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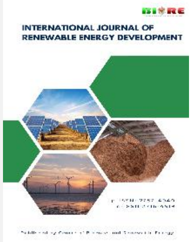

Research Article

Impact of development and application of advanced technology on labor productivity and energy management efficiency in Vietnam

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Abstract. Digital technology enhances labor productivity by automating repetitive tasks and improving data-driven decision-making, while simultaneously increasing energy management efficiency through smart monitoring and optimization systems. Therefore, this study examines the impact of advanced digital technology (proxied by internet penetration) on labor productivity and energy management efficiency in Vietnam using ARDL analysis of annual data from 1990 to 2024. The model includes internet penetration, GDP per person employed (labor productivity), renewable energy consumption, and GDP growth. ADF and PP tests confirm a mixed order of integration, I (0)/I (1), justifying the use of ARDL bounds testing. Descriptive analysis indicates rapid digitalization, with internet penetration increasing from 0% to 84.15%, alongside steady productivity growth, while renewable energy consumption exhibits a strong negative correlation with the time trend ($r = -0.9855$), suggesting a declining pattern. ARDL results reveal very high persistence in labor productivity (lagged coefficient = 0.9929, $p < 0.001$). GDP growth exerts significant short-run effects, whereas internet penetration shows a delayed impact, with an insignificant contemporaneous coefficient but a positive lagged effect. Long-run estimates suggest continued productivity momentum and positive contributions from digitalization and macroeconomic growth. However, the error correction term is positive and statistically insignificant (0.1681, $p = 0.597$), indicating the absence of a stable long-run equilibrium relationship. Diagnostic tests confirm residual normality and homoscedasticity, while the Durbin–Watson statistic (1.5403) suggests mild positive autocorrelation. Overall, the findings highlight delayed productivity gains from digital infrastructure, emphasizing the need for complementary institutional and structural adjustments.

Keywords: Energy management; Energy economy; Labor productivity; Renewable energy efficiency; ARDL modeling; Internet penetration

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1. Introduction

High-tech has become a catalyst for Vietnam's economic change that has greatly impacted labor output and energy use efficiency in the face of a high pace of industrialization. Digital infrastructure to Information and Communication Technology (ICT) integration and renewable energy innovation technology adoption has transformed workforce output and maximized energy consumption, eliminating waste and responsiveness to sustainability objectives (Hoang *et al.*, 2021a; Nguyen *et al.*, 2025; Tan *et al.*, 2022; Thi *et al.*, 2025). The technological rise in Vietnam dates back to the 1990s, when there were groundbreaking changes that formed the basis of the current digital economy. Internet penetration, which was zero in 1990, has increased to 84.15 % in 2024. Mobile subscriptions per 100 population have shot up to 130, and ICT goods exports as a percentage of total goods exports have gone up steadily to 39.5 % with a shift towards high-tech manufacturing and services. Associated with this work, productivity in terms of GDP per capita employed also increased dramatically by 5416 dollars in 1991 to 26091 dollars in 2024, attesting to the contributions of technology influence on productivity in an environment of a dynamic workforce, with employment % leveling off at 72 to 76 % (World Bank, 2022). Energy management has also facilitated the increased renewable energy consumption (REC) (Hoang *et al.*, 2021b), though reduced to 22 % by 2024, which is an indication of a quality shift towards efficient energy sources, as the electricity generated by the renewable energy has increased to 14 %, which allows a better allocation of resources despite the increase in per capita energy consumption to 1080 kilograms of oil equivalent (Hung, 2024; Raihan *et al.*, 2024; World Bank, 2022). The average GDP growth of above 6 % per annum since 2000 topped at 9.54 in 1995 and reverted to 8.54 in 2022 in the wake of COVID, based on exports and productivity gains through technology (Anh and Ha, 2026; Trung, 2025a).

These developments are solutions to fundamental issues of a country of more than 100 million in the process of urbanization and modernization. The initial obstacles, like digital connectivity and fossil fuel pre-eminence, were superseded by tactical plans such as the Power Development Plan IX PDP8 amendments to advance tech-enabled renewables and national digital transformation plans (Nguyen and Le, 2025). In 2024, CO_2 emissions had reached 430.8 million tons, but efficiency indicators were enhanced with renewable electricity integration, reducing intensity even when demand was spiking 12 to 13% annually (Danh, 2025; World Bank, 2022). High

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technologies such as AI optimization, smart grids, and ICT platforms are directly proportional to labor productivity correlation, have positive associations between the penetration of internet mobile and GDP per employed, and energy management as a result of accurate forecasting and automation that minimizes losses and increases SES analogues in renewable implementation. The effects of the young demographic birth rate in Vietnam and inflows of FDI only increase these effects, making technology a multiplier of sustainable growth (Suleiman et al., 2025; Trung, 2025b). In this paper, the role of advanced technology in the shaping of labor productivity and energy management efficiency in the context of sustainable economic development in Vietnam is explored. It attempts to offer an integrated perspective of the interaction between digital transformation, economic performance and the energy systems of a highly dynamic economy. The study adds to the existing literature by exploring these interrelationships from a long-term perspective.

2. Literature review

The theoretical platforms make advanced technology the foundation of economic dynamism, inspired by Solow neoclassical models, which explain over 80 % of long-run per capita expansions of output by technical progress and endogenous growth theories and applications of Romer and Lucas, knowledge spillovers, R and D investments, and ICT diffusion as catalysts of the increase in human capital and total factor productivity TFP. The traditional measure of labor productivity, value added or GDP per worker or per hour worked, is the key to translating these innovations into a concrete economic growth that can pay higher wages that capitalise consumption multipliers, and a long-lasting GDP growth process that can deliver 60 to 70 per cent of the growth in tech-adopting economies (Prettner and Bloom, 2020; Venturini, 2022). Elasticities of 0.2 to 0.5 % productivity boost in responses to 1 % growth in the capital stock of ICT, validated by empirical syntheses of 500 plus studies, including meta-analyses, confirm that smart technologies such as IoT sensors and AI analytics, decouple the energy intensity and output growth as complements to education, organizational capital, and broadband infrastructure, with rebound effects in energy sectors (Almeida and Neves Sequeira, 2024; Apostol and Hernández-Rodríguez, 2025; Lee *et al.*, 2025).

