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ENERGY VULNERABILITY, DIGITAL TRANSFORMATION AND SUSTAINABLE ECONOMIC DEVELOPMENT IN ASIA AND THE PACIFIC: THE MODERATING ROLE OF GREEN TECHNOLOGICAL INNOVATION AND INSTITUTIONAL QUALITY

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Abstract
This study examines the relationship between energy vulnerability, digital transformation, and sustainable economic development in Asia and the Pacific, with particular attention to the moderating roles of green technological innovation and institutional quality. Using illustrative panel data and country and year fixed-effects models, the study finds that energy vulnerability has a significant negative effect on sustainable economic development, while digital transformation has a significant positive effect. The results further indicate that green technological innovation weakens the adverse effect of energy vulnerability and strengthens the sustainability benefits of digital transformation. Institutional quality also mitigates the negative effect of energy vulnerability and enhances the contribution of digital transformation to sustainable development.The findings suggest that energy diversification, digital transformation, green technological innovation, and stronger institutions are complementary pathways for promoting sustainable economic development in the Asia-Pacific region. The study highlights the importance of combining energy-transition policies with digital and technological innovation and effective institutional governance.

1: INTRODUCTION

1.1 Background

Asia and the Pacific is experiencing a simultaneous transformation of its energy systems, digital economy, production structures, and institutional environment. The region has become an important center of global economic activity, technological innovation, manufacturing, trade, and investment. At the same time, many economies remain exposed to energy-import dependence, fossil-fuel reliance, energy-price volatility, energy-intensity pressures, infrastructure constraints, and unequal access to reliable energy. These challenges create an important development question because economic growth increasingly depends on secure, affordable, and sustainable energy systems.

Energy vulnerability can constrain sustainable economic development through several channels. High dependence on imported fossil fuels can expose economies to international price shocks and supply disruptions. Energy-intensive production can increase production costs and environmental pressures, while limited diversification of energy supply can increase

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macroeconomic instability. Energy insecurity can also reduce the capacity of governments and firms to invest in productive, social, and environmental priorities. ADB's recent assessment of developing Asia and the Pacific emphasizes that energy-transition readiness depends on the capacity to create energy systems that are secure, sustainable, and equitable.

At the same time, digital transformation is changing how economies produce, consume, trade, communicate, and deliver public services. Digital infrastructure, internet connectivity, mobile technologies, digital finance, cloud computing, artificial intelligence, Internet of Things applications, and digital platforms can improve productivity, information access, resource allocation, financial inclusion, and public-sector efficiency. ADB identifies digital transformation as an important mechanism for advancing inclusive and sustainable development in Asia and the Pacific, while also emphasizing that digital divides and poorly managed digitalization can create new economic and environmental challenges.

Digital technologies may contribute to sustainable economic development through improved resource efficiency, smart energy systems, digital financial services, precision agriculture, intelligent transportation, environmental monitoring, and improved disaster-risk management. However, digital transformation itself can increase electricity demand, electronic waste, infrastructure requirements, and energy consumption. Consequently, the effect of digital transformation on sustainable development may depend on the availability of green technologies and the quality of institutions.

Green technological innovation represents a potentially important mechanism through which economies can simultaneously address energy vulnerability and improve sustainable development. Green innovation includes renewable-energy technologies, energy-efficient technologies, environmental patents, clean production processes, low-carbon technologies, and resource-saving innovations. Endogenous growth theory suggests that technological progress and knowledge accumulation can generate persistent improvements in productivity, while environmentally oriented innovation can redirect technological progress toward cleaner and more sustainable production.

Institutional quality provides another important enabling condition. Effective governments, appropriate regulatory systems, rule of law, control of corruption, political stability, and accountability can influence whether energy, digital, and green technologies are efficiently adopted. Strong institutions may improve investment conditions, strengthen environmental regulation, reduce policy uncertainty, and facilitate the implementation of digital and clean-energy strategies.

Recent ADB research similarly emphasizes that digital technologies can improve resource management, monitoring, productivity, climate resilience, and access to services, but that policy and institutional conditions determine whether these benefits translate into inclusive and sustainable development.

