

“Digital infrastructure and renewable energy transition: Evidence from ASEAN economies”

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DIGITAL INFRASTRUCTURE AND RENEWABLE ENERGY TRANSITION: EVIDENCE FROM ASEAN ECONOMIES

Abstract

As economies become increasingly interconnected through digitalization while facing growing sustainability challenges, understanding the drivers of export competitiveness has become an important policy and research concern. This issue is particularly relevant in ASEAN, where digital infrastructure and renewable energy transition have progressed unevenly across member states. Despite growing interest in these transformations, their implications for export performance remain insufficiently understood. This study examines the relationships among digital infrastructure, the renewable energy transition, and export performance across eight ASEAN economies from 2010 to 2021. Using World Bank World Development Indicators data, a balanced panel of 96 country-year observations is analyzed through a fixed-effects model. Internet penetration and renewable energy consumption are specified as the main explanatory variables, while manufacturing value added and foreign direct investment are included as control variables. The results indicate that internet penetration, manufacturing value added, and foreign direct investment are positively and significantly associated with export performance, whereas renewable energy consumption exhibits a significant negative relationship. The estimated model explains approximately 63.5% of the within-country variation in export performance. These findings suggest that digital infrastructure, industrial capability, and foreign investment can strengthen export competitiveness. At the same time, the short-run effects of the renewable energy transition may reflect structural adjustment costs during the transformation process. The study contributes new evidence from ASEAN and highlights the importance of combining digital development with industrial upgrading and supportive policy frameworks to enhance long-term export performance.

Keywords

export performance, digital infrastructure, renewable
energy transition, manufacturing capability, ASEAN,
panel data

JEL Classification

F14, O33, Q42, C23

INTRODUCTION

The global economy is currently undergoing two profound and interconnected transformations. The first concerns the rapid diffusion of digital technologies, which has reshaped production systems, communication networks, and cross-border economic activities. The second is the growing transition to renewable energy as governments and businesses respond to environmental challenges, climate commitments, and long-term sustainability objectives. Together, these developments are increasingly influencing the way countries participate in international trade and pursue economic competitiveness in a changing global environment (World Bank, n.d.; UNCTAD, 2023).

Beyond their technological and environmental dimensions, digitalization and renewable energy development have gradually become strategic components of contemporary economic policy. Investments in digital infrastructure can facilitate information exchange, improve connectivity, and support market integration, while renewable energy deploy-

ment is often seen as a key foundation for sustainable growth and industrial modernization. Consequently, many economies have incorporated both digital and green transitions into broader national development agendas to strengthen resilience and competitiveness in the global marketplace (IEA, 2023).

These developments appear particularly relevant in the ASEAN region. Over the past two decades, ASEAN economies have strengthened their integration into global value chains and expanded their role within international production networks. At the same time, the region continues to experience substantial variation in digital readiness, energy structures, institutional capacity, and economic development levels. While some ASEAN countries have achieved relatively advanced digital connectivity and technology adoption, others still face infrastructure gaps and resource constraints. Similar differences can also be observed in the pace and scale of renewable energy transition initiatives across the region (ASEAN Secretariat, 2024).

Against this backdrop, an important scientific question emerges. Although digital transformation and renewable energy development are widely regarded as desirable policy objectives, it remains unclear whether improvements in these areas necessarily translate into stronger export performance. The relationship may be more complex than often assumed. In practice, the benefits associated with digitalization and renewable energy transition may depend on industrial capability, investment conditions, and the ability of firms and economies to adapt to structural change. Consequently, outcomes may vary considerably across countries and stages of development.

The complexity of this issue is particularly evident in emerging economies, where digital expansion and sustainability transition frequently occur alongside broader economic and institutional transformation processes. Under such conditions, technological and environmental initiatives may generate both opportunities and adjustment pressures. While long-term gains are often anticipated, short-term outcomes may vary with local circumstances and implementation capacity. As a result, understanding how these transformations relate to export performance remains an important empirical challenge.

1. LITERATURE REVIEW AND HYPOTHESES

Recent discussions on economic competitiveness increasingly converge around three interconnected themes: digitalization, sustainability transition, and international trade. Rather than operating independently, these processes are becoming progressively intertwined as countries seek to strengthen productivity, resilience, and long-term development capacity in an increasingly complex global environment. Digital technologies reshape the way firms access markets and coordinate production, while renewable energy development is transforming industrial systems and investment priorities. At the same time, export performance remains one of the most visible indicators of international competitiveness. Consequently, understanding how digital and green transformations interact with export outcomes has emerged as an important area of contemporary economic inquiry. Although substantial progress has been made, existing knowledge remains dispersed across dif-

ferent theoretical traditions, empirical settings, and policy perspectives, creating a need for a more integrated understanding of these relationships.

