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Research article

Unleashing the critical role of renewable energy through global value chains and digitalization: A path towards environmental sustainability

Long Zhang [a], Zuoxiang Zhao [b,*], Ghulam Muhammad Qamri [c,d,**], Samariddin Makhmudov [e,f,g]

[a] Environmental Economy, Economic Law. HSBC Business School, Peking University, Shenzhen, China
[b] School of Economics and Management, Beijing University of Chemical Technology, Beijing, 100029, China
[c] Institute of International Economics and Collaborative Innovation Center for China Economy, Nankai University, Tianjin, 300071, China
[d] Department of Economics, University of Sargodha, Pakistan
[e] Department of Finance and Tourism, Termez University of Economics and Service, Termez, Uzbekistan
[f] Department of Finance, Alfraganus University, Tashkent, Uzbekistan
[g] Department of Economics, Mamun University, Khiva, 220900, Uzbekistan

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ABSTRACT

Sustainable energy promotion within global value chains depends on exchanging green technologies and knowledge, but it also requires international environmental regulations. The study examines how global value chains, labor force, gross fixed capital digitalization, and GDP influence renewable energy. The Pooled Mean Group (PMG) estimators have been used to estimate the renewable energy patterns in ASEAN countries from 1995 to 2018. The findings show that renewable energy receives negative influences from the labor force, gross fixed capital, and digitalization over long periods. The relationship between global value chains, labor force, and GDP shows negative results in the short term. The analysis establishes that the labor force, digitalization, and GDP negatively affect renewable energy over a longer period. The combination of global value chains, labor force, gross fixed capital, and digitalization produces negative results for renewable energy in the short run. It also shows renewable energy receives positive impacts from the interaction between digitalization and global value chains. Our findings also show that digitalization (DIGI) lowers the adverse effect of the global value chains (GVCPR), acting as a buffer against the adverse impacts of the GVCPR in the short run, and GVCPR lessens the negative effects of the digitalization acting as a stabilizer in the long run. The study reveals that governments need to integrate digital technology infrastructure with global value chains to achieve positive effects on renewable energy production. Sustainable energy practices enable resilient energy operations by creating energy practices through the beneficial relationships between digital innovation and global value chains.

1. Introduction

Energy sector operations worldwide experienced major alterations in recent years since countries invested in developing sustainable renewable energy alternatives from conventional fuel sources (Al-Shetwi, 2022; Gollakota and Shu, 2023; Gayen et al., 2024; Zhang et al., 2024a, b,c, Bingxin et al., 2025). Renewable energy systems started delivering sustainable environmental outcomes in various forms for several decades while fighting climate change and reducing carbon dioxide pollution (Buhari et al., 2020,Katral et al., 2024, Ozcan et al., 2024; Balsalobre-Lorente et al., 2025). The implementation of renewable energy is based on two essential innovation drivers which are global value chains (GVCs) and digitalization. The framework provides new opportunities to countries and organizations through modern green technology accessibility, better energy efficiency, and quicker sustainability-driven energy solution implementation. The study investigates the connection between Global Value Chains and digitalization methods in the renewable energy sector. This study employed conceptual models and robust economic approaches to examine global energy transition by studying these phenomena.

* Corresponding author.
** Corresponding author. Institute of International Economics and Collaborative Innovation Center for China Economy, Nankai University, Tianjin, 300071, China.
E-mail addresses: zhanglong@phbs.pku.edu (L. Zhang), zhaozuoxiang@buct.edu.cn (Z. Zhao), gmqammar@hotmail.com (G.M. Qamri), samariddin_maxmudov@tues.uz, s.maxmudov@afu.uz, maxmudov_samariddin@mamunedu.uz (S. Makhmudov).

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The success of the world economy relies on global value chains for proper operation. The system enables nations to exchange materials along with service provisions through technological transfers on an international level. The participation of firms in Global Value Chains enables them to receive international energy sustainability standards while gaining access to modern industrial innovations from around the world (Sinkovics et al., 2021; Wang et al., 2021; Lee and Wen, 2025; Saberi et al., 2019; Waris and Tariq, 2024; Li et al., 2025a,b). Technological diffusion theory, among other fundamental perspectives, verifies how global value chains have become vital resources for renewable energy production. The spread of green technology across countries uses Global Value chain mechanisms based on the Technological Diffusion Theory. Developing countries acquire technological advancements through this procedure even when their native capabilities would be insufficient to purchase them independently (De Marchi et al., 2020; Liu et al., 2020; Pandey et al., 2022; Khan et al., 2023; Isharyani et al., 2024). The collaboration with Global Value chain companies enables enterprises to obtain green energy development methods that cut down fossil fuel requirements and optimize energy resource management. Global Value Chains allow developing economies to benefit from the Resource-Based View (RBV) by introducing them to international markets, leading to productivity advancements. Implementing outstanding sustainable methods allowing renewable power development receives external motivation from businesses (Gereffi et al., 2005; Gawusu et al., 2022; Agostino et al., 2023; Odeyemi et al., 2024; Li et al., 2025a,b).

Digitalization mainly supports green energy transitions, though Global Value Chains contribute complementary effects. Integrating AI smart grid and IoT technology substantially modifies energy generation, consumption, and management. Technology diffusion happens worldwide due to digitalization based on the standards of the Technological Diffusion Theory. Through its framework, the system allows data sharing abilities and enables knowledge exchange alongside inter-border cooperative efforts (Nicolas, 2017, Tsanova et al., 2020, Fang et al., 2023; Tapalova et al., 2024; Di et al., 2024, Qamri et al., 2025). Implementing digital platforms will enable companies to track their customers' energy consumption to optimize performance while implementing more efficient renewable energy capabilities. The participant countries within Global Value Chains benefit from digital transformations that minimize renewable energy production costs while fostering investment into green and clean energy domains, according to Gawusu et al. (2022) and Waris and Sri (2024).

