materials, and infrastructure services, and how these flows shape resource efficiency and environmental performance.

Other broad perspectives, such as environmental sustainability and energy transition, are not treated as separate theories in this study. Environmental sustainability represents the broader policy objective, while energy transition is treated as an empirical mechanism within Ecological Modernization Theory. This focused theoretical selection avoids conceptual overlap and provides a clearer basis for developing testable hypotheses.

Ecological Modernization Theory supports the inclusion of energy transition, GDP per unit of energy use, and industrial value added. Energy transition reflects the movement from fossil-fuel-dependent systems toward cleaner and renewable-energy systems. Under this theory, renewable-energy adoption and cleaner technologies are expected to reduce energy intensity by improving energy-system performance and reducing dependence on inefficient fossil-fuel use. GDP per unit of energy use represents economic-energy productivity and captures the ability of an economy to produce more output from each unit of energy. Higher economic-energy productivity is expected to reduce energy intensity because it reflects better energy management, technological improvement, and economic decoupling. Industrial value added is also linked to Ecological Modernization Theory because industrial modernization can improve energy performance through cleaner production, digital technologies, and energy-saving equipment. However, industrial expansion can also increase energy intensity when production remains fossil-fuel-based or energy-intensive.

Urban Metabolism Theory supports the inclusion of population density and annual freshwater withdrawals. Population density captures the urban structure of APEC economies and influences energy demand through transport systems, infrastructure networks, building patterns, and service delivery. Compact and well-planned density may reduce energy intensity through shared infrastructure, public transport, shorter travel distances, and efficient energy distribution. Poorly managed density may increase congestion, electricity demand, and pressure on infrastructure. Annual freshwater withdrawals represent resource-use pressure within the water–energy nexus. Water extraction, pumping, treatment, irrigation, industrial cooling, and distribution require energy inputs. Higher freshwater withdrawals may therefore increase energy intensity, especially in economies with water-intensive agriculture, industry, or thermal power generation.

Together, Ecological Modernization Theory and Urban Metabolism Theory provide an integrated explanation of energy-intensity performance in APEC economies. Ecological Modernization Theory explains the technological-economic pathway through which renewable-energy transition, economic-energy productivity, and industrial modernization influence energy intensity. Urban Metabolism Theory explains the resource-urban pathway through which population density and freshwater withdrawals influence energy demand, infrastructure pressure, and resource-use efficiency. The two theories are therefore not treated as separate or competing explanations. Instead, they are integrated into a single empirical framework in which energy intensity is shaped by both technological-economic transformation and resource-urban system dynamics. This integrated framework generates five testable propositions: energy transition and economic-energy productivity are expected to reduce energy intensity; industrial value added may either reduce or increase energy intensity depending on the modernization level of industry; population density may reduce energy intensity when supported by efficient infrastructure but may increase it under poorly planned

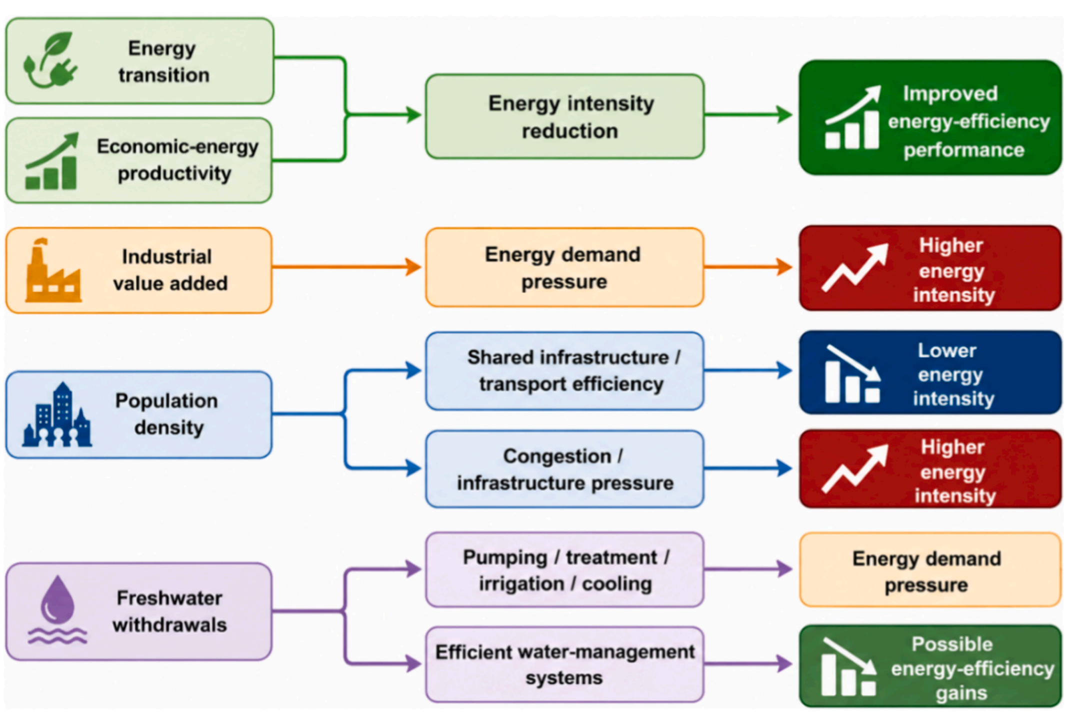

Fig. 2. Proposed mechanism linking structural determinants with energy-efficiency performance in APEC economies.

urbanization; and freshwater withdrawals may affect energy intensity through the water–energy nexus, with the direction depending on water-use efficiency, sectoral productivity, and infrastructure quality.

3.2. Econometric modeling and data

This research uses panel-data econometric techniques to examine the relationship between energy transition, economic productivity, industrial structure, population density, freshwater withdrawals, and energy-efficiency performance in APEC economies. The panel combines cross-sectional variation across 21 economies with annual variation from 1999 to 2023. This structure allows the study to capture both long-term trends and inter-economy differences in energy-efficiency performance.

The dataset was prepared in four stages. In the first stage, annual data for all variables were collected for the 21 APEC economies over 1999–2023. In the second stage, economy names and year identifiers were standardized to ensure correct matching across data sources. In the third stage, the variables were harmonized according to their measurement definitions: energy intensity for energy efficiency, renewable/cleaner-energy transition for ET, population density for PD, annual freshwater withdrawals for ANF, industry's contribution to GDP for IND, and GDP per unit of energy use for GDPE. In the fourth stage, the merged panel was checked for missing values, abnormal entries, and unit inconsistency. The final panel was then used for descriptive statistics, PCA, correlation analysis, cross-sectional dependence testing, Westerlund cointegration analysis, Driscoll–Kraay estimation, and PCSE estimation.

Principal Component Analysis (PCA) is used before regression analysis to assess the underlying structure of the study variables and examine potential multicollinearity, especially among energy transition, population density, industrial activity, freshwater withdrawals, and GDP per unit of energy use. PCA reduces dimensionality by consolidating correlated variables into uncorrelated components while preserving the main variation in the dataset. The variables were standardized before PCA so that differences in measurement scale would not dominate the extracted components. PCA is used as a diagnostic tool only. It does not replace the regression variables but strengthens the empirical analysis by confirming whether the selected variables represent distinct yet related dimensions of energy efficiency. Fresh water withdrawals may increase energy intensity through pumping, treatment, irrigation, cooling, and distribution. However, in economies with efficient water infrastructure or productive water-intensive sectors, higher withdrawals may be associated with lower measured energy intensity. Therefore, the expected effect is theoretically context-dependent.