1.1. Digitalization, connectivity, and export competitiveness

The growing diffusion of digital technologies has fundamentally altered the mechanisms through which firms and economies participate in international trade. Advances in information and communication technologies have reduced geographical barriers, accelerated information flows, and improved coordination across increasingly fragmented production networks. From this perspective, digitalization is commonly viewed as an important driver of export competitiveness because it lowers transaction costs, facilitates access to market information, and strengthens cross-border connectivity (Baldwin, 2016; Brynjolfsson & McAfee, 2014; Schwab, 2016).

A substantial body of research further suggests that digital infrastructure contributes to econom-

ic modernization by enhancing communication efficiency, supporting knowledge exchange, and improving firms' ability to engage in international markets. Greater internet penetration and digital connectivity may facilitate participation in global value chains, improve logistics coordination, and reduce informational asymmetries that often constrain export-oriented activities, particularly in developing economies (Saba et al., 2024; Xiaobin et al., 2024). Under this view, digital transformation is expected to strengthen competitiveness by enabling firms to reach foreign customers more effectively and respond more rapidly to changing market conditions.

Nevertheless, the benefits associated with digitalization may not emerge automatically. Economic outcomes of digital transformation depend on a broader set of institutional and organizational conditions. The effectiveness of digital infrastructure appears to be shaped by governance quality, technological readiness, human capital, and the absorptive capacity of firms and economies (Kai et al., 2026; T. Chatterjee & N. Chatterjee, 2026). Where complementary capabilities remain limited, digital expansion may improve communication and consumption without necessarily translating into productivity gains or stronger export performance.

This issue appears particularly relevant in developing and emerging economies, where digital transformation often occurs alongside broader structural and institutional change. Consequently, while digital infrastructure is generally expected to influence export competitiveness, the magnitude and even the direction of this relationship may vary across economic contexts. The literature therefore points to a potentially important but not yet fully understood relationship, particularly in rapidly transforming regional economies such as ASEAN.

1.2. Renewable energy transition and export performance

The growing transition to renewable energy has become a central dimension of contemporary economic transformation. Beyond environmental considerations, renewable energy development is increasingly viewed as a strategic component of

long-term competitiveness because it influences production systems, industrial upgrading, and participation in international markets. As sustainability requirements become more prominent within global trade and investment networks, the relationship between renewable energy transition and export performance has attracted growing scholarly attention.

One stream of literature suggests that renewable energy development can strengthen economic and trade competitiveness. Under this perspective, green transformation improves energy security, supports sustainable production, and facilitates compliance with increasingly stringent environmental standards imposed by international markets. The expansion of renewable energy infrastructure may therefore enhance the attractiveness of export-oriented industries and improve integration into global value chains characterized by rising sustainability expectations (Bhuiyan et al., 2022; Li et al., 2023; Sharif et al., 2026; Zhang et al., 2025). Renewable energy and digital transformation may jointly contribute to broader patterns of sustainable growth and structural modernization, particularly in developing economies seeking to improve their long-term competitive position (Qamruzzaman et al., 2026).

At the same time, a second line of argument emphasizes that the benefits of renewable energy transition may not emerge immediately. The shift from conventional energy systems frequently requires substantial investment, technological adaptation, and industrial restructuring. In many developing economies, these adjustments can generate short-term economic pressures, particularly when infrastructure, financing mechanisms, or technological capabilities remain limited. From this perspective, green transformation may initially increase production costs or create transitional inefficiencies before longer-term gains become visible (Acemoglu et al., 2012; Stern, 2017). Consequently, the short-run effects of renewable energy transition on export competitiveness may differ considerably across countries and stages of development.

These contrasting perspectives suggest that the relationship between renewable energy transition and export performance remains far from

straightforward. While renewable energy development may create opportunities for sustainable competitiveness and market access, its effects are likely to depend on the capacity of economies to absorb adjustment costs and manage broader structural transformations. This issue appears particularly relevant in ASEAN economies, where substantial differences remain in energy structures, technological readiness, and sustainability pathways.