Implementing digitalization for renewable energy transition encounters difficulties because the Jevons Paradox activates negative consequences associated with digital systems. Elevating energy efficiency results in expanded total power usage now and in the future. This development aligns with the present need for digital infrastructure systems, including data centers, AI applications, and blockchain technology, because they require substantial power inputs (Polzin et al., 2015; Kumari et al., 2020; Ahmed et al., 2022; Khalid, 2024; Abiodun, 2025).The global advancement of digitalization technologies leads to diminishing benefits from renewable energy integration because of rising energy use. The environmental effects of this implementation can decrease through Borowski (2021); Hasan et al. (2024). The Technological Lock-In Theory shows that digitalization systems tend to create a lock-in effect. Companies make considerable digital infrastructure investments that prevent them from connecting to renewable energy systems that support non-renewable energy sources (Gielen et al., 2019; X. Zhang et al., 2024a,b,c). Current technology fails to meet sustainability and cleanliness requirements, so the flavor remains. The potential for technological advancement does not affect renewable energy transitions because of the Technological Lock-In Theory, as noted by Unruh (2000); Qadir et al., (2021).

The study relies on five essential theoretical frameworks: technological diffusion theory, resource-based view, dynamic capabilities theory, Jevons paradox, and technological lock-in theory. The connection between GVCs, digitalization, and renewable energy transition is clarified through multiple important theories. Multiple theories provide the research project with perceptive findings that explain how technology transfers affect global trade and energy sustainability relationships. The study has examined the hidden effects of digitalization on renewable energy change through analysis of the Jevons Paradox and Technological Lock-In. This study presents crucial matters and explains the complete digitalization process for worldwide energy transformations. The research delivers critical insights to policymakers who need instructions on using digitalization benefits to manage its possible adverse consequences.

Renewable energy production experiences its main speed boost through digitalization and GVCs. These factors create the overall effects of GVCs and digitalization on global energy system transits. The analysis of renewable energy production depends on assessments of global value chains, labor force operations, gross fixed capital formation, digitalization, and GDP metrics. The research has implemented advanced statistical approaches to analyze long and short-term relationships between these key determinants. Research conducted by Pesaran et al. (1999) and Arora and Siddique (2024) applies the Pooled Mean Group (PMG) estimator to analyze both transient and sustained connections between GVC and digitalization in renewable energy generation. One of the contributions is that the study has used data on renewable energy innovation which shows the real picture of renewable energy generation. Secondly, the interaction term of GVCPR and DIGI is significant and positive in both the short and long run, indicating that the DIGI lessens the adverse effect of GVCPR on renewable energy generations in the short run. GVCPR reduces the long-run adverse impact of digitalization on renewable energy innovations, unleashing the complementary role of GVCs and digitalization for each other in the short and long run. Thirdly this study provides strong policy implications that can help the stakeholders benefit the economies and regions.

The research investigation generates important findings that direct companies and policy organizations to increase renewable energy usage via GVC collaboration alongside digitalization initiatives. Combining GVCs and digitalization creates complex immediate effects in countries with strong digitization infrastructure and those primarily using non-renewable energy sources. Digitalization and GVCs operate as strong, sustainable tools that drive renewable energy use over extended periods. The study documents the difficulties emerging from joining GVCs and implementing digitalization systems. Supporting policies require development at the same pace as investment programs because both are essential for renewable energy source transition. This study presents innovative combined research about GVCs, renewable energy knowledge, and digitalization technologies. A combination of important theoretical models and advanced statistical methods creates an analysis of global energy transition elements in this research. The study delivers beneficial findings guiding regulatory organizations and businesses aiming to enhance green energy systems under modern digital conditions.

2. Review of relevant literature

Sustainability needs and green energy use have created a relationship between Global Value Chains and digitalization practices. The literature review of this study outlines the impact of GVCs and digitalization on renewable energy transitions through essential research evidence and main theoretical frameworks and research. The study evaluates the advantages of organizations joining GVCs to create and market environmentally friendly and clean technology. Papagiannidis et al. (2023) explain how digitalization fastens renewable energy system adoption while bringing unpredictable changes to the process. This study examines changes in renewable power production from digitalization while investigating nationwide differences in GVC participation that produce varied outcomes. The international network established through Global Value Chains enables governments and industries to link up with improved supply chain operations that transform the worldwide economic system (Gereffi and Fernandez-Stark, 2011; Awan et al., 2022; Epede and Wang, 2022; Ameh, 2024). GVC participation allows business firms in developing nations to access better technologies and resources beyond their local capabilities. Various studies prove that GVCs are essential for companies to adopt renewable technologies. Knowledge exchange, spreading technology, and cross-border teamwork represent fundamental elements of these investigations.

Research on GVCs mainly focuses on technology-sharing methods and knowledge distribution practices. Relevant literature describes GVCs as one of the primary channels for developing countries to receive renewable power technologies from industrial nations (Glachant et al., 2013; De Marchi et al., 2020; Garsous and Worack, 2022). Developing country companies accessing contemporary renewable energy technologies through GVC participation enables better energy efficiency while moving away from fossil fuel dependency. The renewable energy sector values GVCs because modern technologies are out of reach because of their high price and lacking technical skills (Liu et al., 2020; Hu et al., 2021; Wang et al., 2021). The main contributor to business achievement in developing nations is their participation in global value chains. Firms can access renewable technology through GVC because energy resources remain limited in their procurement. Developing nation firms gain operational effectiveness because GVCs link them to global markets while constraining them to adopt modern business techniques and technology (Gereffi et al., 2005; Jer, 2014; Chatterjee et al., 2024). Organizations adopt the exposure instrument to advance their worldwide business activities and choose energy solutions that promote sustainability (Doh et al., 2021; Manes-Rossi and Nicolo' 2022; Onabowale, 2024; Yang et al., 2024).