1.2 Research Problem

Despite substantial economic and technological progress, countries in Asia and the Pacific differ considerably in their exposure to energy vulnerability, their level of digital transformation, their capacity for green technological innovation, and the quality of their institutions. These differences mean that the same energy shock or digital transformation process may produce different development outcomes across countries.

Existing studies frequently examine energy vulnerability, digitalization, technological innovation, environmental sustainability, or institutional quality separately. However, sustainable economic development increasingly depends on the interaction among these dimensions. Energy vulnerability may constrain development, while digital transformation may create new opportunities for productivity and inclusion. Green technological innovation can potentially reduce the negative effects associated with energy vulnerability and improve the sustainability of digitalization. Institutional quality can further determine whether these

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technological opportunities are converted into productive and sustainable economic outcomes. The central problem addressed by this research is therefore the absence of an integrated empirical framework explaining how energy vulnerability and digital transformation jointly influence sustainable economic development and how green technological innovation and institutional quality condition these relationships in Asia and the Pacific.

1.3 Research Questions

The study addresses the following two research questions:

Q1: What are the effects of **energy vulnerability and digital transformation** on sustainable economic development in Asia and the Pacific, and to what extent do **green technological innovation and institutional quality** influence these relationships?

Q2: How do **green technological innovation and institutional quality jointly moderate** the relationship between energy vulnerability, digital transformation, and sustainable economic development in Asia and the Pacific?

1.4 Research Objectives

1. **To examine the effects of energy vulnerability and digital transformation on sustainable economic development, and to assess the moderating roles of green technological innovation and institutional quality in these relationships.**
2. **To investigate the joint moderating effects of green technological innovation and institutional quality and develop policy implications for resilient, inclusive, digitally enabled, and environmentally sustainable development in Asia and the Pacific.**

1.5 Contributions of the Study

The study is expected to make four contributions.

Theoretical contribution: It integrates sustainable development theory, endogenous growth theory, institutional theory, and the technology–environment nexus into a unified analytical framework.

Empirical contribution: It provides country-level panel evidence for Asia and the Pacific by simultaneously considering energy vulnerability and digital transformation.

Methodological contribution: It constructs multidimensional indices for sustainable economic development, energy vulnerability, digital transformation, green technological innovation, and institutional quality and applies interaction-based panel econometric models.

Policy contribution: It can provide evidence relevant to energy diversification, renewable-energy investment, digital infrastructure, green innovation, institutional reform, and regional cooperation.

2: Literature Review

2.1 Energy Vulnerability and Economic Development

Energy is a fundamental input into production, transportation, communication, trade, and household welfare. Consequently, energy insecurity can influence economic development through production costs, investment decisions, fiscal pressures, external balances, and environmental outcomes.

Energy vulnerability is broader than simple energy dependence. It incorporates exposure to external energy shocks, fossil-fuel dependence, energy intensity, supply concentration, price volatility, insufficient diversification, and energy-access constraints. An economy that relies heavily on imported fossil fuels may be particularly vulnerable to international price fluctuations and geopolitical disruptions.

The literature on energy security suggests that diversification and renewable-energy development can reduce exposure to external shocks. However, the relationship between energy security and sustainable development is complex because rapid economic growth may initially increase energy demand. Sustainable development therefore requires the transition from energy-intensive and fossil-fuel-dependent development toward diversified, efficient, and cleaner energy systems.

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For Asia and the Pacific, this issue is particularly important because the region contains both advanced and developing economies with substantially different energy structures. ADB's Energy Transition Readiness Assessment specifically emphasizes secure, sustainable, and equitable energy systems as central to the region's transition.

2.2 Digital Transformation and Sustainable Development

Digital transformation can affect sustainable development through productivity, innovation, financial inclusion, information access, public-service delivery, and resource efficiency.

Digital technologies can reduce transaction costs and improve access to markets. Digital financial services can expand financial inclusion, while digital platforms can connect small firms and households to markets and services. Digital monitoring can improve environmental regulation and resource management. Smart grids, digital energy-management systems, precision agriculture, intelligent transportation, and remote sensing can increase efficiency.

However, digital transformation may also generate environmental pressures through increased electricity demand, data-center energy consumption, electronic waste, and expansion of ICT infrastructure. Therefore, digital transformation should not automatically be interpreted as environmentally beneficial. Its contribution to sustainable development depends partly on whether digital growth is accompanied by clean energy, green innovation, appropriate regulation, and adequate institutional capacity.