1.3. Manufacturing capability, foreign direct investment, and export performance

Manufacturing capability and foreign direct investment are widely recognized as key determinants of export performance because they enhance production capacity, technological upgrading, and firms' participation in international markets. Industrial capability, productive investment, and technological accumulation are fundamental drivers of long-term competitiveness and economic performance (North, 1990; Barro, 1991; Acemoglu et al., 2014). A stronger manufacturing sector promotes higher value-added production and deeper integration into global value chains, while foreign direct investment supports capital accumulation, technology transfer, and international production networks. Recent evidence further confirms that these structural factors remain important for improving export competitiveness in developing economies (Aly & Zaki, 2025).

One stream of literature emphasizes that manufacturing capability is a fundamental driver of export competitiveness because it strengthens production capacity, technological upgrading, and firms' integration into regional and global value chains. Economies with stronger industrial bases are generally better positioned to generate higher value-added production and sustain long-term productivity growth (Barro, 1991; Acemoglu et al., 2014). Manufacturing development also facilitates knowledge accumulation and skill formation, both of which are essential for enhancing export competitiveness (Hanushek & Woessmann, 2008). Consequently, manufacturing value added is widely employed as an indicator of industrial capability and productive capacity in studies of export performance.

However, the relationship between economic development and export performance may not always be straightforward. Structural transformation often alters the composition of economic activity as economies gradually shift from manufacturing-based production toward services and domestic consumption. Under such circumstances, rising income levels do not necessarily translate into stronger export growth. Rodrik (2016) argues that several developing economies have experienced premature deindustrialization, whereby industrial sectors lose momentum before reaching the productivity levels historically observed in advanced economies. This suggests that the export implications of economic development depend not only on income growth itself but also on the nature of structural change accompanying that growth.

Foreign direct investment (FDI) is another important driver of export performance because it provides access to capital, advanced technologies, managerial expertise, and international business networks, thereby improving productive efficiency and participation in global value chains. Previous studies suggest that FDI promotes technological diffusion and productivity growth when recipient economies possess sufficient absorptive capacity (Borensztein et al., 1998; Chatterjee & Kundu, 2021; Mohanty & Sethi, 2019). Through these channels, foreign investment can support knowledge transfer and industrial upgrading.

However, the export benefits of FDI are not automatic. Their effectiveness depends on complementary institutional and economic conditions, including governance quality, trade integration, supply-chain connectivity, and domestic capabilities (Aly & Zaki, 2025; Ando et al., 2024). Where these conditions remain weak, spillover effects may be limited, reducing the contribution of FDI to export competitiveness. Consequently, investment conditions are expected to influence export performance, although their effects are likely to vary across ASEAN economies.

Institutional economics and international trade perspectives further suggest that the export effects of digital infrastructure and renewable energy transition operate through different channels. While digital infrastructure may facilitate firms'

integration into international markets, the contribution of the renewable energy transition likely depends on structural adjustment and complementary industrial capabilities. This theoretical perspective provides the basis for identifying the remaining research gaps.

1.4. Research gaps

Despite the growing literature on digitalization, renewable energy transition, and international trade, several important gaps remain unresolved.

First, prior studies have often examined digital transformation and sustainability transition separately rather than as interconnected structural processes influencing export competitiveness simultaneously. Existing findings therefore remain fragmented across theoretical and regional contexts.

Second, the empirical evidence regarding digital infrastructure and export performance remains inconsistent. While many studies report positive effects of ICT expansion on trade integration and productivity, other studies suggest that the benefits of digitalization depend heavily on institutional quality, industrial capability, and absorptive capacity.

Third, although the renewable energy transition is commonly associated with sustainable development, limited attention has been given to its short-run adjustment costs within developing and export-dependent economies. Existing research rarely investigates whether the green transition may temporarily constrain export performance during early stages of structural restructuring.

Finally, ASEAN economies remain relatively underexplored despite their growing importance in global production networks and regional trade integration. Differences in institutional capacity, digital readiness, and energy transition pathways across ASEAN countries provide an important context for further investigation.

Therefore, this study addresses these gaps by examining the relationships among digital infrastructure, renewable energy transition, and export performance in selected ASEAN economies using a panel-data approach.

1.5. Research aim and hypotheses

Against the backdrop of accelerating digitalization and growing commitments to sustainable energy development, this study explores whether improvements in digital infrastructure and the transition toward renewable energy are associated with export performance across selected ASEAN economies between 2010 and 2021. Particular attention is also given to manufacturing capability and foreign direct investment, which are included as control variables to capture industrial capacity and investment conditions.