Research by Ponte and Sturgeon (2017), along with Zhang et al. (2024a,b,c) demonstrates that firms use GVCs to let developing nations access international markets and acquire sustainable energy technologies. The referenced study shows that firms develop better renewable energy technologies through GVCs, which allows them to lower their reliance on fossil fuels. Global sustainability achievements will become possible for participants in this initiative. Taglioni and Winkler (2016) demonstrate through their research that GVCs drive economic and environmental sustainability by facilitating environmentally sustainable technology development. Developing nations face special difficulties when joining global value chains for business operations. Baldwin and Lopez-Gonzalez (2015) and Thi Mai Hoa et al. (2024) prove that nations that produce energy-intensive consumer goods for GVCs raise their immediate dependence on non-renewable energy resources. The industrial sector struggles to use renewable energy technologies because it employs outdated manufacturing methods to secure its energy needs. Insufficient energy infrastructure regions show temporary dependence on conventional energy sources after joining Global Value Chain networks, according to studies by Bamber et al. (2014) and Timmer et al. (2014). Other major factors alongside digitalization expedite the worldwide shift toward renewable energy. Firms benefit from digital technologies such as AI, the IoT, and smart grids because these advances help them decrease their energy expenses while improving their energy management and maximizing power usage effectiveness. According to Bartczak (2021), these modern technologies combine with Blichfeldt and Faullant's (2021) and Hu et al (2022) research to allow firms to establish innovative methods for sustainable energy management. Monitoring energy utilization in real-time is enabled by digitalization due to its system, which tracks operations continuously. Companies can detect their ineffectual strategies through monitoring systems to foster the adoption of renewable energy methods.

Digitalization helps companies develop innovative approaches to acquiring internal capabilities that are useful for optimizing their management quality Wu et al., (2022), Tagscherer and Carbon (2023), Zheng et al. 2023, (Zaman et al., 2025). Digital platforms would allow companies to detect and monitor their energy efficiency problems. The works of Tsanove et al. (2020), alongside Mondejar et al. (2021), establish that renewable energy solution implementations yield operational improvements and reduce operational costs across various business operations. Through digital systems, companies enhance their use of wind and solar energy, thus advancing the adoption of renewable energy systems. As per Rai et al. (2018) and Karlilar et al. (2023), digitalization is a pivotal agent that advances the development of energy technology renewal. Digitization gives businesses the power to use more energy and allows them to substitute traditional energy sources with alternate renewable options. The research confirms that every GVC member state should adopt digital technologies as fundamental components that facilitate their companies' integration of green power into present utility systems. Decision-making strategies must rely on data-based decisions when implementing digital technology into global supply chains, as Benigni et al. (2021) and Ozkan-Ozen et al. (2023) noted. The combination of AI and IoT technologies operates as digital tools that enable efficient energy extraction and green energy process implementation for organizations.

Global energy resource distribution receives a digital boost because it enhances overseas information exchange and international partnerships Li et al. (2024). The paper by Tsanova et al. (2020) and Lee and Mwebaza (2021) evaluated digital platforms as per Technological Diffusion Theory for their role in advancing green energy solutions through interactive data-sharing platforms. The rollout of sustainable energy systems requires various business entities worldwide to collaborate within GVCs (Usman et al., 2024). Digitalization establishes itself as the main fundamental factor that drives energy efficiency promotion. Schleicher (2012) and Ahmad and Zhang (2021) explained that businesses gain real-time capacity to monitor their energy consumption through modern digital systems. This ability enables firms to increase their energy efficiency, create sustainable practices, and detect areas of waste. Sustainable energy approaches need detailed consideration within Global Value Chains because various countries participate in different industrial sectors between their member firms. Combining digital innovations with GVC participation increases the creation of renewable energy systems. Academic research has established various direct and indirect negative impacts of GVC involvement and digitalization on renewable energy resources. Zhang et al. (2017) and Sajid et al. (2021) documented how blockchain technology and data center development boost energy utilization. The environmental advantages of renewable energy sources have become disregarded because of this phenomenon. Every industry using digital technology must monitor their energy consumption because they currently function within the digitalized world.

Moreover, Unruh highlights (2000) the challenges of lock-in technology. Unruh's evaluation shows that organizations using significant non-renewable energy holdings experience implementation barriers specifically caused by the expensive construction needed for modern infrastructure. Organizations need to build their renewable energy policy framework first and secondly target the removal of fossil fuel dependency. According to research papers, GVCs are part of a complex network where digitalization integrates with renewable energy generation activities. The GVC, with its digitalization elements, is an essential tool for establishing sustainable energy transformations. Various aspects, including development indices, framework infrastructure, and governance regulations, influence the degree of their impact. The review gathers necessary summaries of theoretical structures, key research findings, and performance limitations. The research investigates how GVCs function with digitalization as a system to support renewable energy adoption. The paper stresses the significance of unique governmental policies coupled with international cooperation to solve GVC and digitalization issues, including Jevons Paradox and technological lock-in.

3. Methods

3.1. Theoretical background and data sources

The nationwide exchange of green energy technologies, financial resources, and best practices happens through global value chains (GVCs). Through GVC participation, firms obtain recent innovations immediately while international environmental standards force them to implement cleaner energy solutions. This process resulted in energy efficiency, reduced petroleum product usage, and faster worldwide efforts for sustainable energy development (Zhang et al., 2016; Popp, 2011). According to theoretical analyses, renewable energy production relies heavily on global value chains because they support fast information sharing and improved technology transmission. According to the "technological diffusion theory," GVCs have adopted a model to deliver renewable energy technology across countries, granting emerging businesses commercial benefits. The main drivers of GVCs are multinational corporations that are one of the major sources of technology diffusion and knowledge spillovers. According to the "resource-based view," GVCS spurs domestic companies' interaction with international players, leading to upgraded productive abilities that provide them a competitive advantage while investing in green technologies. GVCs enhance global energy sustainability by uniting innovation with sustainability-based cooperation through these theories, according to Gereffi et al. (2005) and Eicke and Weko (2022).