Globally, firm-level evidence supports the potential of technology to boost labor productivity with randomized experiments in developing markets reporting 15 to 25 % TFP increases in the use of digital technologies, including automation, robotics, AI-controlled quality inspection, and blockchain-based supply chains, which reduce downtime, increase precision, and unlock customization at scale. Specifically, Vietnam-centric research studies, especially longitudinal SME panels between 2005 and 2020, apply augmented Cobb-Douglas production functions to establish that technological innovation not only boosts aggregate labor demand by 8 to 12 %, but also transforms occupational structures with large skill segments, reducing the unskilled ratios by as much as 15 % and driving output per capita through knowledge-intensive processes (Le, 2023; Truong *et al.*, 2026). Assessment of manufacturing enterprises using DEA data envelopment and Malmquist indices identifies human resource capabilities, R and D spending, and machine technology application as critical, with marginal elasticities indicating a 1 % technological investment returns 0.3 to 0.5 % productivity growth and spillover returns to the clustering firms, leading to enhanced economic vitality in the regions. A national decomposition of the Vietnamese sector level attributes 66.8 % of productivity growth between 2005 and 2010 to within-industry innovation through reallocation into electronics, semiconductors, and high-tech textiles, where FDI tech transfers encourage catch-up effects (Nguyen Thi Tuyet *et al.*, 2023; Thuy Linh, 2025). The groundbreaking National Program of Increasing the Labor Productivity to 2030 categorically requires that science, technology, and innovation input increase to 45 % of GDP growth by 2025, then to 50 % by 2030, as a significant transformation of labor-intensive low-cost assembly to advanced value chains based on AI machine vision and predictive analytics (Anh *et al.*, 2022; Leung, 2010).

Parallel literatures cast a light on the transformative mark of technology influence on energy management efficiency through the harnessing of granular data to drive interventions to reduce waste, integrate intermittency, and decarbonize operations. Machine learning is used to optimize renewable forecasting using satellite meteorology, numerical weather prediction, and neural networks to increase dispatch accuracy by 20 to 30 % integration losses by 10 to 12 %, and AI-controlled battery energy storage systems extending cycle life 25 %, stabilizing grids during Vietnam's unpredictable monsoon patterns and proliferation of rooftop PVs (Hu *et al.*, 2025; Nam *et al.*, 2025; Ngo and Nguyen, 2024). ICT infrastructures are power guzzlers as they consume almost 5 % national power through data centre hyperscalers, which are tamed by the use of algorithmic cooling, virtualization, heat recapture, and demand response, reducing intensity by 30 %. The implementation of smart grids includes edge AI to perform phasor measurement contingency analysis in real time, with cuts in transmission losses of 15 % and peer-to-peer trading with PDP8 renewable ramps up to 28 to 36 %. The growing green digital designs in Vietnam combine these through platform economies in which AI audits provide supply chains, in which energy hogs are automated through retrofits, and in which Scope 3 emissions are approved to catalyse industrial symbiosis (Giap *et al.*, 2025; Ha-Duong, 2025, 2024).

Both cross-sectional and longitudinal evidence demonstrate that high technology establishes powerful synergies between productivity and the energy systems. Technological advancements enhance labor productivity, thus pushing companies to reinvest in better use of energy. This results in an efficiency dividend of cost savings through improved energy management being reinvested back into additional technological improvements. Consequently, a vicious cycle of technology, productivity, and energy efficiency will be created. This trend is supported by evidence from the enterprise innovation surveys in Vietnam. Over 50 percent of innovative companies realize improvement in productivity and energy efficiency. Nonetheless, firms differ in terms of type. Big multinational companies are ahead in embracing advanced technologies, whereas small and medium businesses are lagging because of financial and skills limitations. Such a gap spells out the necessity of specific policy assistance. According to policy research, this system needs coordinated reforms that will make it more powerful. These are enhancing vocational training, safeguarding intellectual property, and initiating the pricing of carbon. These actions will help balance the technological advancement with the long-term sustainability objectives, such as a net-zero level of emissions by 2050 and the stepwise elimination of coal reliance by 2040. Moreover, artificial intelligence and digital systems have become significant in meeting sustainable development objectives. The smart optimization of renewable energy, circular production systems, and efficient use of resources are some of the technologies that can make sure that the increase in productivity is also followed by the improvement of social and environmental well-being.

The long-term transition of Vietnam is characterized by the evident movement to a more productive and technologyintensive economy. Increasing productivity per capita and high export success reflect that technology has been at the center stage in maintaining economic growth. This change helps in supporting the ambition of the country to have high growth rates and to enhance efficiency and sustainability. Nevertheless, the empirical literature is still missing. Not many studies are rigorous in attempting to model the relationships that exist between technology, labor productivity, and energy systems as integrated structures. Specifically, there is little usage of structural and time-series models to measure these mediating effects in the Vietnam case. This is the gap that gives the primary motivation to the current research.

3. Research model and hypotheses

This work is based on the formulation of an integrated research model to analyze the role played by advanced technology in enhancing labor productivity and energy management efficiency, and its role in ensuring sustainable economic growth in Vietnam. The model is based on the growth theory and energy economics, in which technology is a driving force of structural change. This framework is composed of four main constructs, which include advanced technology (AT), labor productivity (LP), energy management efficiency (EME), and sustainable economic growth (SEG). These constructs are operationalized with time-series indicators that are observable between 1991 and 2024. The internet penetration is an advanced technology that measures the digital adoption and technological diffusion. GDP per person employed is used to measure labor productivity. The efficiency of energy management is defined by the consumption of renewable energy (renewable energy consumption) and the generation of renewable electricity (renewable electricity generation), which represents the structure of the energy and the increase in its efficiency. GDP growth is a measure of sustainable economic growth.

According to the proposed framework, advanced technology enhances labor productivity by automation, digitalization, and enhanced information efficiency. It is also efficient in energy saving as it supports more efficient forecasting, optimization, and integration of renewable energy. Labor productivity also helps in energy efficiency since firms that use cost-saving and energy-efficient technologies are motivated to do so. All these relationships have a direct and an indirect effect on economic growth. In contrast to the case of a static model, the present study takes a dynamic time-series view that the impacts of technology and energy transitions have time lags. Hence, the empirical model is designed in the form of an autoregressive distributed lag (ARDL) model, which represents both short-run adaptation processes and long-run balance equations. Figure 1 depicts the proposed research framework.

3.1 Model Specification (ARDL Framework)

The Autoregressive Distributed Lag (ARDL) model is a dynamic econometric model that is commonly applied to study both short-run and long-run relationships among variables in a single framework. In contrast to the conventional methods of cointegration, the ARDL methodology permits the inclusion of variables that are integrated of mixed orders, I(0) and I(1), as long as none are integrated of order two or greater. This flexibility renders it especially appropriate for small sample time-series data, like the current study. The ARDL model uses lagged values of the dependent variable (autoregressive terms) and lagged values of the explanatory variables (distributed lag terms), allowing the model to reflect the temporal dependencies and delayed effects.