Based on the theoretical arguments and empirical evidence reviewed above, the following hypotheses are proposed:

H1: Digital infrastructure is positively associated with export performance.

H2: Renewable energy transition is significantly associated with export performance.

2. METHODS

2.1. Research design and data source

This study employs a quantitative panel-data design to examine the relationship between digital infrastructure, renewable energy transition, and export performance across ASEAN economies. Compared with cross-sectional analysis, panel data capture both cross-country heterogeneity and changes over time, making them well suited to analyzing export performance in a region characterized by diverse levels of digital development and economic transformation.

The empirical analysis uses secondary data from the World Bank's World Development Indicators (WDI). The sample consists of eight ASEAN economies: Brunei Darussalam, Cambodia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam, selected because they provide broad variation in economic development and export structures while ensuring complete data availability. Singapore was retained as a major export-oriented economy within ASEAN, while the fixed-effects estimator controlled for country-specific

Table 1. Variable description and measurement

Source: Our compilation based on World Bank World Development Indicators (WDI).

Variable	Symbol	World Bank indicator code	Role
Export performance	exports	NE.EXP.GNFS.KD	Dependent variable
Digital infrastructure	internet	IT.NET.USER.ZS	Main independent variable
Renewable energy transition	renewable	EG.FEC.RNEW.ZS	Main independent variable
Manufacturing value added (% of GDP)	manufacturing	NV.IND.MANF.ZS	Control variable
Foreign direct investment	fdi	BX.KLT.DINV.WD.GD.ZS	Control variable

structural differences. Because of data availability for the renewable energy indicator, the analysis covers 2010–2021, resulting in a balanced panel of 96 country-year observations. Restricting the sample to this period ensures consistent measurement across all variables without requiring data imputation or interpolation.

Table 1 presents the variables used in the empirical analysis together with their corresponding World Bank indicator codes. Export performance is measured by the real value of exports of goods and services. Digital infrastructure, proxied by the share of individuals using the Internet, and renewable energy transition constitute the principal explanatory variables. Manufacturing value added and foreign direct investment are included as control variables because both reflect industrial capacity and international capital inflows that may systematically influence export competitiveness. The selected indicators have been widely adopted in studies examining digitalization, industrial development, sustainable transition, and international trade. Table 1 presents the variables used in the study.

2.2. Model specification

To examine the effects of digital infrastructure and renewable energy transition on export performance, the study estimates the following panel regression model:

$$\begin{aligned} Exports_{it} = & \beta_0 + \beta_1 Internet_{it} \\ & + \beta_2 Renewable_{it} + \beta_3 Manufacturing_{it} \\ & + \beta_4 FDI_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \end{aligned} \quad (1)$$

where $Exports_{it}$ represents the real value of exports of goods and services for country i in year t ; $Internet_{it}$ denotes the proportion of individuals using the Internet, serving as a proxy for digital infrastructure; $Renewable_{it}$ refers to renewable en-

ergy consumption measured as a percentage of total final energy; $Manufacturing_{it}$ represents manufacturing value added as a percentage of GDP ; FDI_{it} denotes foreign direct investment net inflows measured as a percentage of GDP; μ_i captures unobserved country-specific effects that remain constant over time; λ_t denotes year-specific effects common to all countries; ε_{it} is the error term.

To obtain reliable estimates, the empirical analysis initially considers pooled ordinary least squares (OLS), fixed-effects (FE), and random-effects (RE) estimators. The Hausman specification test (Hausman, 1978) is then used to determine whether the fixed-effects or random-effects specification better represents the data. This sequential estimation strategy allows the model to account for unobserved heterogeneity while maintaining consistency in parameter estimation.

2.3. Analytical procedures

The empirical analysis was performed using *R* (version 4.5.1). Data processing and panel-data estimation were conducted using several widely adopted *R* packages, including *dplyr*, *tidyr*, *plm*, *lme4*, *sandwich*, and *car*.

The analytical procedure consisted of several stages. First, we cleaned the dataset, reorganized it into panel format, and checked for missing observations and data consistency. Descriptive statistics were then calculated to summarize the characteristics of each variable, followed by Pearson correlation analysis to examine pairwise associations and identify potential multicollinearity. Variance inflation factors (VIFs) were further computed to confirm that collinearity among the explanatory variables remained within acceptable limits.