ADB's recent work describes digital technologies as potentially supporting productivity, resource efficiency, climate resilience, environmental monitoring, and sustainable development, while also highlighting digital divides and sustainability risks.

2.3 Green Technological Innovation

Green technological innovation refers to technological improvements designed to reduce environmental damage while improving productivity and resource efficiency. It encompasses renewable-energy technologies, energy-efficient production, pollution-control technologies, environmental patents, clean transportation, circular production systems, and other environmentally oriented innovations.

The theoretical foundation can be traced to endogenous growth theory, particularly the role of knowledge accumulation and technological progress in generating long-run productivity improvements. Romer (1990) emphasizes knowledge and technological change as endogenous sources of growth. In environmental economics, Acemoglu et al. (2012) demonstrate how directed technological change can influence the transition toward cleaner technologies.

Green technological innovation may influence sustainable development directly by increasing resource efficiency and reducing environmental pressures. More importantly for this study, it may moderate the effects of energy vulnerability and digital transformation.

For example, when an economy experiences energy vulnerability, green technological innovation can facilitate renewable-energy substitution, energy efficiency, storage technologies, and cleaner production. Similarly, when digital transformation increases energy demand, green technologies may reduce the environmental cost of digital infrastructure.

2.4 Institutional Quality

Institutional quality refers to the effectiveness and reliability of formal governance arrangements that shape economic behavior and public policy. Key dimensions include government effectiveness, regulatory quality, rule of law, control of corruption, political stability, and voice and accountability.

Institutions can affect sustainable development through investment protection, regulatory enforcement, public-sector effectiveness, environmental governance, and technology adoption. Weak institutions may reduce the effectiveness of energy policies, environmental regulation, and innovation incentives. Stronger institutions may improve coordination among governments, firms, financial institutions, and research organizations.

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Institutional quality may therefore function as a moderator rather than merely a direct determinant. When institutions are stronger, countries may be better positioned to manage energy risks, implement digital policies, protect innovation investment, enforce environmental standards, and coordinate long-term sustainability strategies.

2.5 Energy–Digital Nexus

The energy–digital nexus represents the interaction between digital transformation and energy systems. Digital technologies require energy, but they can also improve the efficiency and reliability of energy systems.

Digitalization can support smart grids, demand management, renewable-energy forecasting, electricity-market management, energy monitoring, and industrial efficiency. Conversely, increasing digitalization can generate additional electricity demand through data centers, networks, cloud computing, and connected devices.

This creates a two-sided relationship. Digitalization can improve energy efficiency while simultaneously increasing energy demand. Green technological innovation can potentially shift this balance toward greater sustainability.

2.6 Hypotheses

Based on the theoretical framework and existing literature, the study proposes three overarching hypotheses that capture the **direct effects of energy vulnerability and digital transformation and the combined moderating role of green technological innovation and institutional quality** in shaping sustainable economic development in Asia and the Pacific.

H_1: Energy vulnerability has a **negative effect** on sustainable economic development.

H_2: Digital transformation has a **positive effect** on sustainable economic development.

H_3: Green technological innovation and institutional quality **positively moderate** the effects of energy vulnerability and digital transformation on sustainable economic development, such that higher levels of green technological innovation and stronger institutional quality reduce the adverse effects associated with energy vulnerability and strengthen the contribution of digital transformation to sustainable economic development.

2.7 Research Gap

First, much of the existing energy literature focuses on energy security, energy consumption, renewable energy, or energy dependence rather than treating energy vulnerability as a multidimensional development constraint.Second, the digitalization literature increasingly examines digital transformation and economic growth, but relatively fewer studies integrate digital transformation into an energy-vulnerability framework for sustainable economic development.Third, green technological innovation is often examined as a direct determinant of environmental performance rather than as a moderator that can alter the relationship between energy vulnerability, digital transformation, and development.Fourth, institutional quality is commonly incorporated as a control variable or independent determinant rather than being modeled explicitly as a moderating mechanism.Accordingly, this study develops an integrated **energy–digital–green technology–institutional framework** for Asia and the Pacific.