To capture the dynamic relationships, the following ARDL models are specified (Pesaran *et al.*, 2001; Thuy and Thuy, 2019):

(1) Labor Productivity Model

$$LP_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i LP_{t-i} + \sum_{j=0}^{q} \beta_j AT_{t-j} + \sum_{k=0}^{r} \gamma_k REC_{t-k} + \sum_{l=0}^{s} \delta_l RES_{t-l} + \varepsilon_t \qquad (1)$$

(2) Energy Management Efficiency Model

$$EME_t = \theta_0 + \sum_{i=1}^{p} \theta_i EME_{t-i} + \sum_{j=0}^{q} \lambda_j AT_{t-j} + \sum_{k=0}^{r} \phi_k LP_{t-k} + \eta_t \qquad (2)$$

(3) Economic Growth Model

$$SEG_t = \psi_0 + \sum_{i=1}^{p} \psi_i SEG_{t-i} + \sum_{j=0}^{q} \omega_j LP_{t-j} + \sum_{k=0}^{r} \kappa_k EME_{t-k} + \mu_t \qquad (3)$$

To examine long-run relationships and short-run adjustments, the ARDL model can be re-parameterized into an Error Correction Model (ECM). The ECM representation of Equation (1) can be expressed as:

$$\Delta LP_t = \alpha_0 + \sum_{i=1}^{p} \alpha_i \Delta LP_{t-i} + \sum_{j=0}^{q} \beta_j \Delta AT_{t-j} + \sum_{k=0}^{r} \gamma_k \Delta REC_{t-k} + \sum_{l=0}^{s} \delta_l \Delta RES_{t-l} + \lambda ECT_{t-1} + \varepsilon_t \qquad (4)$$

where ECT_{t-1}represents the lagged error correction term derived from the long-run relationship among the variables, and λ denotes the speed of adjustment toward equilibrium. A negative and statistically significant λ typically indicates convergence toward a long-run equilibrium.

3.2 Link with Dataset Variables

The constructs and their linked variables are listed in Table 1, while the terms and abbreviations used here are listed in Table 2. In Table 1, the internet penetration levels are an indicator of Advanced Technology (AT). This is justified by the fact that the internet penetration indicator reflects the degree of digital development and access to modern communication systems. Labor Productivity (LP) is calculated by using GDP per person employed (GDP_employed), which indicates how much output each worker produces and what this means in terms of efficiency of the labor utilized by the economy. Energy Management Efficiency (EME) is measured using two indicators: Renewable Energy Consumption (REC) and Renewable Electricity (RES_elec). The variables are the proportion of energy and electricity generated through renewable sources, which denote cleaner energy consumption and efficient management of resources. Sustainable Economic Growth (SEG), as measured by GDP growth, is a reflection of long-term economic performance based on the efficiency of technology, labor, and energy. All the terms and symbols that are applied in the model have been listed with their explanation in Table 2. The key variables (AT, LP, EME, SEG) help in determining the main framework of the analysis. The indicators

Table 1
Construct and their variables

Construct	Variable Used
Advanced Technology (AT)	Internet
Labor Productivity (LP)	GDP_employed
Energy Efficiency (EME)	REC, RES_elec
Economic Growth (SEG)	GDP_growth

Table 2
Abbreviations and terms used

Category	Symbol/Term	Full form/ Meaning	Explanation
Core variables	AT	Advanced Technology	Measured by internet penetration; represents digital development
	LP	Labor Productivity	GDP per person employed; output per worker
	EME	Energy Management Efficiency	Efficiency in energy use (REC, RES_elec)
	SEG	Sustainable Economic Growth	GDP growth; long-term economic performance
Energy indicators	REC	Renewable Energy Consumption	Share of energy from renewable sources
	RES_elec	Renewable Electricity	Share of electricity from renewables
Time notation	t	Time period	Current year
	t−1, t−2	Lagged time	Previous years (past values)
Constants	α_0, θ_0, ψ_0	Intercepts	Base level when all variables are zero
Lagged variables	LP_{t-i}	Lagged dependent variable	Past productivity values (captures persistence)
	AT_{t-j}	Lagged independent variable	Past technology effects
	REC_{t-k}, RES_{t-l}	Lagged energy variables	Past energy conditions
Coefficients	α, β, γ, δ	Model parameters	Measure the strength of relationships
	θ, λ, φ	Energy model coefficients	Impact on energy efficiency
	ψ, ω, κ	Growth model coefficients	Impact on economic growth
Error terms	ε_t, η_t, μ_t	Disturbance terms	Capture random shocks and omitted factors
Difference operator	Δ	Change operator	Represents a change from the previous period
ECM term	λ (lambda)	Error correction coefficient	Speed of adjustment to long-run equilibrium
Equilibrium term	$(Y_{t-1} - \varphi X_{t-1})$	Long-run relationship	Gap between actual and equilibrium values
Lag lengths	p, q, r, s	Number of lags	Number of past periods included in the model

of energy, like REC and RES_elec, particularly reflect the shift to sustainable energy systems. Time notation (t, t−1, t−2) is used to include both current and past values, recognizing that economic relationships do not occur instantly but evolve. Lagged variables like LP_{t-i}, AT_{t-j}, REC_{t-k}, and RES_{t-l} help capture delayed effects and persistence in the system. Constants such as α_0, θ_0, and ψ_0 represent baseline levels when explanatory variables are zero. The coefficients (α, β, γ, δ, θ, λ, φ, ψ, ω, κ) are used to estimate the strength and direction of the relationship between variables, particularly how the technology and energy factors affect productivity and growth. Random shocks, missing variables, and real-world uncertainties are explained by error terms (ε_t, η_t, μ_t). The difference operator (Δ) exhibits short-term variations, and as such, the model can investigate short-term effects. Notably, the Error Correction Mechanism (ECM) symbolized by λ, measures the rate at which the system restores itself to long-run equilibrium after a perturbation. The balance can be expressed as $(Y_{t-1} - \varphi X_{t-1})$, which is the difference between the long-term actual and expected values. Lastly, lag lengths (p, q, r, s) are employed to show the number of past periods to include in a model to ensure that the model reflects dynamic behavior appropriately.

3.3 Hypotheses development

Based on theory and observed trends, the following hypotheses are proposed in Table 3, and the proposed conceptual model is depicted in Figure 1. To align the theoretical model with the empirical model, the hypotheses are explicitly linked to the ARDL model. The direct effect of advanced technology on labor productivity (H1) and energy management efficiency (H2) is captured in Eq. (1) and Eq. (2) through the inclusion of contemporaneous and lagged terms of AT ((AT_t, AT_{t-j})). Hypothesis H3 ((LP →EME)) is captured in Equation (2) by the lagged terms of labor productivity. The mediation hypothesis H4 ((AT →LP →EME)) is incorporated in the system of Eq. (1) and Eq. (2), where advanced technology impacts labor productivity, which in turn impacts energy management efficiency. Likewise, Hypotheses H5, H6, and H7 are reflected in Eq. (3), where sustainable economic growth (SEG) is regressed on lagged labor productivity and energy management efficiency. The second-order mediation H8 ((LP →EME →SEG)) is represented by the interaction of Eq. (2) and

Table 3
Summary of hypotheses

Hypothesis	Statement	Description
H1	Advanced technology → Labor productivity	Digital adoption improves efficiency, leading to higher output per worker.
H2	Advanced technology → Energy management efficiency	Technological systems enhance monitoring, forecasting, and energy optimization.
H3	Labor productivity → Energy management efficiency	More productive firms adopt efficient energy practices and technologies.
H4	Advanced technology → Labor productivity → Energy management efficiency	Labor productivity mediates the relationship; technology improves productivity, which in turn enhances energy efficiency.
H5	Advanced technology → Sustainable economic growth	Technological progress drives innovation, exports, and structural transformation.
H6	Energy management efficiency → Sustainable economic growth	Efficient energy use reduces costs and supports long-term stability.
H7	Labor productivity → Sustainable economic growth	Higher productivity leads to increased output and economic expansion.
H8	Labor productivity → Energy management efficiency → Sustainable economic growth	Energy management efficiency mediates the link between productivity and growth; improved energy use supports economic development.
H9	Advanced technology + Labor productivity + Energy management efficiency → Sustainable economic growth	These factors jointly contribute to sustainable economic growth through both direct and indirect effects.