Subsequently, pooled OLS, fixed-effects, and random-effects models were estimated and compared.

The Hausman specification test was employed to select the most appropriate panel-data estimator. To improve the reliability of statistical inference, we reported heteroskedasticity-consistent robust standard errors for the final regression model, reducing the potential influence of heteroskedasticity and within-panel serial correlation on the estimated coefficients.

3. RESULTS

3.1. Descriptive statistics

Table 2 reports the descriptive statistics for the variables included in the empirical analysis. The balanced panel dataset consists of 96 country-year observations, covering eight ASEAN economies over the period 2010–2021. Overall, the descriptive results indicate considerable variation across countries, suggesting notable differences in export performance, digital development, industrial structure, renewable energy utilization, and foreign investment within the region. Such diversity is expected because ASEAN economies remain heterogeneous in terms of economic structure and development trajectories.

Table 2. Descriptive statistics

Source: Our calculation based on World Bank data.

Variable	N	Mean	SD	Min	Max
ln_exports	96	25.3	1.44	22.6	27.3
Internet	96	53.8	26.3	1.26	97.6
Renewable	96	21.7	19.1	0	65
Manufacturing	96	19.6	7.02	1.14	30.9
FDI	96	6.26	7.16	-1.32	32.3

The logarithm of export value (ln_exports) records an average of 25.30, with values ranging from 22.60 to 27.30. Although the dispersion is relatively modest compared with the original export values, the observed range still reflects meaningful differences in export capacity among ASEAN economies. The logarithmic transformation was adopted to reduce skewness and improve the statistical properties of the regression model.

Digital infrastructure, measured by the percentage of individuals using the Internet, varies substantially across the sample. The average Internet penetration reaches 53.80%, while the minimum

and maximum values range from 1.26% to 97.60%. This broad distribution suggests that ASEAN countries have progressed at markedly different speeds in digital infrastructure development, with some economies approaching universal Internet access whereas others remain at earlier stages of digital transformation.

Renewable energy accounts for an average of 21.70% of total final energy consumption, although considerable cross-country differences are evident. The standard deviation of 19.10 and the wide range between 0% and 65% imply that the transition toward renewable energy has followed distinct national pathways, reflecting differences in resource endowments, energy policies, and stages of economic development.

Manufacturing value added represents, on average, 19.60% of GDP across the observed economies. Compared with the other explanatory variables, manufacturing displays a relatively lower level of dispersion, indicating that industrial activity constitutes a relatively stable component of economic structure within the sample despite differences in industrial specialization.

Foreign direct investment (FDI) averages 6.26% of GDP, with values ranging from -1.32% to 32.30%. The negative minimum indicates that several country-year observations experienced net capital outflows or disinvestment, whereas the upper end of the distribution reflects periods of exceptionally strong foreign investment inflows. Overall, the descriptive statistics reveal substantial structural heterogeneity across ASEAN economies, providing empirical support for employing panel-data techniques that explicitly account for country-specific characteristics in the subsequent analysis.

3.2. Correlation matrix

Table 3 reports the Pearson correlation coefficients among the variables employed in the empirical analysis. The estimated coefficients provide an initial overview of the linear relationships among export performance, digital infrastructure, renewable energy transition, manufacturing activity, and foreign direct investment across the sampled ASEAN economies. Overall, the observed correlations are generally moderate, suggesting that the

Table 3. Correlation matrix of variables

Source: Our calculation based on World Bank data.

Variables	ln_exports	Internet	Renewable	Manufacturing	FDI
ln_exports	1				
Internet	0.162	1			
Renewable	-0.304	-0.756	1		
Manufacturing	0.617	-0.339	0.43	1	
FDI	0.27	0.313	-0.175	0.02	1

explanatory variables capture related but distinct dimensions of economic development.

The results indicate that manufacturing value added exhibits the strongest positive association with export performance ($r = 0.617$). This pattern is broadly consistent with the export-oriented production structure of many ASEAN economies, where manufacturing activities continue to play a central role in generating merchandise exports. By comparison, the positive correlations between Internet penetration ($r = 0.162$) and FDI ($r = 0.270$) with export performance are relatively modest, implying that improvements in digital connectivity and foreign investment alone may not immediately translate into stronger export outcomes without complementary production capabilities.

Renewable energy consumption displays a moderate negative correlation with export performance ($r = -0.304$). Although the coefficient should not be interpreted as evidence of causality, it may reflect differences in national development priorities or the transitional nature of green transformation across ASEAN countries. In some economies, expanding renewable energy adoption could coincide with structural adjustments that influence export performance during the observation period.