3. Research Methodology

3.1 Study Area and Sample

This study focuses on **countries in Asia and the Pacific**, a region characterized by considerable differences in economic development, energy structures, digital infrastructure, technological capabilities, institutional quality, and environmental conditions. This regional setting provides an appropriate context for examining how energy vulnerability and digital transformation influence sustainable economic development and how green technological innovation and institutional quality may condition these relationships. The sample will include countries for which sufficiently consistent and comparable data are available for the dependent, explanatory, moderating, and control variables. Therefore, the final sample

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will primarily depend on **data availability and comparability**. Where data are missing for particular countries or years, the study may employ an **unbalanced panel**. This approach allows the analysis to capture both differences across countries and changes within countries over time.

3.2 Data Sources

The study will use **secondary panel data** collected from internationally recognized and reliable databases. Data for sustainable economic development, energy vulnerability, digital transformation, green technological innovation, institutional quality, and control variables will be compiled from sources such as the **Asian Development Bank (ADB), ADB Institute (ADBI), World Bank, International Energy Agency (IEA), International Renewable Energy Agency (IRENA), International Telecommunication Union (ITU), World Intellectual Property Organization (WIPO), Worldwide Governance Indicators (WGI), OECD**, and relevant national statistical agencies, subject to data availability. Institutional quality will be measured using the six WGI dimensions: Government Effectiveness, Regulatory Quality, Rule of Law, Control of Corruption, Political Stability, and Voice and Accountability. The study will use available country-year observations and may therefore result in an unbalanced panel. Composite indicators will be constructed from normalized underlying variables using **Principal Component Analysis (PCA)**, while equal-weighted indices will be used as an alternative measure for robustness.

The main variables include **SED** as the dependent variable; **EV and DT** as the principal explanatory variables; **GTI and IQ** as moderating variables; and GDP per capita, trade openness, FDI, urbanization, industrialization, human capital, and renewable-energy consumption as control variables. SED is constructed as a multidimensional index covering economic, social, and environmental dimensions, while EV combines indicators such as energy dependence, import exposure, energy intensity, price exposure, diversification, electricity access, and renewable-energy availability.

3.3 Analytical Design

The study adopts a **quantitative, longitudinal, and non-experimental panel research design**. The panel structure combines observations across countries and over time, allowing the analysis to control for both country-specific characteristics and common year-specific shocks. The empirical strategy first examines the direct effects of **energy vulnerability and digital transformation on sustainable economic development** and then evaluates the moderating roles of green technological innovation and institutional quality through interaction terms.

The main empirical framework is a **country and year two-way fixed-effects model**:

$$SED_{it}=\beta_0+\beta_1 EV_{it}+\beta_2 DT_{it}+\beta_3 GTI_{it}+\beta_4 IQ_{it}+\beta_5(DT_{it}\times GTI_{it})+\beta_6(DT_{it}\times IQ_{it})+\gamma' X_{it}+\mu_i+\lambda_t+\varepsilon_{it}$$

Where:

SED_{it} represents sustainable economic development in country i and year t; EVit denotes energy vulnerability; DT_{it} represents digital transformation; GTI_{it} captures green technological innovation; IQ_{it} represents institutional quality; $DT_{it}\times GTIi_t$ is the interaction between digital transformation and green technological innovation; DTit×IQit captures the moderating role of institutional quality; X_{it} is a vector of control variables; μ_i represents country fixed effects; λ_t represents year fixed effects; and ε_{it} is the idiosyncratic error term.

The principal expected relationships are:$\beta 1<0$, $\beta 2>0$,$\beta 5>0$ and $\beta 6>0$

Thus, the integrated model simultaneously evaluates whether **energy vulnerability constrains sustainable economic development**, whether **digital transformation contributes to sustainable development**, and whether **green technological innovation and institutional quality strengthen the contribution of digital transformation to sustainable economic development**. The inclusion of country and year fixed effects controls for unobserved time-invariant country characteristics and common time-specific shocks, respectively. This integrated specification provides a unified empirical

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framework for testing the proposed direct and moderating relationships rather than estimating separate baseline equations.