Energy efficiency is quantified by energy intensity, indicating the energy used to generate economic output. The energy transition variable assesses the movement toward cleaner energy sources by comparing renewable and fossil-fuel energy patterns. Population density indicates urban structure and its influence on infrastructure and energy requirements. Economic-energy productivity is measured by GDP per unit of energy use. Freshwater withdrawals capture environmental and resource-use pressure. Industrial activity is measured by the contribution of industry to GDP. Together, these variables provide a comprehensive framework for assessing energy-efficiency outcomes.

The baseline panel specification is provided as follows:

$$\boldsymbol{EE_{it}} = \boldsymbol{a_0} + \boldsymbol{a_1 ET_{it}} + \boldsymbol{a_2 PD_{it}} + \boldsymbol{a_3 GDPE_{it}} + \boldsymbol{a_4 ANF_{it}} + \boldsymbol{a_5 IND_{it}} + \boldsymbol{u_i} + \boldsymbol{\tau_t} + \boldsymbol{\varepsilon_{it}} \tag{1}$$

where $\boldsymbol{EE_{it}}$ represents energy intensity for economy $\boldsymbol{i}$ at year $\boldsymbol{t}$, $\boldsymbol{ET_{it}}$ represents energy transition, $\boldsymbol{PD_{it}}$ represents population density, $\boldsymbol{GDPE_{it}}$ represents GDP per unit of energy use, $\boldsymbol{ANF_{it}}$ represents annual freshwater withdrawals, and $\boldsymbol{IND_{it}}$ represents industrial value added. The

Fig. 3. Heatmap of energy-efficiency scores across APEC economies.

term u_i captures economy-specific effects, τ_t captures time-specific effects, and ε_{it} is the idiosyncratic error term.

3.2.1. Omitted-variable risk and sensitivity strategy

Potential omitted-variable bias remains a limitation because consistent annual data on energy prices, technological innovation, institutional quality, and environmental regulation were unavailable for all APEC economies throughout the study period. To mitigate this concern, the analysis incorporates economy and time fixed effects together with robust panel estimators. Accordingly, the findings should be interpreted as conditional associations rather than definitive causal relationships.

Since these variables are not consistently available for all APEC economies over the full study period, they are not included in the baseline model. The limitation is addressed by interpreting the coefficients as associations conditional on the included variables and fixed effects. Future research should extend the model by incorporating comparable measures of energy prices, innovation, institutional quality, and environmental regulation when consistent data are available across economies and years. In addition, the inclusion of economy-specific and time fixed effects absorbs a substantial share of cross-economy heterogeneity and common temporal shocks. Consequently, any remaining omitted-variable bias would require omitted factors to be systematically correlated with both the included explanatory variables and the unexplained component of energy intensity. While such bias cannot be completely excluded, the fixed-effects framework reduces its potential influence on the estimated relationships.

Statistical significance is evaluated at the 1%, 5%, and 10% levels. Regression tables report coefficients, robust standard errors, t-statistics, p-values, and confidence intervals where applicable. This reporting structure improves reproducibility and allows readers to assess both statistical significance and estimation uncertainty.

3.3. Cross-sectional dependence

Cross-sectional dependence arises when different units in a panel dataset are affected by common shocks, global trends, regional policy changes, trade linkages, or unobserved shared factors. This issue is highly relevant for APEC economies because they are connected through trade, investment, energy markets, technology diffusion, supply chains, and regional policy cooperation. Ignoring cross-sectional dependence may bias standard errors and weaken statistical inference. The study therefore applies cross-sectional dependence testing before selecting the final estimation strategy.

The general panel structure is expressed as:

$$y_{it} = \alpha_i + \beta x_{it} + u_{it}, i = 1, \ldots, N; t = 1, \ldots, T \tag{2}$$

where y_{it} represents the dependent variable for economy i at time t, x_{it} represents the explanatory variable, α_i represents unit-specific effects, β captures the estimated relationship, and u_{it} is the error term.

The Pesaran cross-sectional dependence statistic is expressed as:

$$CD_\rho = \sqrt{\frac{2}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \sqrt{T_{ij}}\hat{\rho}_{ij} \rightarrow N(0,1) \tag{3}$$

where $\hat{\rho}_{ij}$ denotes the pairwise correlation of residuals between economies i and j, and T_{ij} represents the number of common observations. Rejection of the null hypothesis indicates cross-sectional dependence. If cross-sectional dependence is detected, estimators robust to common shocks and inter-panel correlation, such as Driscoll–Kraay and PCSE, are preferred.

3.4. Pre-estimation diagnostics and cross-sectional dependence

Before estimating the regression models, the study conducts pre-estimation diagnostics to assess the structure and reliability of the panel dataset. These diagnostics include descriptive statistics, partial and semi-partial correlations, PCA, and cross-sectional dependence testing. Cross-sectional dependence is especially important in the APEC context because economies may be affected by common shocks such as global financial crises, energy-market volatility, COVID-19 disruptions, and regional policy coordination. The cross-sectional dependence results guide the choice of Driscoll–Kraay and PCSE estimators, which are robust to heteroscedasticity, autocorrelation, and contemporaneous correlation across panels.

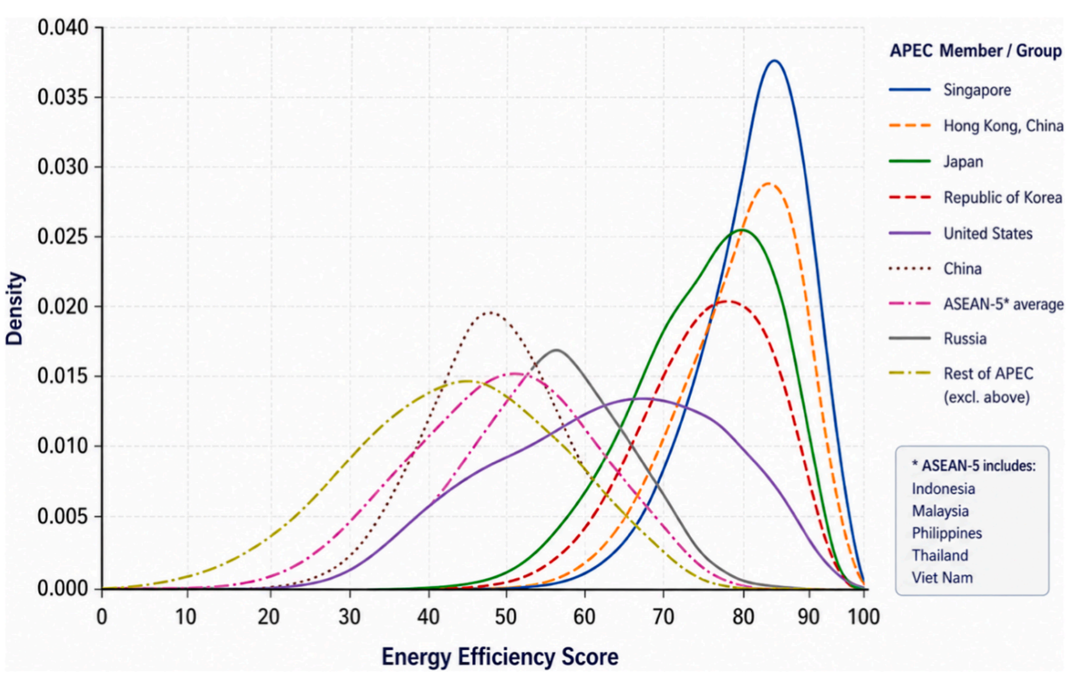

Fig. 4. Density distribution of energy-efficiency performance across selected APEC economies.