Among the explanatory variables, the highest absolute correlation is observed between Internet penetration and renewable energy consumption ($r = -0.756$). While this relationship is comparatively strong, it remains below the commonly cited threshold of 0.80, suggesting that serious multicollinearity is unlikely to arise based solely on pairwise correlations. The remaining coefficients are generally low to moderate. For example, the correlation between manufacturing and FDI is close to zero ($r = 0.020$), indicating that these variables capture different aspects of economic activity within the sample.

Overall, the correlation matrix provides preliminary evidence that the explanatory variables are sufficiently distinct for subsequent econometric analysis. Nevertheless, pairwise correlations alone cannot determine whether multicollinearity is problematic in a regression setting. Consequently, variance inflation factor (VIF) diagnostics are performed before estimating the panel regression models to verify that multicollinearity does not materially affect the empirical results.

3.3. Multicollinearity diagnostics

Before estimating the panel regression models, multicollinearity among the explanatory variables was assessed using the Variance Inflation Factor (VIF). Examining VIF values prior to model estimation is a common diagnostic procedure because high collinearity may inflate standard errors and reduce the reliability of coefficient estimates.

Table 4. Variance Inflation Factor (VIF)

Source: Our calculations based on World Development Indicators (WDI).

Variable	VIF
Internet	2.545
Renewable	2.548
Manufacturing	1.245
FDI	1.136

As shown in Table 4, the VIF values range from 1.136 to 2.548, remaining well below the commonly accepted thresholds of 5 and 10 reported in the econometric literature. These results suggest that multicollinearity is unlikely to bias the estimated coefficients or substantially inflate their standard errors.

Among the explanatory variables, Internet penetration and renewable energy consumption record the highest VIF values. This outcome is consistent with the relatively strong negative correlation identified above. Nevertheless, the corresponding VIF statistics remain comfortably within ac-

ceptable limits, indicating that the two variables provide complementary rather than overlapping information in explaining export performance. Meanwhile, manufacturing value added and foreign direct investment exhibit considerably lower VIF values, implying minimal collinearity with the remaining regressors.

Taken together, the diagnostic results indicate that the explanatory variables satisfy the multicollinearity assumption. Accordingly, all variables are retained in the subsequent panel regression analysis.

3.4. Fixed-effects regression results

Table 5 presents the estimation results obtained from the fixed-effects panel regression model. Overall, the model is statistically significant ($F = 36.478$, $p < 0.001$) and explains approximately 63.5% of the within-country variation in export performance ($R^2 = 0.635$). These statistics suggest that the selected explanatory variables jointly provide substantial explanatory power for differences in export performance across the sampled ASEAN economies over the study period.

Table 5. Fixed effects regression results

Source: Our estimation based on World Bank World Development Indicators (WDI).

Variables	Coefficient	Robust SE	t-value	p-value
Internet	0.0035**	0.0011	3.259	0.0016
Renewable	-0.0299***	0.005	-5.941	< 0.001
Manufacturing	0.0240**	0.0091	2.638	0.0099
FDI	0.0172*	0.0078	2.205	0.0302
Statistic		Value		
R^2		0.635		
Adjusted R^2		0.587		
F-statistic		36.478		
Observations		96		
Countries		8		
Years		12		

Note: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

The empirical findings (Table 6) indicate that Internet penetration is positively and significantly associated with export performance ($\beta = 0.0035$, $p = 0.0016$). Holding other factors constant, im-

provements in digital connectivity appear to enhance export performance among ASEAN economies. This result is consistent with the argument that digital infrastructure facilitates information exchange, reduces transaction costs, and strengthens firms' participation in international markets.

In contrast, renewable energy consumption exhibits a statistically significant negative coefficient ($\beta = -0.0299$, $p < 0.001$). Although this finding should not be interpreted as a causal trade-off between sustainability and exports, it may suggest that economies undergoing energy transition face adjustment costs or structural changes that temporarily constrain export performance. The result therefore reflects the complexity of balancing environmental objectives with trade competitiveness during the transition period.

The coefficient of manufacturing value added is positive and statistically significant ($\beta = 0.0240$, $p = 0.0099$), indicating that a stronger manufacturing base contributes positively to export performance. This finding highlights the continuing importance of industrial production as a foundation for export expansion within ASEAN economies.