3.4 Statistical Analysis

The statistical analysis will proceed in several stages. First, **descriptive statistics** will be used to summarize the mean, standard deviation, minimum, and maximum values of all variables. Second, a **Pearson correlation matrix** will be employed to examine the direction and strength of bivariate relationships and to identify potential multicollinearity. Third, pooled OLS, fixed-effects, and random-effects models will initially be estimated, with the **Hausman test** used to guide the choice between fixed and random effects. The preferred specification will use country and year fixed effects, with robust or clustered standard errors; where appropriate, Driscoll–Kraay standard errors will be considered to address cross-sectional dependence and serial correlation.

For interaction models, continuous variables will be centered or standardized before constructing interaction terms to reduce non-essential multicollinearity and facilitate interpretation. The analysis will also conduct **robustness and endogeneity tests**, including lagged explanatory variables, alternative measures of key variables, alternative index-construction methods, additional controls, subsample analysis, dynamic panel specifications, and System-GMM where appropriate. Panel unit-root tests such as LLC, IPS, and Fisher-type tests may be applied, while Pedroni, Kao, or Westerlund panel cointegration tests may be considered where appropriate. **Variance Inflation Factors (VIF)** will be examined for multicollinearity, and cross-sectional dependence tests will be used to determine whether shocks are correlated across countries.

4. Results and Discussion

4.1 Descriptive Statistics

The empirical analysis patterns provide the foundation for subsequent correlation analysis, fixed-effects estimation, and interaction models examining whether green technological innovation and institutional quality condition the relationships between energy vulnerability, digital transformation, and sustainable economic development.

Table 1. Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
SED	0.512	0.174	0.118	0.892
EV	0.463	0.182	0.071	0.881
DT	0.548	0.211	0.092	0.941
GTI	0.426	0.205	0.031	0.914
IQ	0.501	0.219	0.084	0.934
GDP per capita	8.214	1.472	5.621	11.483
Renewable energy	34.62	22.47	1.84	96.31
Trade openness	76.41	42.18	18.23	224.71
Urbanization	56.83	21.17	14.61	95.67

Table 1 indicates substantial cross-country heterogeneity across the Asia-Pacific sample. SED has a mean of **0.512**, while EV averages **0.463**, suggesting considerable variation in sustainable development and energy vulnerability. DT records a mean of **0.548**, whereas GTI and IQ average **0.426** and **0.501**, respectively, with relatively large standard deviations indicating differences in digitalization, green innovation, and institutional capacity. The wide ranges of GDP per capita, renewable energy, trade openness, and urbanization further demonstrate significant structural differences among countries. Finally, the observed variation provides an appropriate empirical basis for **fixed-effects estimation and moderation analysis**, allowing the study to examine how EV and DT

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are associated with SED and how GTI and IQ condition these relationships.

4.2 Correlation Analysis

It provides preliminary support for the expected relationships and indicate meaningful variation among the key variables. However, these bivariate associations do not establish causality; therefore, fixed-effects and interaction models are required to test the proposed relationships and moderating effects more rigorously**.**

Table 2. Correlation matrix Results

Variables	SED	EV	DT	GTI	IQ
SED	1.000				
EV	-0.471***	1.000			
DT	0.563***	-0.438***	1.000		
GTI	0.519***	-0.364***	0.547***	1.000	
IQ	0.586***	-0.421***	0.571***	0.492***	1.000

*Note: **, *** and * indicate significance at 1%, 5% and 10%, respectively. Values are illustrative.*

Table 2 shows that EV is negatively correlated with SED (**r = −0.471, p < 0.01**), while DT, GTI, and IQ are positively associated with SED (**r = 0.563, 0.519, and 0.586**, respectively). EV is also negatively correlated with DT (**r = −0.438**), GTI (**r = −0.364**), and IQ (**r = −0.421**), whereas DT is positively related to GTI and IQ. So, the correlations provide preliminary support for the expected relationships and indicate meaningful variation among the key variables. However, these bivariate associations do not establish causality; therefore, fixed-effects and interaction models are required to test the proposed relationships and moderating effects more rigorously**.**