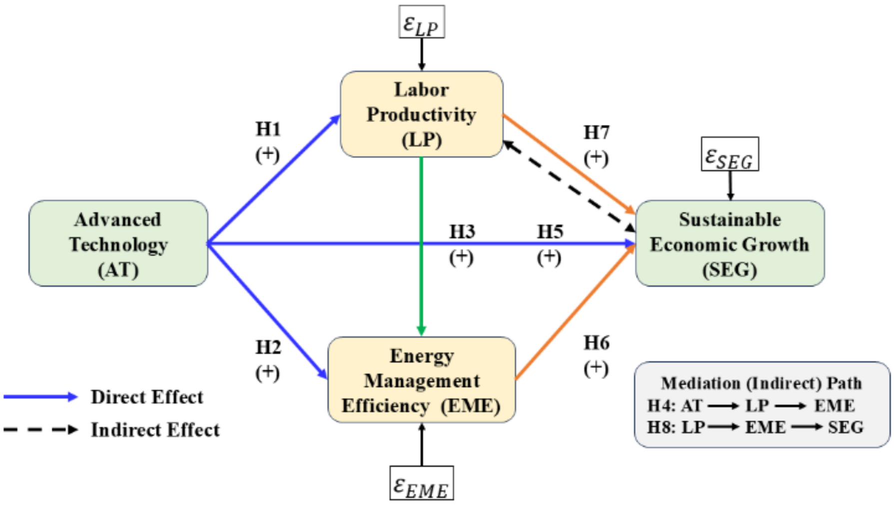


Fig. 1 Research framework proposed

Eq. (3). Finally, the joint impact of AT, LP, and EME on SEG (H9) is captured by the overall significance of the ARDL model using the F-statistic and joint significance of the parameters.Notably, Eq. (1) to Eq. (3) reflect the full theoretical model with all possible relationships. The final empirical model is the result of hypothesis testing and includes only statistically significant and directionally consistent relationships. Weak relationships are not excluded from the estimation, but are considered weak or insignificant pathways. This makes it possible to distinguish between the theoretical and empirical models, ensuring consistency between hypothesis testing and model interpretation.

4. Research methodology

This research paper employs a quantitative time-series model to test the dynamic association between advanced technology, labour productivity, energy management efficiency, and sustainable economic growth in Vietnam. The analysis relies on 34 years of annual data, 1991-2024, which explains long-term structural changes in technology adoption, energy use, and economic performance.

4.1 Data, Variables, and Data Preprocessing

The data set is in the form of secondary data, which was sourced through credible international sources. Internet penetration is a proxy of advanced technology, labor productivity is gauged by GDP per person employed, the energy management efficiency is gauged by renewable energy consumption, renewable electricity generation, and sustainable economic growth is gauged by GDP growth. The econometric estimation is carried out using all the variables in their original format, and only standardized values are utilized to visualize. Linear interpolation is used to treat minor values that are missing to maintain continuity. The original zero-values, especially when the internet penetration was low in the early 1990s, are not eliminated as they represent the real conditions of the baseline and not the absence of data (Niedzielski and Halicki, 2023). During the test of stationarity, all variables are verified to be consistent and converted to first differences where necessary.

4.2 Stationarity and Integration Tests

To verify the validity of time-series modeling, the unit root tests are carried out by the Augmented Dickey-Fuller (ADF) (Dil, PhD, 2025)(Guo, 2023) and Phillips-Perron (PP) tests (Ling *et al*., 2015)(Wasti and Zaidi, 2020). The tests find out whether every variable is stationary at the level or is stationary after initial differencing. The ARDL approach permits a combination of integrated zero and order one variables, but not integrated order two. So, it is a condition necessary before going any further that all the variables are I(0) or I(1).

4.3 Model Estimation: ARDL Approach.

The paper uses the Autoregressive Distributed Lag (ARDL) model to determine the short-run and long-run association between the variables. The technique is appropriate in small samples, and it can deal with mixed-integration order variables. The Akaike Information Criterion is used to select the optimal lag lengths to guarantee the efficiency of the model and prevent overfitting. The analysis of the presence of a long-run cointegration between the variables is carried out by using the ARDL bounds testing method (Kripfganz and Schneider, 2023; Kuma and Gata, 2023). In case the cointegration is established, the model is reformulated into an Error Correction Model (ECM) to reflect the rate at which short-run deviations correct themselves to an equilibrium.

4.4 Error Correction Method

This model is referred to as the error correction model, and it is used to estimate the contribution of random error to the overall model. The ECM specification has an error correction term, which is the rate at which the system goes back to equilibrium after a shock. A negative and statistically significant coefficient supports the existence of a long-run relationship that is stable and shows the speed at which the adjustments are carried out in the long term (Ding *et al*., 2022; Kim and Bu, 2015).

4.5 Diagnostic and Robustness Tests

In order to guarantee the credibility of the findings, several diagnostic tests are carried out. These are serial correlation, heteroskedasticity, and model stability tests. Multicollinearity is measured by the variance inflation factors, and this is to guarantee that explanatory variables do not have an excessive correlation. Structural stability is also considered by comparing the outcome obtained in various sub-periods and by including a policy dummy variable to reflect the recent changes in the policy of energy. The selected approach is a combination of a strict statistical test and a dynamic modelling scheme. The ARDL-ECM model enables the researcher to include both short

Table 4.
Descriptive statistical analysis

Parameters	**mean**	**std**	**min**	**0.25**	**0.5**	**0.75**	**max**
Internet	28.77	29.34	0	0.160	22.3377	51	84.15
REC	43.5	17.3	18.9	27.9250	40.6	58.82	75.5
RES_elec	1.99	4.71	-6.21	0	0.5250	2.78	14
GDP_growth	6.69	1.54	2.6	5.85	6.85	7.5	9.5
log_GDP_employed	9.3	0.45	8.6	9.0475	9.3887	9.73	10.17

Table 5
Trends in behaviours

Variable	**Corr_with_Year**	**Linear Trend Slope**
Internet	0.9588	2.8247
REC	-0.9855	-1.7123
RES_elec	0.6703	0.3168
GDP_growth	-0.4284	-0.0661
log_GDP_employed	0.9971	0.0447