Similarly, foreign direct investment exerts a positive and statistically significant effect on export performance ($\beta = 0.0172$, $p = 0.0302$). This evidence suggests that inward FDI may promote exports by improving production efficiency, facilitating technology transfer, and integrating domestic firms into global value chains.

Taken together, the fixed-effects estimates reveal that digital infrastructure, manufacturing capability, and foreign direct investment are positively associated with export performance. In contrast, the renewable energy transition is negatively related to exports during the observed period. Overall, the findings support the proposition that export competitiveness in ASEAN is shaped by the interaction between digital development, industrial capacity, international investment, and the ongoing transformation of national energy systems.

Table 6. Summary of hypothesis testing

Hypothesis	Proposed relationship	Empirical result	Decision
H1	Digital infrastructure → Export performance	Positive and significant	Supported
H2	Renewable energy transition → Export performance	Negative and significant	Supported

3.5. Hausman test

To determine the appropriate panel-data estimator, the Hausman specification test (Table 7) was performed to compare the fixed-effects and random-effects models. The null hypothesis states that the random-effects estimator is consistent, whereas the alternative hypothesis indicates that the fixed-effects estimator is preferred due to correlation between the individual effects and the explanatory variables (Hausman, 1978).

Table 7. Hausman test results

Test	Chi-square	df	p-value	Decision
Hausman test	41.814	4	<0.001	Fixed effects preferred

The Hausman test produces a chi-square statistic of 41.814 with a p-value below 0.001, leading to the rejection of the null hypothesis. This finding indicates that the unobserved country-specific effects are correlated with the explanatory variables, violating the assumptions underlying the random-effects estimator. Consequently, the fixed-effects specification is considered more appropriate for the present analysis and is retained as the final model for hypothesis testing. The result also strengthens the reliability of the estimated coefficients by accounting for time-invariant heterogeneity across ASEAN economies.

3.6. Model diagnostic tests

Before interpreting the regression coefficients, several diagnostic tests were conducted to evaluate the suitability of the empirical model. Specifically, the Hausman specification test was employed to determine the appropriate panel estimator, while the variance inflation factor (VIF), the Breusch–Pagan test, and the Wooldridge test were performed to assess multicollinearity, heteroskedasticity, and serial correlation, respectively. Table 7 reports the results.

Table 8. Model diagnostic tests

Test	Statistic	p-value	Decision
Hausman test	$\chi^2 = 41.814$	< 0.001	Fixed-effects preferred
Variance Inflation Factor	Max VIF = 2.548	–	No multicollinearity
Breusch–Pagan test	BP = 5.767	0.217	Homoskedasticity not rejected
Wooldridge test	F = 139.72	<0.001	Serial correlation detected
Estimation method	Cluster-robust FE	–	Robust SE reported

The Hausman test rejects the null hypothesis ($\chi^2 = 41.814$, $p < 0.001$), indicating that the fixed-effects estimator is more appropriate than the random-effects alternative because unobserved country-specific effects are correlated with the explanatory variables (Table 8). The VIF values remain well below the commonly accepted threshold, suggesting that multicollinearity is not a concern. Likewise, the Breusch–Pagan test provides no evidence of heteroskedasticity ($p = 0.217$). However, the Wooldridge test indicates first-order serial correlation in the panel data ($p < 0.001$). To obtain statistically reliable inference under these conditions, the final model is estimated using fixed effects with cluster-robust standard errors. Overall, these diagnostic results support the robustness and appropriateness of the empirical specification adopted in this study.

4. DISCUSSION

The empirical findings provide further evidence that digital infrastructure, renewable energy transition, industrial capability, and foreign direct investment are associated with export performance in ASEAN economies. However, the direction and magnitude of these relationships differ. Overall, the results indicate that export competitiveness depends not only on digital and environmental transformation but also on countries' ability to translate these structural changes into productive and trade-oriented outcomes.

Internet penetration exerts a positive and statistically significant effect on export performance. This finding is consistent with Kai et al. (2026), who reported that digitalization facilitates global value chain upgrading in ASEAN economies, and T. Chatterjee and N. Chatterjee (2025), who highlighted the contribution of digitalization and skills to long-run economic development. Greater internet access may reduce information costs, fa-

cilitate digital trade, and strengthen firms' participation in international markets. However, these benefits are unlikely to be fully realized without industrial upgrading, technological capability, and supportive institutions. This interpretation is consistent with Acemoglu et al. (2014) and Liu and Marcus (2026), who argued that digital technologies improve productivity only when supported by strong institutions, human capital, and effective governance.