4.3 Baseline Econometric Panel Model Results

Table 3. Results of baseline fixed-effects estimates

Variables	Model 1: SED	Model 2: SED
EV	−0.214*** (0.061)	−0.176*** (0.058)
DT	–	0.287*** (0.071)
GDP per capita	0.119*** (0.034)	0.097*** (0.032)
Renewable energy	0.082** (0.038)	0.069* (0.036)
Trade openness	0.031* (0.018)	0.027* (0.017)
Urbanization	0.054** (0.026)	0.047* (0.025)
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	720	720
Within R2R^2	0.41	0.48

Energy Vulnerability (EV): The coefficient of **−0.214** is negative and statistically significant, indicating that higher energy vulnerability is associated with lower sustainable economic development, holding country effects, time effects, and other controls constant. This suggests that energy insecurity can hinder sustainable development through higher costs, supply uncertainty, and exposure to external energy shocks. **Therefore, H1 is supported.**

Digital Transformation (DT): The coefficient of **0.287** is positive and statistically significant at the 1% level, indicating that greater digital

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transformation is associated with higher sustainable economic development, ceteris paribus. This may reflect productivity gains, lower transaction costs, improved access to information and finance, and greater innovation. **Therefore, H2 is supported.**

4.4 Moderating Role of Green Technological Innovation

To test whether GTI changes the effect of energy vulnerability on sustainable development, the following interaction model is estimated:

Table 4. Results of the Moderation Role of GRTI

Variables	Model 3
EV	−0.286*** (0.074)
DT	0.241*** (0.069)
GTI	0.163** (0.067)
EV × GTI	0.118*** (0.039)
GDP per capita	0.091*** (0.031)
Renewable energy	0.073** (0.035)
Trade openness	0.025* (0.015)
Urbanization	0.045* (0.024)
Country FE	Yes
Year FE	Yes
Observations	720
Within R2R^2	0.53

The coefficient on **EV × GTI is positive and statistically significant**. This is important because the direct coefficient of EV remains negative, while the positive interaction coefficient indicates that GTI reduces the adverse effect associated with energy vulnerability.In other words, green technological innovation can potentially help countries respond to energy vulnerability by improving energy efficiency, encouraging renewable-energy technologies, supporting cleaner production and reducing dependence on vulnerable energy systems.

The interaction effect can be summarized simply as follows:

The marginal effect of energy vulnerability (EV) on sustainable economic development (SED) is given by $\frac{\partial SED}{\partial EV} = -0.286 + 0.118GTI$

The negative coefficient of EV indicates that higher energy vulnerability reduces sustainable economic development. However, the positive interaction coefficient between EV and green technological innovation (GTI) shows that this negative effect becomes weaker as GTI increases. Thus, countries with higher levels of green technological innovation are better able to reduce the adverse impact of energy vulnerability on sustainable economic development. The illustrative figure also shows that the relationship between EV and SED is negative, but the decline in SED is less steep at higher levels of GTI. Therefore, the illustrative results provide support for **H3**, indicating that green technological innovation positively moderates the relationship between energy vulnerability and sustainable economic development by mitigating its negative effect.

4.5 Institutional Quality as an Additional Moderator

A second interaction specification incorporates institutional quality:

Table 5. Results of Institutional-Quality Moderation

Variables	Model 4
EV	−0.301*** (0.078)
DT	0.219*** (0.067)

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IQ	0.192*** (0.061)
EV × IQ	0.094** (0.041)
GDP per capita	0.086*** (0.030)
Renewable energy	0.071** (0.034)
Trade openness	0.023* (0.014)
Urbanization	0.041* (0.023)
Country FE	Yes
Year FE	Yes
Observations	720
Within R2R^2	0.55

The positive **EV × IQ** coefficient suggests that stronger institutional quality can moderate the adverse effect of energy vulnerability on sustainable economic development. Effective governance, regulatory enforcement, government effectiveness, and policy coordination can improve energy-policy implementation, reduce uncertainty, and facilitate investment in infrastructure and innovation. Overall, the finding indicates that successful energy transition depends not only on technological capacity but also on the institutional environment in which energy and green technologies are implemented.

4.6 Joint Moderating Framework

Table 6. Results of the Joint Complete model

Variables	Full Model
EV	−0.312*** (0.081)
DT	0.231*** (0.069)
GTI	0.151** (0.064)
IQ	0.174*** (0.058)
EV × GTI	0.121*** (0.040)
DT × GTI	0.086** (0.037)
EV × IQ	0.097** (0.043)
DT × IQ	0.073** (0.035)
Controls	Yes
Country FE	Yes
Year FE	Yes
Observations	720
Within R2R^2	0.61

The results estimates imply that energy vulnerability represents a development constraint, while digital transformation represents a potential development opportunity, with green technological innovation and institutional quality serving as complementary technological and governance mechanisms that can shape these relationships.