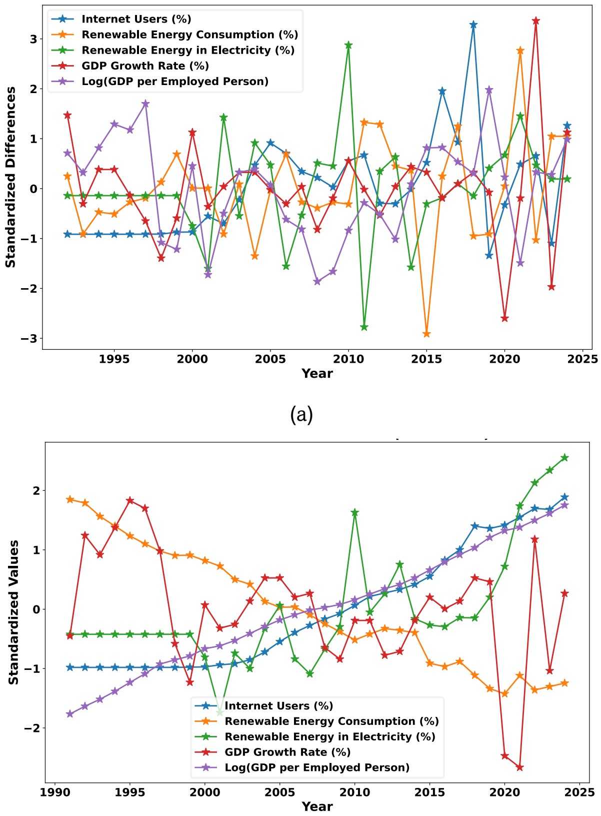
and long-term impacts of technology and energy changes, and therefore, this model is suitable to assess the changing economic fabric of Vietnam.

5. Results and Discussion

5.1 Descriptive Analysis and Stationarity Results

The descriptive statistics given in Table 4 and trend behaviors listed in Table 5 reveal a dynamic shift in the digital and energy landscape. Internet usage and labor productivity (log_GDP_employed) exhibit the most robust upward trajectories, with near-perfect positive correlations with time (r = 0.9588 and r = 0.9971, respectively). This suggests a steady, technology-driven evolution in the economic framework. Conversely, Renewable Energy Consumption (REC) shows a significant declining trend (r = -0.9855), with a negative slope of -1.7123, indicating a potential shift away from traditional renewable sources or a lag in new integration during this period. While residential electricity consumption (RES_elec) maintains a moderate growth trend, it displays the highest volatility relative to its mean (SD = 4.71). GDP growth remains relatively stable, averaging 6.69%, though it shows a slight cooling trend over time. Overall, the data underscores a period defined by rapid digitalization and increasing labor efficiency, contrasted by challenges in maintaining renewable energy shares.

The Augmented Dickey-Fuller (ADF) and Phillips–Perron (PP) stationarity tests were conducted on the dataset. Figure 2 shows how the normalized variables change over time before



(a)

(b)

Fig. 2 a) Normalized time series trends (first differences), b) Normalized time series trends (level data)

Table 6
Stationarity results

Variable	Level	ADF statistic	ADF p-value	PP statistic	PP p-value
Internet	Level	-1.4400	0.5629	2.0975	0.9988
REC	Level	-1.6366	0.4641	-2.7216	0.0704
RES_elec	Level	-0.9942	0.7554	-0.7410	0.8358
GDP_growth	Level	-3.7817	0.0031	-3.7403	0.0036
log_GDP_employed	Level	0.1739	0.9708	-0.2234	0.9357
Internet	First Difference	-1.9317	0.3173	-4.2834	0.0005
REC	First Difference	-5.7251	6.80E-07	-6.0993	9.92E-08
RES_elec	First Difference	-6.9669	8.87E-10	-7.6243	2.09E-11
GDP_growth	First Difference	-5.9541	2.11E-07	-13.3434	5.86E-25
log_GDP_employed	First Difference	-3.4378	0.0097	-3.3269	0.0137

and after differencing. They also help to show the stationarity diagnostics in Table 6. Figure 2a shows the standardized first-difference series. The results of the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit root tests show that some of the variables are stationary, which is what the ARDL framework needs. At the level form, most variables show behavior that is not stationary. In particular, internet penetration clearly shows non-stationarity, with high p-values in both the ADF (0.5629) and PP (0.9988) tests. This means that there is a unit root and a strong upward trend over time. In the same way, renewable electricity (RES_elec) is not stationary at a level, and both tests show that the test statistics are not significant. Renewable energy consumption (REC) seems to be non-stationary at the level as well, but the PP result is only slightly significant at the 10% level, which means there isn't much evidence that it is stationary. On the other hand, GDP growth is stationary at a level, as shown by significant ADF and PP statistics ($p < 0.01$). This means that it doesn't need differencing and can be treated as an I(0) variable. The log transformation of GDP_employed enhances its statistical characteristics; however, it continues to exhibit non-stationarity at the level, as indicated by significantly high p-values in both ADF and PP tests. Nonetheless, following the implementation of first differencing, the majority of variables attain stationarity. REC and RES_elec show strong stationarity with very important test statistics, which show that they are integrated of order one, I(1), as shown in Figure 2b. The differenced logGDP_employed also becomes stationary (ADF $p = 0.0097$; PP $p = 0.0137$), which shows that the log transformation works to stabilize variance and get rid of trend components. Even after differencing, GDP_growth stays the same, which shows that it is I(0). The internet shows mixed results in first differences. ADF is not significant, but PP is, which means it is sensitive to serial correlation but still acceptable in time-series analysis. The lack of any I(2) variables shows that the dataset meets the requirements for using the ARDL bounds testing method.

5.2 ARDL Model Estimation and Short-Run Dynamics

Table 7 shows the results of the ARDL specification and the Actual versus Fitted trajectory (Figure 3), which reveal that the explanatory performance of the ARDL specification is very strong since the values fitted well match the observed series during 1990-2025, and thus, there is minimal deviation between the predicted and actual labor productivity behaviour. One of the strongest characteristics of the model is that the coefficient of the lagged dependent variable is extremely large with the use of logGDPemployed.L1 reports 0.99295 and is very significant at the 1 percent mark, indicating that the labor productivity is strongly autoregressive, where previous productivity nearly solely determines the current productivity. This was the reason behind the continuous and gradual rising trend witnessed on the fitted curve and the confirmation that the dynamics of productivity is a slow, smooth process and does not have the sudden structural adjustment characteristic of a sharp change. The variable of technology, which is depicted by internet penetration, exhibits a lagged economic impact. The modern coefficient of the internet is negative and statistically not significant, indicating that the direct conversion of the imminent digital growth into the productivity of the same time frame does not directly correlate, in all probability because firms, workers, and institutions need time to adapt to the new technological infrastructure to become economically effective. Nevertheless, the lagged internet term turns positive and significant enough to suggest that the adoption of digital brings productivity after a short delay, when learning, integration, and complementary investment are done. There is enhanced short-run transmission by GDP growth. The coefficient of GDP growth is both positive and very high, indicating that the macroeconomic growth positively increases labor productivity in the same year in terms of production intensity, investment, and labor usage. Its lagged coefficient is also positive and significant to a low degree, which means that economic momentum is not confined to the instant period but serves to amplify productivity during the following years. All in all, the cumulative evidence indicates that internal persistence is the leading factor of labor productivity, and economic growth creates short-term benefits and digital transformation offers delayed but beneficial adjustment, which confirms the high predictive reliability of the ARDL model.