Digitalization enhances the worldwide movement of renewable power technology through fast data-sharing systems, creating partnerships between international organizations according to "Technological Diffusion Theory." Digitalization supports firm internal capability development via "Resource-Based View (RBV)" because it offers application tools like AI, smart grids, and IoT for enhanced energy management and optimization and innovation capabilities. Adopting digitalization methods within renewable energy systems makes operations more efficient while decreasing production costs for better future financial stability that contributes positively to their competitive edge over other firms (Loock, 2020; Huang and Tan, 2025). Organizations must engage in market transformation and technological development in the energy sector according to the "Dynamic capabilities theory." Companies requiring fast adaptation to emerging technologies and regulatory changes in the renewable energy field should focus on this aspect. The digitalization process aids renewable energy expansion through its ability to enhance organizational flexibility and responsiveness (Teece, 2018). Digitalization through the "Jevon Paradox" produces paradoxical results by improving operational efficiency, but it leads to rising total energy consumption, especially when involving non-renewable power sources. The energy requirements from these growing data centers, emerging blockchain systems, and AI systems can potentially diminish the environmental benefits of renewable energy integration (Polzin et al., 2015).

The "Technological Lock-in Theory demonstrates how digitalization causes firms to lock into current digital infrastructures that may not support renewable energy effectively. Lower costs combined with established technologies within existing systems sometimes prevent the transition to renewable energy, even though such systems have potential optimization opportunities (Unruh, 2000). The research model for the current study is presented in Equation (1), derived from the predictions and linkages outlined by the theories above. This study examines the impact of global value chains, labor force, gross fixed capital formation, digitalization, and GDP on renewable energy production (dependent variable). Renewable energy data is sourced from the Organization for Economic Cooperation and Development (OECD), labor force statistics from the United Nations Conference on Trade and Development (UNCTAD), and additional variables from the World Development Indicators (WDI). Equation (1) depicts the theoretical model.

$$\textit{Renewable Energy} = f(\textit{Global Value Chains}, \textit{Digitalization}, \textit{and Control variables}) \tag{1}$$

Table 1 reports the definition of variables along with data sources and their acronyms belonging to equation (1). The data of renewable energy innovation is taken from OECD Stats and data of global value chains is collected from United Nation Conference on Trade and Development. The data of digitalization is obtained from World Development Indicators.

3.2. Econometric methodology

3.2.1. Preliminary assumptions

Initially, this study uses a cross-section dependence test to detect the existence of spatial and temporal correlation among cross-sectional units of the panel proposed by Pesaran (2015, 2021). Then, in light of the results of this test, the current research applies the second-generation unit panel root test introduced by Pesaran (2007), which accounts for the cross-section dependence in panel data while running the panel unit root test. The purpose of this test was to improve the reliability of the panel unit root test results because conventional panel unit root tests cannot consider the spatial correlation while detecting the unit root process of variables. Therefore, this study also uses the second-order panel unit root test proposed by Pesaran (2007) to determine the order of integration of variables of the model. Unit root tests, including the Pesaran CADF (Cross-sectional Augmented Dickey-Fuller) test, encounter considerable constraints when cross-sectional dependence exists among panel data units. These tests generally presume that individual series are independent, which may not be valid in interconnected economic data, resulting in size distortions and possible misinterpretation of outcomes. The Pesaran CADF test seeks to enhance the Dickey-Fuller test by incorporating cross-sectional averages of lagged levels and first-differenced variables; however, it may remain ineffective in capturing intricate interdependencies, particularly in panels exhibiting robust or widespread cross-sectional correlations. This study applies the slope heterogeneity test proposed by Pesaran and Yamagata (2008). The primary purpose of this test is to check if slope parameters remain constant across the multiple units in a panel data set or differ between them to prevent wrong findings. The panel data analysis relies heavily on the slope homogeneity test because it establishes whether explanatory variables have the same impact on dependent variables throughout multiple cross-sections. The slope heterogeneity result from the test indicates that the analyzed entities

Table 1
Variables and data sources.

Variable	Definition	Source
RENG	Renewable energy generation (patents)	OECD
GVCP	The sum of forward and backward participation in global value chains as a percentage of total value-added exports	UNCTAD
PWLA	Natural log of the ratio of total land area to total labor force	WDI
INVT	Natural log of ratio gross fixed capital formation to the labor force	WDI
DIGI	Percentage of the population using Internet services	WDI
RGDP	Natural log of GDP (Constant, 2015 US$)	WDI

show different responses to changes in explanatory variables, which suggests that one-fits-all approaches are likely inappropriate. Econometric models need the identification of slope heterogeneity to develop specific policy approaches that respond to individual panel member characteristics and requirements for enhanced forecasting accuracy in outcome predictions and strategic decision guidance.

3.2.2. Pooled Mean Group (PMG) estimator

Based on the previously discussed tests, this research implements Pooled Mean Group (PMG) estimation to determine the effects of GVCs and digitalization on renewable energy generations. The PMG estimator derives from the research of Pesaran et al. (1999). The PMG estimator lets researchers study variable connections among heterogeneous data collection groups in panel datasets. Panel heterogeneity analysis with PMG estimators allows variable parameters in short-term effects while requiring identical long-term variable relationships across all groups. The model demonstrates complete effectiveness in economic analysis of uniform long-term effects where brief-term variations persist between regions or countries. This method provides the most appropriate solution for analysis involving extensive periods together with various entities. The combined approach supplies researchers with better and more accurate estimations of long-run relationships than single-group homogeneous or heterogeneous models.

The PMG estimator contains factors that could restrict its usefulness in specific research scenarios. The PMG approach depends on a crucial assumption that equilibrium relationships run identically across groups, but this condition will probably not apply when distinct structural components affect each group. Additionally, the PMG method assumes that the underlying variables are integrated of order one and that the relationship between them is cointegrated. If these conditions are unmet, the PMG estimator may yield biased or inconsistent results. Therefore, researchers must carefully assess the appropriateness of this model in light of their specific data characteristics and the theoretical underpinnings of their study.