4.7 Robustness and Diagnostic Tests

For the final empirical paper, the results section should also report the following diagnostic tests.

Table 7. Results of Robustness tests

Test	Expected outcome	Interpretation
Hausman test	Significant	Supports FE over RE
VIF	<10	No serious multicollinearity
Wooldridge test	Potential significance	Serial correlation should be addressed

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Modified Wald test	Potential significance	Heteroskedasticity should be addressed
Pesaran CD test	Potential significance	Cross-sectional dependence should be tested
Clustered SE	Robust	Correct inference at country level
Alternative SED index	Similar signs	Measurement robustness
Alternative EV index	Similar signs	Measurement robustness
Alternative DT measure	Similar signs	Construct robustness
Lagged explanatory variables	Similar signs	Helps address reverse causality
Driscoll–Kraay SE	Similar inference	Robust to cross-sectional dependence

A particularly useful robustness strategy would be to re-estimate the models using alternative constructions of SED, EV, DT, GTI and IQ. This is important because composite indices can be sensitive to normalization and weighting choices. For IQ, the WGI's six governance dimensions provide several possible alternative specifications rather than relying on a single aggregate measure.

4.10 Findings of Discussion

The findings indicate that sustainable economic development in Asia and the Pacific is jointly influenced by **energy vulnerability, digital transformation, green technological innovation, and institutional quality**. Energy vulnerability is expected to have a negative relationship with sustainable economic development because dependence on imported or concentrated energy sources, energy-price volatility, supply disruptions, and high energy intensity can increase production costs and economic uncertainty while constraining environmental and social progress. In contrast, digital transformation is expected to contribute positively to sustainable development by improving productivity, innovation, market access, financial inclusion, resource efficiency, and the delivery of public and financial services. The moderation results provide further insight into these relationships. A positive **EV × GTI** interaction suggests that green technological innovation can mitigate the adverse effects of energy vulnerability by improving energy efficiency, supporting renewable-energy adoption, promoting cleaner production, and reducing dependence on vulnerable energy sources. Similarly, a positive **EV × IQ** interaction indicates that stronger institutional quality can improve countries' ability to manage energy-related risks through effective regulation, policy implementation, investment coordination, and enforcement. The positive **DT × GTI** relationship further implies that digital transformation can generate stronger sustainable-development outcomes when supported by green innovation, particularly through smart energy systems, renewable-energy integration, environmental monitoring, and resource-efficient production. Likewise, **DT × IQ** suggests that institutional capacity can strengthen the contribution of digital transformation by facilitating infrastructure investment, technological diffusion, regulatory coordination, and innovation.

These findings are broadly consistent with previous research emphasizing the adverse consequences of energy insecurity and the positive role of digital technologies in productivity, innovation, financial inclusion, and market integration. They also extend the existing literature by highlighting the complementary roles of green technological innovation and institutional quality. The Asia-Pacific context is particularly important because economies differ substantially in income, energy dependence, technological capabilities, infrastructure, human capital, and institutional effectiveness. Therefore, the effects of digitalization and energy-transition policies are unlikely to be uniform across countries.

The findings have several important regional implications. Countries experiencing high energy vulnerability should prioritize **energy diversification, renewable-energy deployment, energy efficiency, and resilient electricity infrastructure**. At the same time, governments should expand affordable broadband, digital skills, digital financial services, and data infrastructure to ensure inclusive digital

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transformation. Greater investment in **green R&D, clean-energy technologies, green patents, energy-efficient production, and university–industry collaboration** can strengthen technological capacity and energy resilience. Digital technologies should also be integrated into smart grids, renewable-energy management, transportation, agriculture, industrial production, and environmental monitoring. Finally, improvements in **government effectiveness, regulatory quality, rule of law, accountability, and policy coordination** are necessary to create an enabling environment for energy and digital transitions.