Renewable energy transition, by contrast, is negatively associated with export performance. Although renewable energy is widely recognized as a cornerstone of sustainable development, the transition process may impose substantial short-term adjustment costs on export-oriented economies. This finding broadly agrees with Sharif et al. (2026), who reported that the economic effects of renewable energy vary across development contexts. It does not, however, contradict the long-term benefits identified by Zhang et al. (2025), as the negative coefficient is likely to capture transitional costs rather than the long-run contribution of green investment. As noted by Qamruzzaman et al. (2026), the effectiveness of renewable energy policies depends on institutional quality, technological capability, financial capacity, and policy coordination.

Manufacturing value added is positively associated with export performance, suggesting that industrial capability remains a key driver of export competitiveness in ASEAN economies. A stronger manufacturing base expands production capacity, facilitates participation in regional and global value chains, and enables firms to utilize digital technologies more effectively. Likewise, foreign direct

investment exerts a positive and statistically significant effect, implying that external capital supports technology transfer, production upgrading, and international market integration. This finding is broadly consistent with Xiaobin et al. (2024), who argued that digitalization, industrial development, and international trade jointly reinforce sustainable economic performance.

Taken together, the findings indicate that digital transformation and green transition should not be viewed as isolated policy initiatives. Their contribution to export competitiveness depends on complementary investments in manufacturing capability, technological upgrading, institutional quality, and policy coordination. While digital infrastructure, industrial development, and foreign investment strengthen export performance, the benefits of the renewable energy transition may emerge more gradually in developing economies because of adjustment costs during the transition process.

From a policy perspective, ASEAN economies should adopt a more integrated approach to export development. Investments in digital infrastructure should be complemented by manufacturing upgrading, logistics modernization, workforce development, and innovation policies. Likewise, the renewable energy transition should be implemented in ways that reduce short-term adjustment costs while strengthening firms' long-term competitiveness in increasingly sustainability-oriented global markets. Overall, the findings suggest that digital and green transitions generate stronger export outcomes when embedded within broader strategies that enhance productive capacity and institutional support.

CONCLUSION

This study examined how digital infrastructure and renewable energy transition influence export performance across eight ASEAN economies during 2010–2021 using a fixed-effects panel-data model. The study included manufacturing value added and foreign direct investment as control variables to account for differences in industrial capacity and external capital inflows.

The empirical findings indicate that Internet penetration, manufacturing value added, and foreign direct investment are positively associated with export performance. In contrast, renewable energy transition exhibits a significant negative relationship during the study period. These results suggest that digital connectivity, industrial development, and foreign investment can strengthen export competitiveness,

while the short-run effects of renewable energy transition may be constrained by adjustment costs and structural challenges in developing economies.

This study contributes to the literature by providing updated evidence on the interaction between digital transformation, green transition, and export performance in ASEAN, a regional context that remains comparatively underexplored. The findings further suggest that digital and environmental policies are unlikely to generate sustained export gains in isolation. Their effectiveness depends on complementary investments in industrial capability, institutional support, and technological upgrading that enable economies to transform structural change into international competitiveness.

From a policy perspective, ASEAN governments should pursue integrated strategies that combine digital infrastructure investment with manufacturing upgrading, innovation support, and workforce development. At the same time, renewable energy policies should be accompanied by measures that reduce transition costs and strengthen firms' capacity to adapt to increasingly sustainability-oriented global markets.

This study is subject to several limitations. The analysis focuses on eight ASEAN economies and relies on aggregate macroeconomic indicators, which may not fully capture cross-country institutional differences or sector-specific export dynamics. Future research could incorporate institutional quality, digital governance, environmental policy indicators, or firm- and industry-level data to provide a more comprehensive understanding of how digital and green transitions shape export performance across different development contexts.

AUTHOR CONTRIBUTIONS

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DECLARATION OF GENERATIVE AI IN THE WRITING PROCESS

During the preparation of this manuscript, the author used Grammarly solely for language editing, grammar checking, spelling correction, and improving the clarity and readability of the manuscript. The tool was not used to generate research content, collect or analyze data, interpret findings, or formulate scientific conclusions. All intellectual content, analyses, interpretations, and conclusions were produced, reviewed, and approved by the author, who takes full responsibility for the accuracy, integrity, and originality of the manuscript.

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