4. Empirical results and discussion

4.1. Empirical results

Table 2 summarizes the data for the current research series, particularly renewable energy generations, global value chain participation, per worker land area, capital deepening, digitalization, and Gross domestic product across 744 perceptions. The mean and standard deviation values are used to analyze the central tendency and dispersion of the data. However, currently, we will explain the descriptive statistics of our model's main variables, namely renewable energy generation, global value chain participation, and internet usage. RENG addresses how much energy is produced from sustainable sources. The average value of RENG across the observations is 4.12. The data of this variable is 1.92 standard deviations away from the sample's mean. GVCP estimates the amount of forward and backward participation in worldwide value chains as a percentage of total value-added exports. The average rate in worldwide value chains is 63.71 %. In the current case, the standard deviation is very high at 67.73, demonstrating a considerable fluctuation across the observations. DIGI addresses the level of the populace utilizing internet providers. Overall, 53.87 % of the populace utilizes Internet providers, and the standard deviation is 30.82, demonstrating a considerable dispersion in Internet use among the population of countries belonging to the current panel.

Table 2
Descriptive and sources of the data.

Variable	Obs	Mean	Std. Dev.
RENG	744	4.12	1.92
GVCPR	744	63.71	67.73
PWLA	744	0.09	0.17
INVT	744	25.23	1.60
DIGI	744	53.87	30.82
RGDP	744	26.75	1.58

Table 3
Correlation Matrix.

Variable	RENG	GVCPR	PWLA	INVT	DIGI	GDPPC
RENG	1					
GVCP	−0.0522	1				
PWLA	0.0817	−0.0834	1			
INVT	0.7445	−0.0419	−0.1327	1		
DIGI	0.3382	−0.0158	0.1075	0.1305	1	
GDPP	0.7442	−0.0551	−0.1359	0.994	0.1248	1

Table 3 presents the degree of linear association between the variable RENG (Renewable Energy Generation) and different factors in the review: GVCP, PWLA, INVT, DIGI, and RGDP. The correlation coefficient values measure the strength and the nature of the correlation between any two variables. RENG has a strong positive correlation with INVT (gross fixed capital formation) and RGDP, showing that nations that are growing and put more into physical infrastructure will quite often produce more sustainable power. However, RENG has a weak correlation with GVCP and PWLA. Unlikely, there is a moderate positive relationship with DIGI, proposing that nations with higher internet use could likewise be bound to create renewable energy generations.

Fig. 1 depicts an inverse relationship between engagement in global value chains and the utilization of renewable energy. The fitted line demonstrates that an increase in participation in global value chains correlates with a decrease in the fitted values of renewable energy consumption. This indicates that greater integration into global value chains may correlate with reduced utilization of renewable energy sources in the examined context, underscoring potential challenges or trade-offs in promoting renewable energy usage alongside global economic activities. Fig. 2 illustrates a positive correlation between digitalization, quantified by the proportion of the population utilizing the internet, and renewable energy consumption. The fitted line indicates a distinct upward trend, implying that greater levels of digitalization within a population correlate with heightened renewable energy consumption. This suggests that digital innovations may facilitate or accelerate the adoption and integration of renewable energy sources, potentially via improved information dissemination, enhanced efficiencies, or more substantial support for sustainable practices.

This study aims to empirically analyze the individual and combined effect of digitalization and participation in global value chains on renewable energy. Table 3 summarizes the empirical results of two critical diagnostic tests of panel data, namely cross-section dependence and slope heterogeneity, that assess vital characteristics of the data. The null hypothesis of cross-sectional dependence posits that there is weak cross-sectional dependence. This suggests that the data is independent

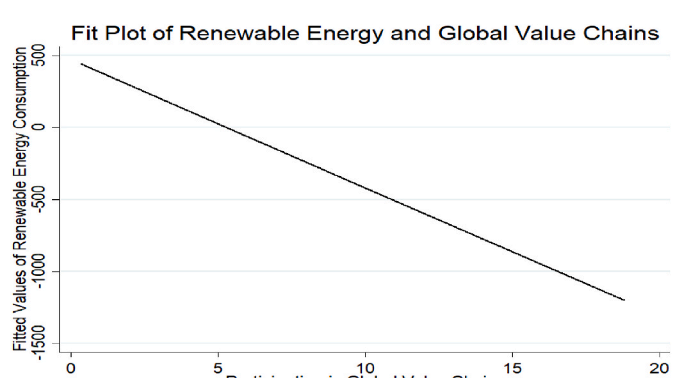

Fig. 1. The relationship between renewable energy and global value chains.

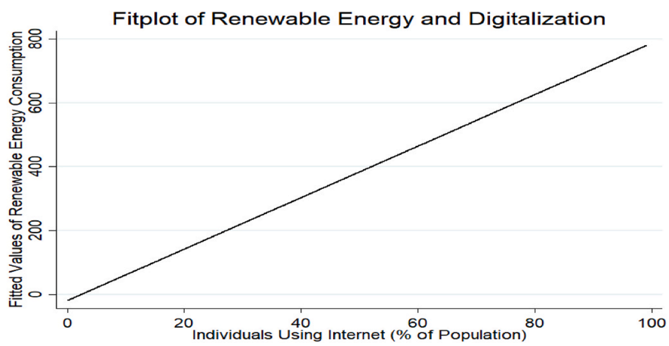

Fig. 2. The relationship between renewable energy and digitalization.

Table 4
Results of Cross-section dependence and slope heterogeneity test.