3.5. Westerlund panel cointegration

The Westerlund panel cointegration test is applied to examine whether energy intensity, energy transition, economic-energy productivity, population density, freshwater withdrawals, and industrial value added share a stable long-run relationship. The test is suitable for heterogeneous panel datasets because it allows the adjustment process to differ across economies. This is important for APEC economies because their energy systems, industrial structures, resource dependence, urban patterns, and policy capacities vary substantially. The test reports four statistics: Gt, Ga, Pt, and Pa. Rejection of the null hypothesis indicates the presence of cointegration among the study variables.

The error-correction form of the Westerlund test can be written as:

$$\Delta y_{it} = \delta_{1i} + \delta_{2i}t + \alpha_i\left(y_{it-1} - \beta_i' x_{it-1}\right) + \sum_{j=1}^{p_i}\gamma_{ij}\Delta y_{it-j} + \sum_{j=-q_i}^{p_i}\theta_{ij}\Delta x_{it-j} + e_{it} \tag{4}$$

where α_i is the error-correction parameter, y_{it} is the dependent variable, x_{it} is the vector of explanatory variables, p_i and q_i are lag and lead orders, and e_{it} is the error term. A significantly negative error-correction term indicates adjustment toward long-run equilibrium.

The auxiliary regression is expressed as:

$$\widehat{u}_{it} = \sum_{j=-q_i}^{p_i}\gamma_{ij}\Delta x_{it-j} + \widehat{e}_{it} \tag{5}$$

The group-mean statistics are expressed as:

$$G_t = \frac{1}{N}\sum_{i=1}^{N}\frac{\widehat{\alpha}_i}{SE(\widehat{\alpha}_i)} \tag{6}$$

$$G_a = \frac{1}{N}\sum_{i=1}^{N}T\widehat{\alpha}_i \tag{7}$$

where $SE(\widehat{\alpha}_i)$ is the standard error of the estimated error-correction parameter. The Westerlund test reports four statistics: G_t, G_a, P_t, and P_a. Rejection of the null hypothesis indicates cointegration among energy intensity, energy transition, population density, GDP per unit of energy use, freshwater withdrawals, and industrial value added.

3.6. Regression with Driscoll–Kraay standard errors

Panel-data studies involving multiple economies often face cross-sectional dependence, autocorrelation, and heteroscedasticity. These issues may bias conventional standard errors and lead to incorrect statistical inference. The Driscoll–Kraay approach is used because it provides standard errors robust to heteroscedasticity, serial correlation, and cross-sectional dependence. This is suitable for APEC economies because they may be affected by common shocks such as global financial crises, energy-market instability, climate policy changes, and international trade disruptions.

The Driscoll–Kraay variance-covariance estimator is expressed as:

$$\widehat{V}_{DK} = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\widehat{u}_{it}^2 Z_{it}Z_{it}' + \sum_{l=1}^{L}w_l\sum_{i=1}^{N}\sum_{t=l+1}^{T}\widehat{u}_{it}\widehat{u}_{it-l}Z_{it}Z_{it-l}' + h.c. \tag{8}$$

where Z represents the regressors, L is the lag truncation parameter, w_l denotes Bartlett weights, and $h.c.$ denotes the Hermitian conjugate term.

Driscoll–Kraay and PCSE estimators are combined to improve the robustness of the empirical findings. Driscoll–Kraay mainly corrects standard errors and is suitable when the time dimension is sufficiently long. PCSE is applied as a complementary estimator because it directly accounts for panel-specific heteroscedasticity and contemporaneous correlation across panels. Comparing both estimators allows the study to determine whether the direction, magnitude, and significance of the coefficients remain stable under alternative panel-error structures.

The PCSE specification is expressed as:

$$EE_{it} = a + \beta_1 ET_{it} + \beta_2 PD_{it} + \beta_3 GDPE_{it} + \beta_4 ANF_{it} + \beta_5 IND_{it} + \varepsilon_{it}, \varepsilon_{it} \sim N(0, \Sigma) \tag{9}$$

where Σ represents the non-diagonal variance-covariance matrix that allows contemporaneous correlation and panel-specific error variance.

3.7. Robustness checks

The robustness of the empirical results is assessed through the consistency of the two reported estimators: Driscoll–Kraay fixed-effects estimation and panel-corrected standard errors. Driscoll–Kraay standard errors correct for heteroskedasticity, autocorrelation, and cross-sectional dependence, while PCSE accounts for panel-specific heteroskedasticity and contemporaneous correlation. The comparison of

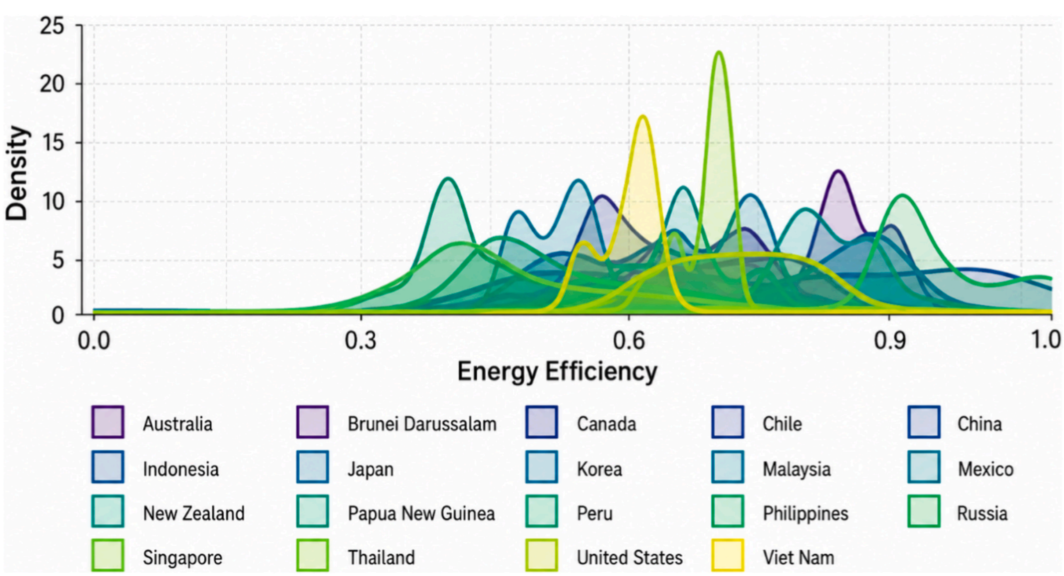

Fig. 5. Density distribution of energy-efficiency performance across APEC economies.

coefficient signs, statistical significance, and economic interpretation across these two estimators allows the study to evaluate whether the main relationships remain stable under alternative panel-error structures (see Table 4).

4. Results and discussion

4.1. Principal component analysis and descriptive statistics

Table 5 reports the principal component analysis results. PCA was applied as a diagnostic procedure to examine the underlying structure of the selected variables and to determine whether they represent distinct but related dimensions of energy-intensity performance. The results show that the first three components explain 81.17% of the total variance. The first component accounts for 37.89%, the second for 24.71%, and the third for 18.57%. The remaining components explain smaller proportions of variance, with Comp4, Comp5, and Comp6 accounting for 9.80%, 6.62%, and 2.48%, respectively. This pattern indicates that most of the information in the dataset is captured by the first three components.