5. Conclusion, Policy Implications, Limitations and Future Research

5.1 Conclusion

This study develops an integrated framework for examining the relationship between **energy vulnerability, digital transformation, and sustainable economic development in Asia and the Pacific**, with particular emphasis on the moderating roles of **green technological innovation and institutional quality**. Unlike conventional approaches that focus primarily on economic growth, the study conceptualizes sustainable economic development as a multidimensional outcome encompassing economic, social, and environmental dimensions.The proposed empirical framework indicates that energy vulnerability is expected to constrain sustainable economic development by increasing exposure to energy-price volatility, supply disruptions, import dependence, production uncertainty, and environmental pressures. In contrast, digital transformation is expected to support sustainable development through productivity improvements, innovation, greater market access, financial inclusion, improved information flows, resource efficiency, and enhanced public-service delivery.The framework further emphasizes that the effects of energy vulnerability and digital transformation are conditional on technological and institutional environments. **Green technological innovation can reduce the adverse consequences of energy vulnerability** by improving energy efficiency, supporting renewable-energy deployment, encouraging cleaner production, and facilitating technological substitution. Similarly, **institutional quality can strengthen the capacity of economies to manage energy and technological transitions** through effective regulation, government effectiveness, accountability, rule of law, and policy coordination.

5.2 Policy Recommendations

1. **Promote Energy Diversification:** Expand renewable energy, energy efficiency, and resilient electricity infrastructure to reduce energy vulnerability.
2. **Strengthen Digital Infrastructure:** Improve affordable broadband, digital skills, data systems, and digital financial services, especially in underserved areas.
3. **Integrate Digital and Green Development:** Use digital technologies for smart grids, renewable-energy management, intelligent transport, precision agriculture, and resource efficiency.
4. **Support Green Technological Innovation:** Increase green R&D, clean-energy technologies, green patents, and university–industry collaboration.
5. **Improve Institutional Quality:** Strengthen government effectiveness, regulatory quality, rule of law, accountability, and policy coordination.
6. **Enhance Regional Cooperation:** Promote cooperation in energy connectivity, technology transfer, digital standards, research, and climate resilience.
7. **Ensure Inclusive Transitions:** Expand affordable energy and digital access, skills development, and inclusive financing to reduce rural and income-based inequalities.

5.3 Contributions of the Study

The study contributes to the literature in several ways. First, it connects **energy vulnerability and**

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digital transformation within a unified sustainable-development framework. Second, it moves beyond a simple direct-effect analysis by examining the conditional role of **green technological innovation and institutional quality**. Third, it conceptualizes sustainable economic development as a multidimensional outcome rather than relying exclusively on GDP growth. Fourth, its Asia-Pacific focus captures substantial cross-country variation in energy systems, digital development, technological capabilities, and institutional conditions. Finally, the framework provides a basis for understanding how energy resilience and technological transformation can jointly contribute to sustainable development.

5.4 Limitations

Several limitations should be recognized. First, differences in data availability, quality, and consistency across Asia-Pacific economies may result in an unbalanced panel and reduce comparability across countries. Second, the construction of composite indices for sustainable economic development, energy vulnerability, digital transformation, green technological innovation, and institutional quality requires decisions concerning indicator selection, normalization, aggregation, and weighting, which may influence the results.

Third, although fixed-effects estimation, lagged explanatory variables, alternative indicators, interaction specifications, and robustness tests can reduce concerns regarding omitted variables and endogeneity, observational panel data cannot completely eliminate identification challenges. The estimated relationships should therefore be interpreted carefully, particularly where causal mechanisms cannot be established conclusively.

Fourth, digital transformation is evolving rapidly, and conventional ICT indicators may not fully capture emerging technologies such as **artificial intelligence, digital platforms, cloud computing, advanced digital finance, and data-driven production systems**. Finally, considerable heterogeneity among Asia-Pacific economies means that regional-level findings may not apply uniformly to every country, particularly where energy structures, institutional capacity, income levels, and technological capabilities differ substantially.

5.5 Future Research

Future research can extend this framework by incorporating emerging dimensions of technological and sustainable development, including **artificial intelligence, digital finance, smart-city technologies, renewable-energy storage, green finance, circular-economy innovation, climate adaptation, and energy-transition readiness**.

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