Test	Null Hypothesis	P-Value	Decision
Cross-section dependence	Weak cross-section dependence	0.000	Strong cross-section dependence exists in the data

across a variety of countries. The null hypothesis is rejected, and the alternative hypothesis, which posits a substantial data dependency among the countries in the current panel, is accepted, as the probability value of this test is less than 0.05. For example, the interdependence of the cross-sectional units in our panel is demonstrated by the potential impact of financial events in a single nation on others.

Table 4 presents the probability values of the second-order panel unit root test, which is usually utilized in time series and panel data analysis to decide if a variable is stationary or nonstationary. Stationarity implies that a variable's mean and variance don't change over time. Non-stationarity demonstrates that these properties can change over time, prompting spurious outcomes in regression analysis that may not be appropriately addressed. These are the series being tested: RENG, GVCP, PWLA, INVT, DIGI, and RGDP. Under the constant-only model, RENG is stationary at level, yet it is nonstationary when a trend is incorporated. This proposes that RENG could display some pattern over time. Likely, GVCP is nonstationary, demonstrating that its mean and variance change over time and could have a unit root.

PWLA is nonstationary at the level, no matter what the model details. INVT is also nonstationary at the level, demonstrating a potential pattern or determination over time. DIGI is stationary at the level, which implies that the statistical properties, mean and variance, are stable over time in both models. RGDP is stationary under the model with constant only but not when a trend is incorporated, proposing some time pattern in Gross domestic product; notwithstanding, all variables with unit roots at their level become stationary after differencing once. This recommends that they are I(1), meaning they become stationary after first differencing (Qamri et al., 2024).

The Pedroni cointegration results in Table 5 confirm with statistical significance that the variables demonstrate a permanent equilibrium relationship. Results from the Modified Phillips-Perron t-statistic testing demonstrate cointegration since it generates a statistically significant value of 2.977 with a p-value of 0.0015. The Phillips-Perron t-statistic shows −8.234, and the Augmented Dickey-Fuller t-statistic exhibits −6.098, indicating a definite rejection of the no cointegration hypothesis given their p-values of 0.0000. The research demonstrates that the variables maintain a lasting association through which they adjust until reaching their long-term connection point. The results of cointegration testing are vital because the discovered stable long-term relationship between variables supports long-term economic analysis and policy recommendations derived from this study.

The estimated coefficients from two Pool Mean Group (PMG) models are presented in Table 6. These models are employed in panel data analysis to assess the short-term and long-term relationships among variables across various cross-sections, such as countries and regions. In this context, the PMG estimator allows short-run coefficients to differ across cross-sections while assuming standard long-run coefficients. The short-run coefficients represent the immediate impact of the independent variables on the dependent variable. The long-run coefficients represent the impact of the independent variables on the dependent variable in the long term after adjustments have occurred. The coefficient of GVCP is −0.027, which is significant at the 10 % level (indicated by *), suggesting a small negative short-run impact of GVCP on renewable energy generation in the short run. Similarly, in model 2, the coefficient of GVCP is −0.091, which is significant at the 5 % level (indicated by **), suggesting a more substantial negative short-run impact on renewable energy innovations. However, in the long run, the coefficient of GVCP is 0.118, which is significant at the 1 % level (indicated by ***), indicating a positive long-term impact of GVCP on renewable energy generation. Like in model 2, the coefficient is 0.132, which is also significant at the 1 % level, reaffirming the positive long-term relationship with renewable energy (see Table 7).

The short-run coefficient of digitalization in model 1 is 0.009, which is significant at the 10 % level, suggesting a small positive short-term impact of digitalization on renewable energy. However, in model 2, the effect of digitalization on renewable energy innovation is adverse for countries with an average level of participation in global value chains. In the long run, digitalization hurts renewable energy generations in countries of panel in model 1 and countries with an average value of participation in global value chains in model 2. The coefficient of interaction term of GVCP and DIGI is significant and positive in both the short run and long run, meaning that the DIGI reduces the undesirable impact of GVCP on renewable energy generations in the short run and GVCP reduces the long run adverse digitalization effect on renewable energy innovations. The coefficient of the current interaction term can be interpreted to mean that the impact of participation in global value chains is positive in countries where the level of digitalization exceeds the panel's average value in the short run. Similarly, the effect of digitalization is favorable in countries where the level of participation in global value chains exceeds the panel's average value in the long run. Therefore, both variables play complementary roles for each other. The coefficient of error correction term (ECT) in both model 1 and model is −0.346 and −0.338, respectively, significant at the 1 % level, indicating a speed of adjustment towards long-term equilibrium of about 34.6 % and 33.8 % per period. This means that deviations from the long-term equilibrium are corrected by about 34.6 %–33.8 % in the following period in model 1 and model 2, respectively. In sum, GVCP has a

Table 5
Results of Pesaran's cross sectional adjusted unit root test.

Variable	P.value at level		P.value at first difference	
	Constant and Trend	Constant Only	Constant and Trend	Constant Only
RENG	0.1000	0.007	0.0000	0.0000
GVCP	1.000	0.841	0.0000	0.0000
PWLA	0.991	0.138	0.0000	0.0000
INVT	0.196	0.076	0.0000	0.0000
DIGI	0.012	0.006	N. A	N. A
RGDP	0.14	0.014	0.0110	0.0000

Table 6
Pedroni test for cointegration.

Estimates	Stats	P-value
Modified Phillips-Perron t	2.977	0.0015
Phillips-Perron t	−8.234	0.0000
Augmented Dickey-Fuller t	−6.098	0.0000

Table 7
Coefficients from two Pool Mean Group (PMG) models.