The component loadings suggest that the variables reflect different structural dimensions. Energy intensity loads negatively on the first component, while population density and annual freshwater withdrawals load positively, indicating that urban-resource characteristics are an important source of variation across APEC economies. Energy transition and GDP per unit of energy use load more strongly on the second component, reflecting the role of cleaner-energy transition and economic-energy productivity. Industrial value added loads strongly on the third component, suggesting that industrial structure represents a separate dimension of variation. These results support the inclusion of the selected variables in the regression framework; however, PCA is used only as a diagnostic tool and should not be interpreted as causal evidence.

The scree plot should display the following explained variance values: PC1 = 37.89%, PC2 = 24.71%, PC3 = 18.57%, PC4 = 9.80%, PC5 = 6.62%, and PC6 = 2.48%. The figure shows a clear decline in explained variance after the third component, supporting the interpretation that the first three components capture the dominant structure of variation in the dataset.

Table 6 reports the descriptive statistics for the main variables. The results show substantial variation across APEC economies and over time. Energy intensity has a mean value of 0.6730, with a higher between-economy standard deviation than within-economy variation. This suggests that long-term structural differences across APEC economies are more important than short-term annual changes in explaining energy-intensity performance.

Energy transition also shows considerable dispersion, indicating that APEC economies differ in their progress toward cleaner energy systems. Population density varies widely across economies, reflecting differences in geography, urbanization, and demographic concentration. Freshwater withdrawals show large variation, which may reflect differences in climate conditions, agricultural systems, industrial water demand, and water-resource governance. Industrial value added is comparatively more stable, but cross-economy differences remain important because industrial structure influences energy demand. GDP per unit of energy use also varies across the sample, indicating differences in economic-energy productivity and the ability of economies to generate output from energy inputs.

4.2. Partial correlations and cross-sectional dependence

Table 7 reports the partial and semi-partial correlations. Since EE is measured through energy intensity, negative associations with EE indicate lower energy intensity and stronger energy-efficiency performance, while positive associations indicate higher energy-intensity pressure. The partial correlations provide a more complex picture than the regression results alone and therefore help avoid overgeneralized interpretation.

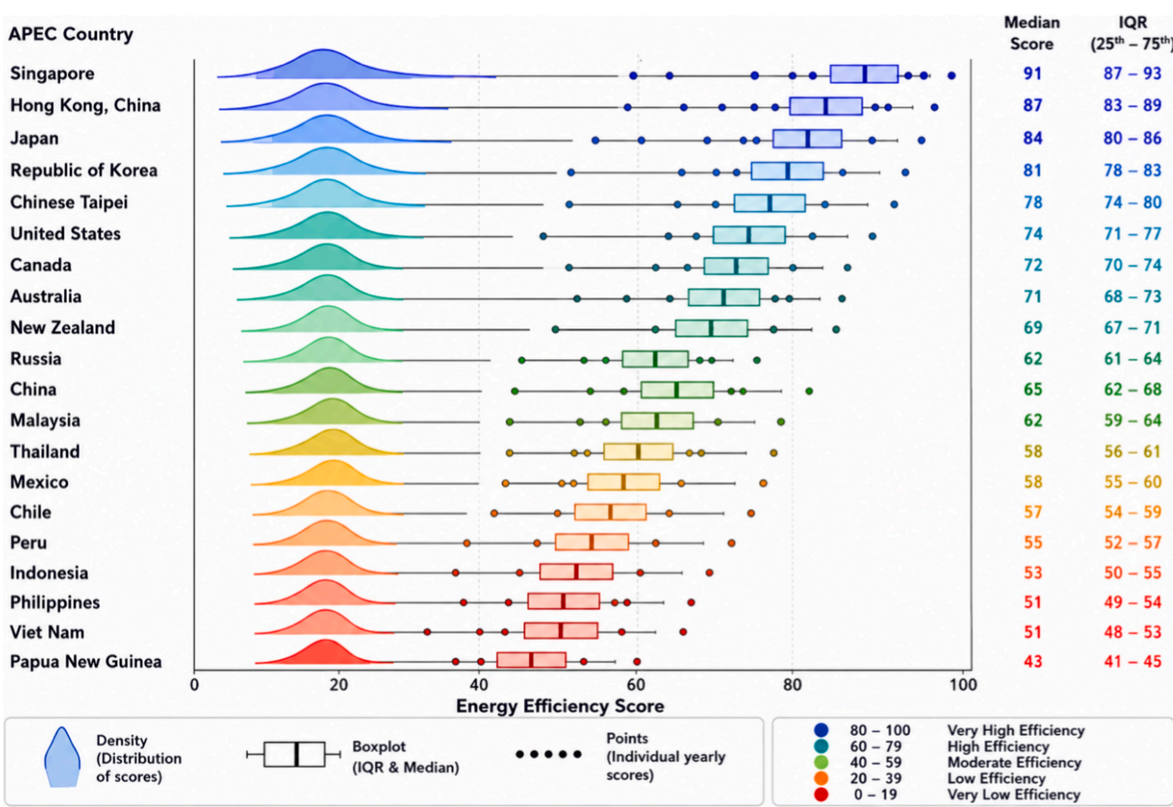

Fig. 6. Raincloud plot of energy-efficiency distribution across APEC economies.

GDP per unit of energy use shows the strongest negative partial correlation with energy intensity (partial correlation = −0.4777, $p < 0.01$). This is consistent with the regression results and indicates that higher economic-energy productivity is associated with lower energy intensity. Industrial value added shows a positive partial correlation with energy intensity (partial correlation = 0.1819, $p < 0.01$), supporting the interpretation that industrial expansion is associated with higher energy-intensity pressure.

Energy transition has a negative partial correlation with energy intensity (partial correlation = −0.1164, $p < 0.05$), but the magnitude is relatively small. This suggests that the relationship between energy transition and energy intensity exists but may be weaker than the relationship between economic-energy productivity and energy intensity. Population density has a negative but statistically insignificant partial correlation (partial correlation = −0.0341, $p = 0.4610$), indicating that its effect is not robust in the correlation analysis. This supports a cautious interpretation of the later regression results, where population density is significant only in the PCSE model.

Annual freshwater withdrawals show a negative and statistically significant partial correlation with energy intensity (partial correlation = −0.2228, $p < 0.01$). This differs from the initial expectation that higher freshwater withdrawals may increase energy intensity through pumping, treatment, irrigation, cooling, and distribution. The result should therefore be interpreted cautiously. It may reflect differences in water-use efficiency, sectoral productivity, infrastructure quality, irrigation systems, industrial water recycling, or resource-management capacity across APEC economies rather than a simple direct effect of freshwater withdrawals on energy efficiency.

Table 8 reports the cross-sectional dependence results. Several variables reject the null hypothesis of cross-sectional independence, indicating that APEC economies are affected by shared shocks and regional linkages. Energy intensity, population density, industrial value added, and GDP per unit of energy use show statistically significant cross-sectional dependence. This suggests that common factors such as global economic cycles, technology diffusion, energy-market volatility, trade integration, and regional policy coordination may influence multiple APEC economies at the same time.

Energy transition and annual freshwater withdrawals do not show statistically significant cross-sectional dependence. This suggests that these variables may be more strongly shaped by country-specific factors, including domestic energy policy, resource endowments, climate conditions, water infrastructure, and national resource-management systems. The presence of cross-sectional dependence in several key variables supports the use of Driscoll–Kraay and PCSE estimators, which are better suited for panel data affected by heteroskedasticity, autocorrelation, and contemporaneous correlation across economies.