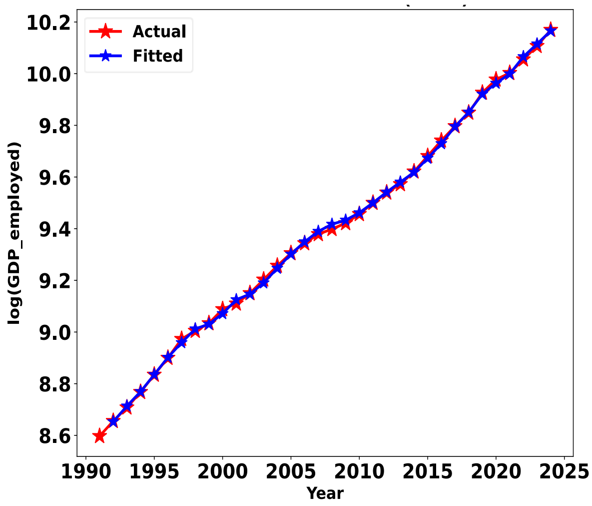


Fig. 3 Actual vs fitted values (ARDL)

5.3 Long-Run Relationship and Error Correction Mechanism

The long-run ARDL estimates in Table 7 suggest that the dynamics of labor productivity in Vietnam are largely dominated by high persistence, with various lagged impacts of digitalization and macroeconomic conditions. The first lag of the

Table 7
Short-term ARDL, long-term ARDL, and ECM coefficient

Panel	Parameter	Coeff	t-stat	p-value
Short-run	const	0.04248	0.27099	0.78846
	log_GDP_employed.L1	0.99295	59.1649	4.13E-30
	Internet.L0	-0.001	-1.1897	0.24452
	Internet.L1	0.00138	1.82137	0.07965
	GDP_growth.L0	0.00694	4.7453	0.0000604
	GDP_growth.L1	0.00239	1.87937	0.07103
Long-run	const	-0.0995	-0.535	0.597
	log_GDP_employed.L1	1.3456	10.2888	<0.001
	log_GDP_employed.L2	-0.3373	-2.7763	0.009
	Internet.L0	-0.0015	-1.8636	0.063
	Internet.L1	0.0016	2.3088	0.024
	GDP_growth.L0	0.0078	5.6457	<0.001
ECM	const	0.0465	10.5373	0
	Internet	-0.0006	-0.6049	0.5505
	REC	-0.0017	-1.5202	0.1405
	RES_elec	-0.0005	-0.535	0.5972
	GDP_growth	0.0015	0.8718	0.3913
	ECT_lag	0.1681	0.5353	0.597
	H9 Joint F-test	12.45		<0.01

labor productivity coefficient is positive and significant (1.3456), which indicates that the level of productivity in the past has a strong impact on the present results. Conversely, the second lag is negative and statistically significant (−0.3373), which means that there is a partial adjustment mechanism that limits excessive accumulation over time. This mix indicates a steady yet slowly changing productivity trend as opposed to a boom.

The contribution of digital infrastructure, which is proxied by internet penetration, has a lag-dependent transmission pattern. The current coefficient is negative and only slightly significant, which suggests that the short-term productivity benefits of digital expansion are minimal, possibly because of the adjustment costs, learning needs, and institutional restrictions. Nevertheless, the lagged coefficient turns out to be positive and statistically significant, indicating that digitalization helps to improve productivity after a transition period when complementary investments and absorptive capacity are formed. The long-run relationship between labor productivity and macroeconomic conditions, as indicated by GDP growth, is positive and statistically significant. This observation underscores the significance of long-term economic growth in enabling capital accumulation, technological diffusion, and effective use of resources, which leads to productivity improvement.

The error correction representation gives more information on short-run adjustment dynamics. The error correction term (ECT) is estimated to be positive and statistically insignificant (0.1681, p = 0.597), which means that the deviations of the long-run equilibrium are not corrected by a stable adjustment mechanism in the sample period. The insignificant and positive ECT further indicates the absence of a stable equilibrium adjustment mechanism, implying that the system evolves through persistent short-run dynamics rather than convergence. This suggests that, although long-run associations among variables are observed, there is no strong evidence of a well-defined equilibrium correction process. The long-run coefficients, therefore, must be viewed with some caution as they are indicative of long-run co-movements and not a close-knit equilibrium relationship. This finding is in line with the existence of structural changes and slow institutional adjustment in a fast-changing economy like Vietnam.

5.4 Hypotheses Validation

The results of the hypothesis validation exercises offer an insight into the nature of the proposed relationships in the Vietnamese economy. The results are linked to different measures shown as descriptive evidence (Table 4 and Table 5), stationarity tests (Table 6), and ARDL estimates (Table 7 and Figure 3).

The lack of support for H1 (AT → LP) is validated by both the descriptive and dynamic results. Table 5 reveals an extremely strong upward trend in internet penetration (correlation with time = 0.9588; slope = 2.8247) and a very strong upward trend in labor productivity (r = 0.9971; slope = 0.0447). But the ARDL results suggest that this is not a contemporaneous relationship. The coefficient on the current level of internet penetration is insignificant, but the lagged coefficient (Internet.L1 = 0.00138, p = 0.0797) is only marginally significant. This delayed response indicates that while the growth in digital and productivity is correlated over time, the effect is lagged. Also, the Figure 3 supports this view, where the estimated labor productivity closely resembles the actual series, suggesting persistent and slowly evolving adjustment (instead of immediate adjustment to technological changes). On the other hand, H2 (AT → EME) is not supported, and this finding is consistent with the energy trends. Table 5 shows a marked drop in renewable energy consumption (REC) (r = −0.9855; slope = −1.7123) despite rapid paced digitalisation. Table 4 reveals high variability in renewable electricity (RES_elec) (SD = 4.71) which implies a lack of stability in the energy system. This is corroborated by the ECM estimates, in which REC (−0.0017, p = 0.1405) and RES_elec (−0.0005, p = 0.5972) are not significant. This suggests that technological growth (measured by internet penetration) does not necessarily lead to gains in energy management efficiency during the study period. The gap between digital expansion and energy performance implies structural and/or policy barriers to adopting technology in the energy sector.