Variables	Model 1		Model 2	
	Short Run	Long Run	Short Run	Long Run
GVCP	−0.027*	0.118***	−0.091**	0.132***
	(0.0143)	(0.0107)	(0.0366)	(0.0134)
PWLA	−1.635	−1.130**	−1.089	−9.123***
	(2.2058)	(0.5235)	(2.3536)	(0.8865)
RGDP	−1.341	1.457***	0.227	−2.918***
	(1.3466)	(0.4710)	(1.3501)	(0.5911)
INVT	0.187	−0.569***	−0.057	0.132
	(0.4288)	(0.2033)	(0.3415)	(0.2364)
DIGI	0.009*	−0.012***	−0.057*	−0.008***
	(0.0049)	(0.0024)	(0.0304)	(0.0025)
GVCP*DIGI	N. A	N. A	0.001**	0.0002**
			(0.0005)	(0.0001)
Constant	−13.769***	N. A	15.756	N. A
	(2.1695)		(3.5752)	
EC	−0.346***	N. A	−0.338***	N. A
	(0.0598)		(0.0650)	

Standard errors in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

significant adverse consequence for renewable energy in the short run but it has a strong positive impact in the long run in both models. In contrast, DIGI has a positive short-term impact in Model 1 but it hurts renewable energy in Model 2, with consistent small undesirable long-term implications. Nevertheless, the interaction term in Model 2 suggests that the impact of internet usage (global value chain participation) on renewable energy generation is enhanced by global value chain participation (digitalization) in the long run (short run), as evidenced by a positive interaction effect in both the short and long term.

4.2. Discussion on results

Taking part in global value chains (GVCs) can prompt expanded dependence on non-sustainable power sources in the short run, as nation's center around energy-intensive assembling or manufacturing for global business sectors. This prioritization of the modern industry and the creation of proficiency over sustainable power framework might defer the quick reception of green advancements. While GVC support can ultimately work with the spread of environmentally friendly power, nations might intensively rely upon conventional energy sources temporarily. These findings are consistent with the former research studies (Wang et al., 2022; Timmer et al., 2014; Baldwin and Lopez-Gonzalez, 2015).

Nonetheless, over the long run, cooperation in GVCs improves sustainable energy generation by working with innovation moves, drawing in green ventures, empowering consistency with global ecological guidelines, and advancing energy effectiveness. As nations and firms in GVCs try to stay serious in worldwide business sectors, environmentally friendly power becomes an undeniably suitable choice because of the falling expenses of innovation and developing customer interest for supportability. This shift is additionally upheld by joint effort, information sharing, and long-run strategy arrangement with global environment and energy objectives. These findings are in line with the interpretation and justification of (Aydin, M. (2019), Gallagher, 2014; Acemoglu et al., 2012; Taglioni and Winkler, 2016; Aydin, M. (2019); Gereffi and Fernandez-Stark 2011; Ponte and Sturgeon, 2017; Zhang and Gallagher, 2016).

The shift from conventional energy to renewable energy requires a considerable interest in upgrading infrastructure, including grid modernization, energy capacity, and the arrangement of sustainable power advances like wind and solar energy. Digital transformation has outperformed renewable energy generation in numerous OECD nations, prompting an expanded dependence on non-environmentally friendly power sources to satisfy the developing energy needs determined by digitalization. The long-run course of foundation advancement for renewable energy generation includes administrative endorsements, mechanical development, and significant investment in physical capital. Modern energy supply management and grid control actively depend on complex digital systems combining wind and solar energy alongside energy management systems. Electric grid stability will require increased non-renewable energy sources if necessary technological developments fail to receive widespread implementation. The research by Schleicher-Tappeser (2012), Zhironkin and Cehlár M. (2022), Miller and Keith (2018), and Bogdanov et al. (2019) supports this discovery.

Digitalization enables supply chains to operate more efficiently, which cancels out the impact of conventional energy usage on global value chain interactions (Parida et al., 2019). Businesses can achieve two goals through digital platforms and AI with the Internet of Things: optimize their energy consumption and embrace sustainable power sources to decrease their need for conventional energy eventually (De Marchi et al., 2020; Hansen and Bøgh, 2021). Combining digital information sharing and worldwide green power innovation distribution helps speed technological progress, making renewable energy cost-effective for extended use (Sinha et al., 2022). Using advanced data analysis and big data enables business organizations to enhance their ability to implement strategic energy-related decisions from both short-term and long-term perspectives (Marinakis et al., 2020).

5. Conclusion and policy implications

This study evaluates the relationships between global value chains and labor force, gross fixed capital formation, digitalization, and GDP in renewable energy production. The analysis adopts PMG methodology to evaluate ASEAN nations from 1995 to 2018. The study deeply examines the multiple elements that affect global energy transition. This research applied strong econometric models while using additional theoretical elements for its investigation. It reveals that digitalization and GVC participation demonstrate their dual benefits and drawbacks for adopting renewable energy. This research supports the position that global value chains serve as crucial mechanisms to help adopt renewable energy technology. Global value chains drive technology adoption through different methods, including knowledge sharing and technological spreading patterns. Particularly in developing countries, theories such as the Technological Diffusion Theory and the Resource-Based View highlight the role of global value chains as a conduit for companies to access advanced renewable energy innovations to improve their productive skills. The participation of global value chains provides firms with all the vital components, such as exposure to international markets, eco-friendly practices, and technological advancements, to accelerate their transition to cleaner energy solutions.

However, this study also highlights the short-run challenges of global value chain participation, especially in those countries or regions heavily dependent on energy-intensive manufacturing. As firms focus mainly on meeting the energy demands of international markets, GVCs have become a reason for increasing the dependency on conventional energy sources for a short period. They can temporarily delay the adoption of renewable energy technologies. However, the benefits of global value chain participation become more evident over the long term as the firms decrease technology costs and adopt cleaner energy solutions up to the mark of international environmental standards and because of the growing demand for sustainability in global markets.