4.3. Westerlund panel cointegration

Table 9 reports the Westerlund cointegration results. The Gt, Pt, and Pa statistics reject the null hypothesis of no cointegration, suggesting the presence of a long-run relationship among energy intensity, energy transition, economic-energy productivity, industrial value added, population density, and freshwater withdrawals. However, the Ga statistic is not statistically significant. This indicates that the evidence of cointegration is strong at the panel level but not uniform across all economies. This mixed result is important because APEC economies differ substantially in development stage, industrial structure, resource dependence, urbanization, policy capacity, and energy-transition maturity. Therefore, the Westerlund results should be interpreted as evidence of a long-run panel relationship, while acknowledging heterogeneity across individual economies.

4.4. Driscoll–Kraay and PCSE regression results

Before interpreting the regression estimates, it is important to clarify the dependent-variable definition. Energy efficiency is proxied by energy intensity. Therefore, a negative coefficient indicates lower energy intensity and stronger energy-efficiency performance, while a positive coefficient indicates higher energy intensity and weaker energy-efficiency performance.

Table 10 reports the Driscoll–Kraay fixed-effects estimates. Energy transition has a negative coefficient ($\beta = -0.0851$), but it is only marginally significant at the 10% level and not significant at the 5% level ($p = 0.063$). This provides weak evidence that cleaner energy transition is associated with lower energy intensity under the Driscoll–Kraay specification. The weaker significance may reflect the conservative nature of Driscoll–Kraay standard errors when correcting for

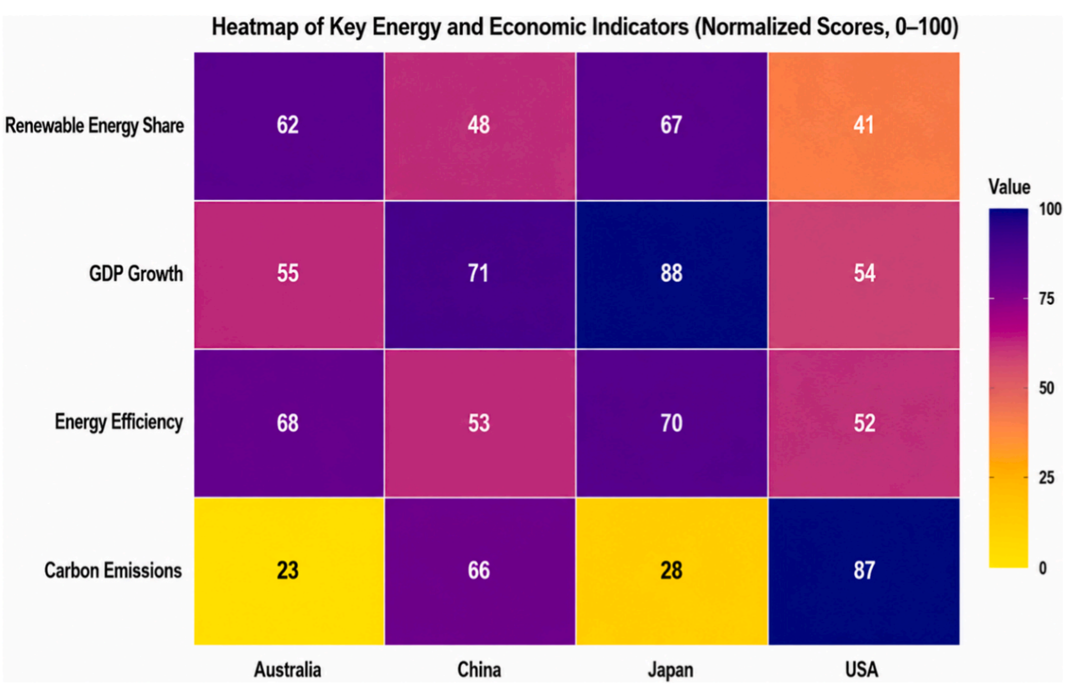

Fig. 7. Heatmap of key energy and economic indicators.

heteroskedasticity, autocorrelation, and cross-sectional dependence.

GDP per unit of energy use has a negative and statistically significant coefficient ($\beta = -0.3694$, $p < 0.01$). This indicates that economies producing more output per unit of energy are associated with lower energy intensity. Industrial value added has a positive and statistically significant coefficient ($\beta = 0.2965$, $p < 0.01$), indicating that industrial expansion is associated with higher energy-intensity pressure. These two variables provide the strongest evidence in the Driscoll–Kraay model.

Population density has a negative but statistically insignificant coefficient ($\beta = -0.0485$, $p = 0.540$), and annual freshwater withdrawals also have a negative but statistically insignificant coefficient ($\beta = -0.0164$, $p = 0.257$). These results do not provide strong evidence that population density or freshwater withdrawals significantly affect energy intensity under the Driscoll–Kraay specification.

Table 11 reports the PCSE estimates. In this specification, energy transition has a negative and statistically significant coefficient ($\beta = -0.0635$, $p < 0.01$), suggesting that cleaner energy transition is associated with lower energy intensity. This result is stronger than the Driscoll–Kraay result, where energy transition is only marginally significant. The difference suggests that the statistical strength of energy transition depends partly on how panel-error structures are treated.

GDP per unit of energy use remains negative and statistically significant ($\beta = -0.3857$, $p < 0.01$), confirming that economic-energy productivity is the most stable negative predictor of energy intensity across the two main estimators. Industrial value added remains positive and statistically significant ($\beta = 0.2134$, $p < 0.01$), confirming that industrial expansion is consistently associated with higher energy intensity.

Population density is negative and statistically significant in the PCSE model ($\beta = -0.0100$, $p = 0.047$). This suggests that compact urban structure may be associated with lower energy intensity, but the result should be interpreted cautiously because population density is statistically insignificant in the Driscoll–Kraay model and in the partial-correlation analysis. Therefore, the population-density result is model-sensitive.

Annual freshwater withdrawals show a negative and statistically significant coefficient in the PCSE model ($\beta = -0.0656$, $p < 0.01$). This sign differs from the initial expectation that higher freshwater withdrawals would increase energy intensity through pumping, treatment, irrigation, cooling, and distribution. Since energy intensity is the dependent variable, the negative coefficient indicates an association with lower energy intensity, not a harmful effect on energy efficiency. This result may reflect differences in water-use efficiency, sectoral productivity, infrastructure quality, irrigation systems, industrial water recycling, or resource-management capacity across APEC economies. Because the Driscoll–Kraay coefficient is statistically insignificant, the freshwater-withdrawal result should be treated as model-sensitive and not interpreted as a direct causal effect.

4.5. Estimator consistency and robustness interpretation

The robustness of the empirical results is assessed through the consistency of the two reported estimators: Driscoll–Kraay fixed-effects estimation and PCSE. This approach is used because both estimators address important panel-data issues, but they treat error structures differently. Driscoll–Kraay standard errors provide correction for heteroskedasticity, autocorrelation, and cross-sectional dependence, while PCSE accounts for panel-specific heteroskedasticity and contemporaneous correlation.

The comparison shows that GDP per unit of energy use and industrial value added are the most robust findings. GDP per unit of energy use is negative and statistically significant in both estimators, while industrial value added is positive and statistically significant in both estimators. Energy transition has a consistent negative sign, but its statistical significance differs across estimators. Population density and freshwater withdrawals are significant only in the PCSE model and insignificant in the Driscoll–Kraay model. Therefore, the strongest conclusions of the study relate to economic-energy productivity and industrial structure, while energy transition, population density, and freshwater withdrawals should be interpreted more cautiously.

Although the estimator comparison supports the robustness of the main findings, omitted-variable bias and reverse causality cannot be completely ruled out. Therefore, the results should be interpreted as conditional associations rather than definitive causal effects.