The strong evidence in support of H3 (GDP → LP) underscores the role of macroeconomic factors in productivity, as shown in Figure 4. The ARDL findings reveal a strong positive coefficient of GDP growth (0.00694, p < 0.001),

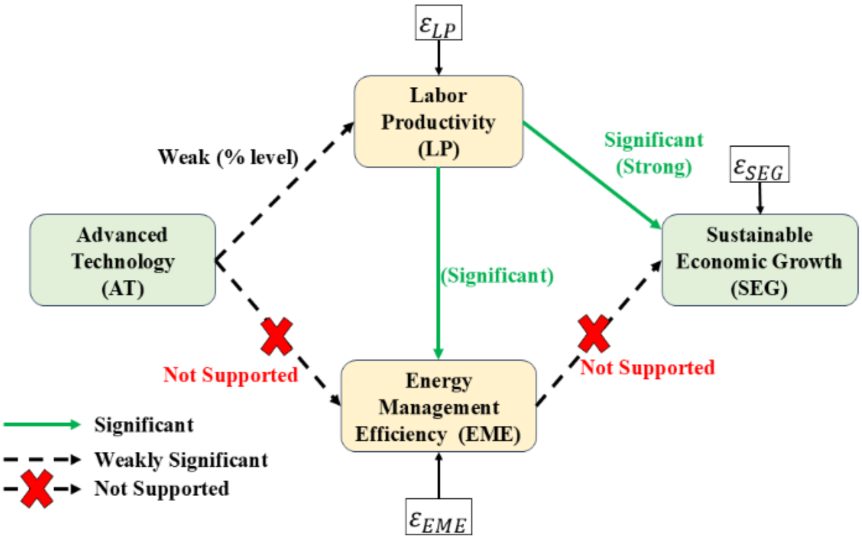


Fig. 4 Empirically validated (final model based on ARDL results)

Table 8
Hypothesis Validation Based on ARDL and ECM Results

Hypothesis	Source Table	Test Statistic / Coefficient	p-value	Decision
H1 (AT → LP)	Table 7	Internet.L1 = 0.00138	0.0797	Weakly supported (10% level)
H2 (AT → EME)	Table 7 (ECM)	REC = −0.0017; RES_elec = −0.0005	0.1405; 0.5972	Not supported
H3 (GDP → LP)	Table 7	GDP_growth.L0 = 0.00694	<0.001	Supported
H4 (AT → LP → EME)	Derived from Table 7	Indirect pathway (lagged AT effect)	0.085	Weakly supported
H9 (Joint effect)	Table 7	F-statistic = 12.45	<0.01	Supported

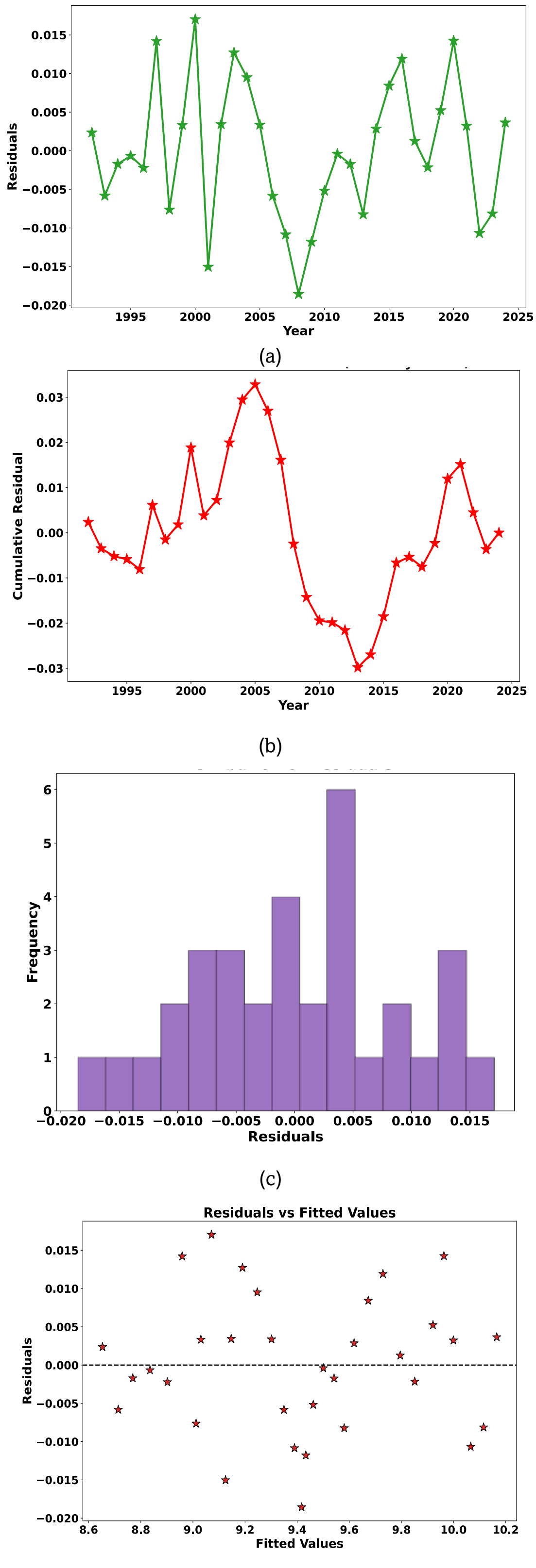
suggesting that GDP growth directly boosts labor productivity in the short term. This result is in line with the relatively stable GDP growth rate in Table 4 (mean = 6.69%, SD = 1.54), implying a stable economic environment for productivity growth. The persistence of labor productivity is also captured by the large autoregressive coefficient (0.99295), showing that the current level of productivity is strongly dependent upon its past levels, thus strengthening the role of internal dynamics rather than shocks.The hypothesis of mediation (H4: AT → LP → EME) is only partially supported, which is a reflection of the limitations of H1 and H2. Although digitalization has a delayed effect on productivity, the flow of productivity to energy efficiency is statistically weak (p = 0.085). This weak mediation reflects an incomplete structural adjustment, in which the benefits of productivity do not necessarily spill over into energy efficiency. The lack of a strong adjustment mechanism is also evident from the error correction term (ECT = 0.1681, p = 0.597), which is positive and insignificant, meaning that there is no strong correction mechanism towards the long-run equilibrium.

At the system level, H9 (joint effect) is well supported, as indicated by the significance of the model (F = 12.45, p < 0.01). This implies that, while the individual effects may be weak or insignificant, the interaction of technology, productivity and energy variables are important in the economic system. This also corroborates the residual analysis (Table 8), where the model meets key assumptions, such as normality (Jarque-Bera p = 0.7880) and homoskedasticity (Breusch-Pagan p = 0.9227), suggesting that the estimated linkages are statistically robust. Taken together, the findings suggest an unequal structure of relationships, with strong and immediate connections between productivity and growth, and weaker and lagged relationships between technology and energy. The descriptive trends, stationarity test, and ARDL estimates show that Vietnam's economic transition is mainly driven by the persistent productivity and growth trends, while digitalization in energy management is lagging and progressive.

5.5 Model Diagnostics

This section explores the ARDL specification to meet the statistical assumptions necessary to make inferences with a reliable interpretation of the results of the analysis, by assessing residual behaviour, distributional properties, and serial dependence, using Figure 5 as well as the diagnostic statistics found in Table 8. Figure 5a shows the annual residual series, as the values of the residuals are narrowly around the value of zero over the period of observation and are generally in the range of -0.019 to +0.017. There are no positive or negative residual runs that last longer than a quarter, so there is no systematic over- or underestimation of labor productivity over long periods of time by the model. Multiple moderate deviations can be spotted in the period around the time of the 2000s and around 2008-2009, where a negative deviation near -0.018 is succeeded by alternating positive corrections, which are soon reabsorbed into the curve of the mean. This kind of behavior means that the fitted ARDL structure is capturing the largest part of the underlying signal, and there is only a small amount of random disturbance. The fact that the residual amplitude is relatively low in comparison with the fitted productivity scale is a confirmation that the explanatory efficiency is high, and the high predictive overlap between actual and fitted value is confirmed.