The econometric analysis of this study shows that while global value chain participation damages renewable energy generation in the short term, it has significant positive long-term effects on renewable energy. GVC participation through firm and country collaboration triggers the usage of renewable energy by enhancing its long-term adoption according to results derived using the Pooled Mean Group (PMG) estimator. This research proves that Global Value Chains are essential for driving worldwide energy transitions throughout different periods. The critical role of digital technology appears as the primary force that drives renewable energy transitions. Companies obtain tools through digitalization that decrease expenses while maximizing energy efficiency and developing renewable power systems. The analysis reveals how digital technologies, particularly Artificial Intelligence and the Internet of Things and smart grids, improve energy management operations and operational efficiency. The real-time monitoring capability of digital platforms enables firms to identify inefficiencies, which subsequently allows them to put effective renewable energy solutions into practice. The Technological Diffusion Theory highlights the role of digitalization in facilitating the worldwide expansion of renewable energy technologies through cross-border knowledge sharing. This is particularly relevant to that context where firms from various countries and industries work together to develop and implement renewable energy solutions, such as the context of global value chains. This study shows the positive relationship between digitalization and renewable energy generation. The econometric analysis of this study supports the argument that digital tools are essential for promoting the integration of renewable energy into existing energy systems.

Moreover, this study specifically points out the challenges posed by digitalization, such as Jevons Paradox and Technological Lock-In. The rise of digital infrastructure, such as blockchain technologies and data centers, increases energy demand; therefore, digitalization may increase overall energy consumption by improving energy efficiency. However, the Technological Lock-In Theory indicates that firms may face difficulties transitioning towards renewable energy sources if they invest in digital infrastructures supporting non-renewable energy systems. The econometric analysis of this study proved that where digitalization has a positive short-term impact on renewable energy production in some cases meanwhile, it can also become a cause of the Lock-In effect. Due to the lock-in effect, firms are slow to adopt renewable energy solutions due to the high maintenance costs of their infrastructure.

This study comprehensively analyzes the relationship between global value chain participation and digitalization and the influence of this relationship on renewable energy generations. The findings of this study indicate that, particularly in those countries where the level of digitalization is above the average value, digitalization can increase the positive impact of GVCs, specifically on renewable energy adoption. The econometric analysis shows a positive and significant effect of the relationship between Global Value chain participation and digitalization on renewable energy generation. Digitalization enables firms to extract the full value from GVC participation in renewable energy transformation. The significant result of this research demonstrates the cooperative power that stems from GVCs paired with digital technologies for advancing worldwide energy system transitions. The combination of GVCs and digitalization produces a more powerful effect on renewable energy adoption in the long term than either factor. Policymakers and firms must dedicate efforts toward integrating digital technology solutions within their global value chains to maximize renewable energy benefits. Such measures increase sustainable energy practices between countries and the international expansion of renewable energy technologies.

5.1. Policy implementations

The research outcomes generate multiple substantial effects that influence policy development. Anticipating global value chains is crucial for policymakers who want to use technological advancement and knowledge sharing to create renewable energy production. Such policies drive quick acceptance of new technology and sustainable worldwide targets that lead to GVC integration, especially for developing country firms. Worldwide cooperation becomes possible through policy-established barrier reduction while organizations receive support to implement clean energy solutions. Special attention from policymakers becomes necessary when addressing digitalization challenges because increasing energy consumption rates and technological restrictions create vital issues. The opportunities from digitalization support renewable energy growth, although proper resource management is critical to avoid dangerous consequences. Creating sustainable policies needs to build infrastructure that stimulates businesses to implement renewable energy systems. Digital infrastructure needs specific specifications about its capacity to enhance energy usage levels.

Implementing these policies serves to develop the existing digital infrastructure needed for renewable energy systems in situations where technological lock-in creates challenges. The evidence proves digital technologies need proper integration with GVCs for renewable energy conversion to achieve maximum potential benefits. Elected officials must create national policies that endorse digital tools, including artificial intelligence, the Internet of Things, and smart grids, so firms can optimize their power usage and execute renewable energy solutions. Governments should create methods to quicken global clean energy system transformations by developing GVC-related digital transformation processes. This research extensively examines the influence of GVCs and digitalization advances on renewable energy transition. The global transition toward renewable energy becomes possible through GVC collaboration and digitalization, which achieve results by facilitating knowledge transfer and technological diffusion and implementing energy optimization systems. The investigation accepts both the positive impact on energy usage and the technical limitations while implementing these procedures. Proper management solutions will solve these difficulties and enable effective renewable energy transitions.

The partnership between GVCs and digitalization systems provides significant advancement opportunities for renewable energy adoption in countries with high digitalization capabilities. Renewable energy generation stands to gain more benefits through GVCs when policymakers work with firms to achieve digitalization integration. The focused GVC policies that drive integration between global value chains help achieve renewable energy adoption by managing digitalization needs to benefit global sustainability. This study deepens our comprehension regarding the active bond between GVCs and digitalization and renewable energy systems. The research findings aid policymakers in developing decisions while providing beneficial information to firms and researchers who strive to achieve enduring environmental sustainability and worldwide energy transitions.

5.2. Limitations and future study recommendations

Although this study thoroughly examines the interconnections between global value chains, labor force, gross fixed capital formation, digitalization, and GDP about renewable energy production, it recognizes specific limitations that future research could address. A significant limitation is the application of the PMG method, which presupposes consistent long-term relationships among various entities. This assumption may trivialize the varied and intricate effects these variables can exert in distinct global contexts, potentially neglecting unique regional or nation-specific factors that influence renewable energy production. Subsequent research could improve this study by utilizing more adaptable econometric models that permit fluctuating coefficients in both long-term and short-term dynamics. Furthermore, integrating a wider array of variables, including policy determinants or consumer behavior indicators, yield an enhanced understanding of the catalysts for renewable energy transitions and assist in formulating more effective energy policies.

CRediT authorship contribution statement

Long Zhang: Validation, Methodology, Investigation, Funding acquisition, Data curation. **Zuoxiang Zhao:** Resources, Investigation, Data curation, Conceptualization. **Ghulam Muhammad Qamri:** Writing – review & editing, Validation, Methodology, Formal analysis. **Samariddin Makhmudov:** Writing – review & editing, Resources.

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

Data will be made available on request.

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