4.6. Mechanism and comparison with previous literature

The empirical findings suggest that energy-intensity performance in APEC economies is shaped by both robust and model-sensitive determinants. Economic-energy productivity is consistently associated with lower energy intensity, suggesting that economies generating more output from each unit of energy achieve stronger energy-efficiency performance. This effect may reflect technological upgrading, service-sector development, better energy management, efficient infrastructure, and stronger economic decoupling.

Industrial value added is consistently associated with higher energy

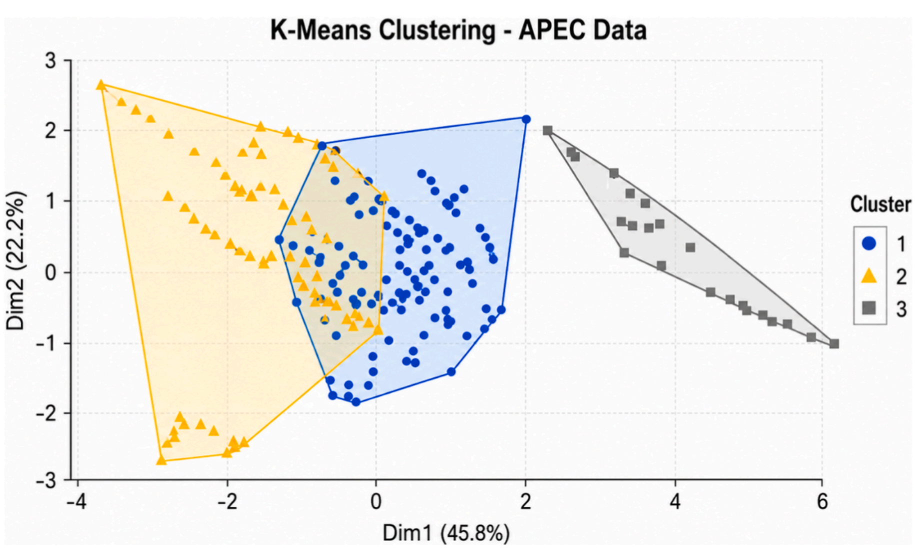

Fig. 8. K-means clustering of APEC economies based on energy and economic characteristics.

Table 2
Integrated theoretical framework and testable propositions.

Theory	Pathway	Variable	Theoretical mechanism	Testable proposition
Ecological Modernization Theory	Technological-economic transformation	Energy transition (ET)	Renewable-energy adoption and cleaner technologies reduce dependence on fossil-fuel systems and improve energy-system performance.	H1: ET is expected to be associated with lower energy intensity.
Ecological Modernization Theory	Technological-economic transformation	GDP per unit of energy use/economic-energy productivity (GDPE)	Higher output per unit of energy reflects better energy management, technological efficiency, and economic decoupling.	H2: GDPE is expected to be associated with lower energy intensity.
Ecological Modernization Theory	Industrial modernization	Industrial value added (IND)	Cleaner production and digital industrial upgrading can reduce energy intensity, while energy-intensive industrial expansion can increase it.	H5: IND is expected to have a significant but directionally context-dependent association with energy intensity.
Urban Metabolism Theory	Urban-resource system dynamics	Population density (PD)	Compact density can reduce energy demand through shared infrastructure and transport efficiency, while unmanaged density can increase congestion and infrastructure pressure.	H3: PD is expected to have a significant but context-dependent association with energy intensity.
Urban Metabolism Theory	Water–energy nexus	Annual freshwater withdrawals (ANF)	Water extraction, pumping, treatment, irrigation, cooling, and distribution require energy inputs, but efficient water systems and productive water-intensive sectors may lower measured energy intensity.	H4: ANF is expected to have a significant but context-dependent association with energy intensity.

Table 3
Expected signs and theoretical justification of variables.

Variable	Measurement/ Proxy	Expected sign	Theoretical justification
Energy transition (ET)	Shift toward renewable/ cleaner energy sources	Negative	Since energy efficiency is proxied by energy intensity, a negative sign indicates that energy transition reduces energy intensity and improves efficiency.
Population density (PD)	Urban population concentration	Ambiguous	Compact density may reduce energy intensity through shared infrastructure, but unmanaged density may increase congestion and energy demand.
Annual freshwater withdrawals (ANF)	Freshwater resource use	Ambiguous	Higher freshwater withdrawals may increase energy demand for pumping, treatment, irrigation, cooling, and distribution, raising energy intensity.
Industrial value added (IND)	Industrial contribution to GDP	Ambiguous	Industrial modernization may improve efficiency, but energy-intensive industry may increase energy intensity.
GDP per unit of energy use/ economic-energy productivity (GDPE)	Economic output generated per unit of energy use	Negative	Higher output per unit of energy implies lower energy intensity and stronger energy-efficiency performance.

Note: The dependent variable is energy intensity; a negative coefficient indicates a reduction in energy intensity and an improvement in energy-efficiency performance.

Table 4
Econometric framework and reported tests.

Empirical step	Method reported	Purpose
Data structure and distribution	Descriptive statistics	Summarizes mean, standard deviation, minimum, maximum, and within/between variation.
Variable structure	Principal component analysis	Examines whether the variables represent distinct but related dimensions of energy-efficiency performance.
Variable association	Partial and semi-partial correlations	Identifies relationships among variables after controlling for other factors.
Cross-sectional dependence	Pesaran CD test	Tests whether APEC economies are affected by common shocks or inter-panel dependence.
Long-run relationship	Westerlund cointegration test	Examines whether the variables share a stable long-run relationship.
Baseline estimation	Driscoll–Kraay fixed-effects regression	Estimates the relationship while correcting for heteroscedasticity, autocorrelation, and cross-sectional dependence.
Alternative estimation	Panel-corrected standard errors	Tests whether the results remain stable under panel-specific heteroscedasticity and contemporaneous correlation.

intensity. This indicates that industrial expansion remains a major efficiency challenge in APEC economies, especially where production depends on fossil fuels, energy-intensive manufacturing, mining, heavy industry, or older industrial technologies. This result supports the view that energy transition alone may not be sufficient to improve energy efficiency unless industrial systems are also modernized through cleaner production, digital monitoring, energy-saving equipment, and circular-economy practices.

Energy transition shows a negative association with energy intensity, but its statistical strength differs across estimators. This suggests that cleaner energy systems may support energy-efficiency improvement, but the measurable effect depends on the structure of the energy system, grid flexibility, renewable-energy integration, storage capacity, electrification, and policy implementation. Population density and freshwater withdrawals represent urban-resource channels. Their model-sensitive results indicate that urban density and water use do not automatically improve or weaken energy efficiency. Their effects depend on infrastructure quality, planning capacity, sectoral productivity, and resource-management systems.

Table 12 compares the present findings with previous literature. The results are broadly consistent with studies showing that renewable-energy adoption and technological upgrading can reduce energy intensity, while industrialization can increase energy intensity when production remains fossil-fuel-based or energy-intensive. The study extends previous evidence by examining these relationships jointly in a heterogeneous APEC panel and by including freshwater withdrawals as part of the water–energy nexus. The comparison also reinforces the need to interpret model-sensitive results carefully rather than presenting all

Table 5
Principal component analysis results.

Category	Item	Eigenvalue	Difference	Explained variance (%)	Cumulative variance (%)	Comp1	Comp2	Comp3	Unexplained
Component Stats	Comp1	2.27274	0.790878	37.89	37.89	—	—	—	—
Component Stats	Comp2	1.48186	0.368480	24.71	62.60	—	—	—	—
Component Stats	Comp3	1.11338	0.525880	18.57	81.17	—	—	—	—
Component Stats	Comp4	0.587486	0.190836	9.80	90.97	—	—	—	—
Component Stats	Comp5	0.396651	0.248724	6.62	97.59	—	—	—	—
Component Stats	Comp6	0.147928	—	2.48	100.00	—	—	—	—
Loadings	Energy efficiency/energy intensity (EE)	—	—	—	—	−0.4766	−0.2518	0.3804	0.2285
Loadings	Energy transition (ET)	—	—	—	—	−0.1565	0.6468	−0.1254	0.3070
Loadings	Population density (PD)	—	—	—	—	0.5803	−0.0244	0.2709	0.1526
Loadings	Annual freshwater withdrawals (ANF)	—	—	—	—	0.5116	−0.4265	−0.0191	0.1353
Loadings	Industrial value added (IND)	—	—	—	—	0.0455	0.2407	0.8728	0.0616
Loadings	GDP per unit of energy use/ economic-energy productivity (GDPE)	—	—	—	—	0.3847	0.5272	−0.0654	0.2475

Table 6
Descriptive statistics of key variables for energy efficiency, economic productivity, and resource use.

Variable	Category	Mean	Std. Dev.	Min	Max
Energy intensity (EE)	Overall	0.6730169	0.1627615	−0.0043648	1.081347
	Between		0.1488975	0.4175108	0.9499941
	Within		0.0737795	0.0965339	0.896127
Efficiency Transition (ET)	Overall	0.283288	0.2657546	0.0030328	1.333423
	Between		0.255327	0.0082883	0.9948387
	Within		0.0934583	−0.1108243	1.011962
Population Density (PD)	Overall	1.808943	0.7766321	0.3889498	3.901234
	Between		0.7959776	0.4625806	3.849034
	Within		0.0407066	1.650461	1.938921
Annual freshwater withdrawals (ANF)	Overall	0.7287902	0.7789256	−1.470023	2.576936
	Between		0.7927241	−1.334864	2.234522
	Within		0.1006577	0.3516221	1.071204
Industrial value added (IND)	Overall	1.514924	0.1239141	1.237234	1.883276
	Between		0.1216181	1.292682	1.82257
	Within		0.0362306	1.351654	1.620588
GDP per unit of energy use /Economic-energy productivity (GDPE)	Overall	0.9568601	0.2075697	0.1552459	1.470794
	Between		0.1815851	0.5883902	1.358443
	Within		0.108543	0.5237158	1.19683

Table 7
Partial and semi-partial correlations.

Variable	Partial Correlation	Semi-Partial Correlation	Partial^2	Semi-Partial^2	p-value
Energy transition (ET)	−0.1164**	−0.0898**	0.0134	0.0079	0.0114
Population density (PD)	−0.0341	−0.0262	0.0011	0.0006	0.4610
Annual freshwater withdrawals (ANF)	−0.2228***	−0.1750***	0.0495	0.0305	0.0000
Industrial value added (IND)	0.1819***	0.1416***	0.0330	0.0200	0.0001
GDP per unit of energy use/ economic-energy productivity (GDPE)	−0.4777***	−0.4162***	0.2280	0.1730	0.0000

Notes: **$p < 0.05$; ***$p < 0.01$.

Table 8
Cross-sectional dependence test.

Variable	CD Value	Probability	Mean Correlation	Absolute Mean Correlation
Energy efficiency (EE)	28.04***	0.000	0.431	0.572
Efficiency Transition (ET)	−1.08	0.275	−0.016	0.523
Population density (PD)	46.56***	0.000	0.714	0.856
Annual freshwater withdrawals (ANF)	−0.08	0.947	−0.003	0.606
Industrial value added (IND)	18.05***	0.000	0.278	0.462
GDP per unit of energy use/ economic-energy productivity (GDPE)	52.63***	0.000	0.807	0.825

variables as equally robust determinants.

Table 9
Westerlund cointegration results.

Test Statistic	Coefficient	Z-Score	p-Value
Gt	−7.846***	−24.187	0.000
Ga	−11.800	−0.042	0.482
Pt	−40.526***	−26.452	0.000
Pa	−34.781***	−14.662	0.000

4.7. Visual evidence on distribution and clustering patterns

The visual results provide descriptive support for the empirical findings and illustrate cross-economy heterogeneity in energy-efficiency performance. These figures should be interpreted as descriptive evidence rather than causal evidence.

The heatmap of energy-efficiency scores shows clear differences across APEC economies. Economies such as Singapore, Hong Kong, Japan, and the Republic of Korea show higher energy-efficiency scores, while several emerging or resource-intensive economies show lower scores. This pattern is consistent with the regression finding that energy-efficiency performance is shaped by structural differences in energy systems, industrial composition, infrastructure, and economic-energy productivity.

The density and raincloud plots further show that energy-efficiency outcomes are unevenly distributed across APEC economies. Some economies have concentrated distributions at higher efficiency levels, while others show wider dispersion. This supports the interpretation that APEC economies do not follow a uniform energy-efficiency pathway and that policy recommendations should account for differences in development stage, industrial structure, infrastructure capacity, and resource-use patterns.

The indicator heatmap provides an additional descriptive comparison of selected energy and economic indicators. It shows that economies may perform differently across renewable-energy share, GDP growth, energy efficiency, and carbon emissions. This supports the argument that energy efficiency should be studied as a multidimensional outcome rather than as the result of renewable-energy transition alone.

The K-means clustering figure groups observations according to similarities in energy and economic characteristics. The clusters suggest that APEC economies differ structurally, with some observations concentrated around higher-efficiency profiles and others reflecting more resource-intensive or transition-stage characteristics. This descriptive clustering supports the broader conclusion that APEC energy-efficiency strategies should be differentiated rather than uniform.

Overall, the visual evidence supports the econometric findings by showing that energy-efficiency performance differs across APEC economies and is linked to structural heterogeneity. However, these figures should not be used as independent proof of causal effects. The main empirical interpretation should rely on the Driscoll–Kraay and PCSE estimates, with PCA, correlations, and figures used as supporting descriptive evidence.

Table 11
Panel-corrected standard error estimates.

Variable	Coefficient	Robust Std. Error	t-Value	p-Value	95% Confidence Interval
Energy transition (ET)	−0.063534	0.0127360	−5.00	0.000	−0.088496
Population density (PD)	−0.010037	0.0050345	−1.98	0.047	−0.019902
Annual freshwater withdrawals (ANF)	−0.065553	0.0057804	−11.35	0.000	−0.076883
Industrial value added (IND)	0.213434	0.0422686	5.04	0.000	0.130588
GDP per unit of energy use/ economic-energy productivity (GDPE)	−0.385670	0.0183769	−21.00	0.000	−0.421688
Constant	0.802640	0.0628542	12.76	0.000	0.679447

5. Conclusion

This study examined the determinants of energy-efficiency performance in 21 APEC economies from 1999 to 2023 using energy intensity as the dependent variable. The analysis integrated energy transition, GDP per unit of energy use, industrial value added, population density, and annual freshwater withdrawals within a unified empirical framework. The study applied PCA, cross-sectional dependence testing, Westerlund cointegration, Driscoll–Kraay fixed-effects estimation, and PCSE estimation.

The strongest findings relate to economic-energy productivity and industrial value added. GDP per unit of energy use is consistently associated with lower energy intensity across both Driscoll–Kraay and PCSE estimations, indicating that economies producing more output from each unit of energy achieve stronger energy-efficiency performance. Industrial value added is consistently associated with higher energy intensity, showing that industrial expansion remains a major source of energy-intensity pressure when production remains energy-intensive.

Energy transition shows a negative association with energy intensity, but its statistical strength differs across estimators. It is marginally significant in the Driscoll–Kraay model and significant in the PCSE model. Therefore, energy transition may support lower energy intensity, but this result should not be overstated as uniformly robust. Population density and freshwater withdrawals are also model-sensitive because they are significant only in the PCSE model. The negative coefficient of freshwater withdrawals differs from the initial theoretical expectation and should be interpreted cautiously. Since the dependent variable is energy intensity, this coefficient indicates lower measured energy intensity rather than a direct efficiency loss.

The scientific value-added of this study lies in showing that energy-efficiency performance in APEC economies is shaped by both robust and

Table 10
Driscoll–Kraay fixed-effects estimates.

Variable	Estimate	Std. Error (DK)	t-value	p-value	Lower 95% CI	Upper 95% CI
Energy transition (ET)	−0.085059*	0.0433712	−1.95	0.063	−0.174573	0.004455
Population density (PD)	−0.048479	0.0781518	−0.63	0.540	−0.209776	0.112818
Annual freshwater withdrawals (ANF)	−0.016404	0.0140951	−1.15	0.257	−0.045492	0.012684
Industrial value added (IND)	0.296535***	0.0679503	4.37	0.000	0.156292	0.436778
GDP per unit of energy use/economic-energy productivity (GDPE)	−0.369400***	0.0613849	−6.03	0.000	−0.496045	−0.242755
Constant	0.700957***	0.1755348	4.00	0.001	0.338668	1.063246

Note: *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively.

Table 12
Comparison of present findings with previous literature.

Theme	Evidence from previous studies	Finding of this study	Scientific contribution
Energy transition	Renewable-energy adoption can reduce energy intensity through cleaner energy systems and technological upgrading [47].	Energy transition reduces energy intensity in APEC economies, especially in the PCSE model.	Confirms that cleaner energy transition improves energy-efficiency performance in a heterogeneous APEC panel.
Economic-energy productivity	Higher GDP per unit of energy use is generally linked with lower energy intensity and stronger decoupling.	GDP per unit of energy use has a strong negative effect on energy intensity.	Shows that productive energy use is one of the strongest channels for efficiency improvement in APEC economies.
Industrial structure	Industrialization can increase energy intensity when production remains fossil-fuel-based or energy-intensive [49].	Industrial value added is associated with higher energy intensity.	Demonstrates that industrial expansion remains a major efficiency challenge in APEC economies.
Population density	Compact urban form can reduce energy use through shared infrastructure, but poor planning can increase congestion and energy demand.	Population density has a negative but model-sensitive effect.	Shows that urban density can support efficiency only when linked with effective planning and infrastructure.
Water–energy nexus	Water extraction, treatment, cooling, irrigation, and distribution require energy inputs [51].	Freshwater withdrawals show a negative coefficient in PCSE but weaker evidence in DK.	Suggests that the water–energy relationship is complex and may depend on water-use efficiency, sectoral structure, and infrastructure quality.
Methodological robustness	Cross-country energy studies may suffer from cross-sectional dependence, heteroskedasticity, and autocorrelation.	Results are compared across Driscoll–Kraay and PCSE estimators,	Strengthens confidence that the main conclusions are not driven by one estimator.

conditional determinants. Economic-energy productivity and industrial structure emerge as the most stable channels, while energy transition, population density, and freshwater withdrawals require more context-specific interpretation. The findings suggest that renewable-energy expansion alone may not guarantee major efficiency gains unless it is supported by productive energy use, cleaner industrial systems, efficient infrastructure, and coordinated water–energy management. The policy relevance of the findings is differentiated rather than generic. Consistent with the objectives of the APEC Energy Working Group, which has promoted regional energy-intensity reduction and energy-efficiency improvement initiatives, APEC economies should prioritize economic-energy productivity through energy-efficiency standards, technological upgrading, digital energy-management systems, and efficient industrial processes. The results suggest that industrial policy should focus on cleaner production methods, energy-efficient machinery, industrial electrification, and low-carbon manufacturing to reduce the energy-intensity pressures associated with industrial expansion. The findings also highlight important differences across APEC economies. For example, Japan has achieved comparatively low energy intensity through advanced manufacturing technologies, strict energy-management practices, and continuous industrial modernization. In contrast, rapidly industrializing economies such as China continue to face greater energy-intensity pressures due to the scale of industrial production, despite substantial investments in renewable-energy deployment and clean-energy infrastructure. These differences suggest that a uniform policy approach may be less effective than strategies tailored to each economy's stage of industrial development, energy structure, and technological capacity. Renewable-energy expansion should therefore be complemented by productive energy use, cleaner industrial systems, efficient infrastructure, and coordinated water-energy management to achieve sustained improvements in energy-efficiency performance across the APEC region.

6. Implications for future research

Future research should include energy prices, technological innovation, institutional quality, and environmental regulation when consistent data are available. These variables may help explain differences in energy-transition performance, industrial energy intensity, and policy effectiveness across APEC economies.

Future studies should also improve the measurement of energy transition by using indicators such as renewable-generation share, installed renewable capacity, grid flexibility, storage capacity, electrification, smart-grid deployment, and energy-management systems. This would provide a more precise assessment of how energy transition affects energy intensity.

Potential reverse causality and endogeneity should be addressed using dynamic panel estimators, instrumental-variable methods, or other verifiable robustness checks. Such methods could help determine whether energy transition and economic-energy productivity reduce energy intensity, or whether more efficient economies are simply better able to invest in cleaner technologies.

Sector-specific analysis is also needed. Future research should examine whether the effect of GDP per unit of energy use is driven by manufacturing modernization, service-sector expansion, transport efficiency, building efficiency, or digital energy management. Similarly, industrial subsector analysis can identify which industries contribute most to energy-intensity pressure.

The model-sensitive effects of population density and freshwater withdrawals require further investigation. Future studies should examine urban transport quality, compact land use, building efficiency, irrigation technology, wastewater reuse, industrial water recycling, desalination, and water-sector electricity consumption. Comparative analysis of advanced, emerging, and resource-intensive APEC economies would also support more targeted policy design.

CRediT author statement

Zhile Liu: Conceptualization, Methodology, Software **Shixiang Lu:** Data curation, Writing- Original draft preparation. **Yilin Zhong:** Visualization, Investigation, Supervision.**:** **Jinjun Zhang:** Software, Validation.**:** **Zhile Liu:** Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Abbreviation

Abbreviation Full Form / Description

ANF: Annual freshwater withdrawals
APEC: Asia-Pacific Economic Cooperation
CD: Cross-sectional dependence
DK: Driscoll–Kraay standard errors
EE: Energy efficiency, measured through energy intensity
ESR: Energy Strategy Reviews
ET: Energy transition
GDPE: GDP per unit of energy use / economic-energy productivity
GDP: Gross domestic product
IND: Industrial value added
PCA: Principal component analysis
PCSE: Panel-corrected standard errors
PD: Population density
SDG 7: Sustainable Development Goal 7: Affordable and clean energy

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作为他的科研指导老师，我对该生的学业和科研情况较为了解。

该生具有较强的创新意识，在参与本人主持的省部级科研项目期间，表现出扎实的科研能力和良好的学术素养。同时，该生还在全国食物经济学术年会上进行了学术汇报，现场交流清晰，获得了与会老师的肯定。

综合来看，该生具备继续深造的学术基础和发展潜力。本人同意推荐刘社乐同学免试攻读硕士学位研究生。

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