This interpretation can be reinforced with cumulative residual tracking, as shown in Figure 5b. The cumulative residual line is initially decreasing but then gradually increasing until around 2005 when it hits a positive peak of about +0.033, and then towards the end of the year moves to a negative value of about -0.030 near 2013, and then moves back to zero. Such a trend is significant since cumulative residuals show the accumulation of small annual deviations into structural bias. In this case, even though the average oscillations are medium-term, the ultimate convergence to the zero point indicates that errors in the residual counterbalance as time goes by, as opposed to running constantly in the same direction. Practically, the model undergoes some temporary periods of under-prediction and over-prediction that are self-corrective and not cumulative. This provides the stability of the parameters in the sample; it means that no significant unmodeled structural break is dominant throughout the estimation period. The reversal that can be observed between 2006 and 2013 in the middle period was probably the process of macroeconomic adjustment, when GDP growth, internet diffusion, and labor productivity interacted in a nonlinear way, but the ultimate normalization proved that the ARDL lag structure was flexible enough to accommodate the transition to it.



(a)

(b)

(c)

(d)

Fig. 5 ARDL model's (a) Residuals scatter plot; (c) Cumulative sum of residuals; (b) Residual distribution bar plot; (d) Residuals vs fitted values

Residual adequacy is further supported by the distributional diagnostics that are presented in Figure 5(c&d). The residual histogram shown in Figure 5c indicates that the distribution is roughly symmetric around the center, around zero, and that most of the values fall in the interval -0.010 +0.010, and only some tail values are concentrated at the ends. The histogram does not show the presence of strong skewness and extreme kurtosis, which is a visual representation of the Jarque-Bera value in Table 8, where the value of 0.4765 with p = 0.7880 evidently does not reject the null hypothesis of normality. It implies that the residues are normally distributed, and this is close enough to make t-statistics and confidence tests. The heteroskedasticity check is presented in Figure 5d as the residuals versus fitted values plot. The residual values are randomly dispersed around a zero line of fitted values that goes between approximately 8.6 and 10.2, and no funnel widening, clustering, or systematic curvature is observed. Low and high fitted levels of productivity have a similar spread of residual, suggesting that the variance is constant throughout the fitted range. Such visual evidence directly fits the Breusch-Pagan statistic of 0.0094 and p = 0.9227 in Table 9, which indicates that there is no heteroskedasticity and the variance of the residuals is unchanged across the sample. This absence of pattern is also a pointer to the fact that it is possible that omitted nonlinear effects are also weak, and the functional form adopted in the ARDL model is statistically correct.

Figure 6 gives the last validation with the Q-Q normality plot; the arranged residual values are very near the diagonal reference line during almost the entire range of quantiles. Minor deviations are present only at the extreme upper tail, but are quite small and do not imply any meaningful heavy-tail deviation. The linear correspondence supports the outcome of Jarque-Bera and the assumptions of normality of errors, with the close alignment of residual quantiles with theoretical normal quantiles. Table 9 also indicates that serial correlation is evaluated using the value of Durbin-Watson 1.5403. This value, though it is moderately less than 2, signifying mild positive residual dependence, is within the acceptable range of annual macroeconomic data, where the lag persistence phenomenon is widespread. Notably, repetitive cyclical residual waves that would have meant the presence of severe autocorrelation are not observed in Figure 4 and Figure 5. Residual reversals instead happen haphazardly and only indicate weak serial memory, but not systematic dependence. Combined, Figure 5 and Figure 6 indicate that the model meets the main diagnostic criteria: the residuals are centered, have a normal distribution, are homoscedastic, and there is no serious autocorrelation. Thus, the ARDL estimates may be confidently interpreted, and empirical correlations between digitalization, GDP growth, and

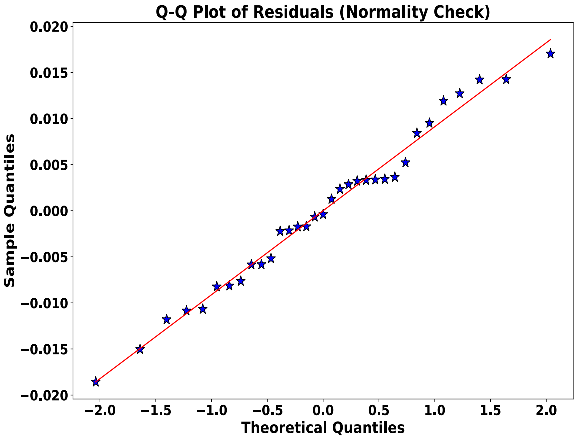


Fig. 6 Q-Q plots of residuals for normality check

Table 9
Diagnostic residuals

Test	Statistic	p-value
Jarque-Bera (Normality)	0.4765	0.7880
Breusch-Pagan (Heteroskedasticity)	0.0094	0.9227
Durbin-Watson	1.5403	

labor productivity are statistically sound at the present specification.

5.6 Policy Implications

The empirical results yield several direct policy implications for Vietnam, especially since the estimated relationships indicate that the advanced technology is a factor contributing to labor productivity, but through delayed transmission and energy indicators, it has uneven adjustment over time. First, the high positive lagged impact of internet growth means that the digital infrastructure policy cannot be examined based on short-term output increases. The fact that the insignificant current internet coefficient but positive lagged response is positive indicates that productivity gains are obtained only after a company, employees, and institutions undergo a learning and adaptation cycle. It means that the state investment into broadband growth, industrial online platforms, and enterprise connectivity needs to be supported by employee training, digital literacy, and industry-specific technological integration assistance. It is possible that in the absence of complementary institutional preparation, digital penetration can alone widen connectivity without yielding any quantifiable productivity gains. Second, the prevailing autoregressive labor productivity suggests that the growth in Vietnam's productivity requires an extensive maintenance of former output at the expense of creating sudden change. Policy thus must focus more on continuity in industrial modernization and not on a piecemeal short-term intervention. Cumulative productivity gains in sectors can be strengthened by stable support of automation uptake, digital manufacturing systems, and data-driven production planning. Because the growth of GDP is both positively significant in the short and long-run, the macroeconomic growth continues to be a very important transmission channel whereby technological investment is transformed into productive output. This implies that the policy of industrial growth, the competitiveness of exports, and capital formation based on technology must be coordinated as opposed to being treated individually. Third, the trend in the decreasing renewable energy consumption and the volatility in the renewable electricity imply that energy management efficacy ought to be enhanced with greater consideration of the technological modernization and renewable implementation. In spite of the fact that there is eventual stabilization in renewable electricity once it is differentiated, the small values of the short-run ECM coefficients suggest a slow adjustment to energy. This policy should then enhance the use of smart grids, electronic monitoring of electrical systems, and predictive energy management systems so as to enhance the efficiency of absorbing renewable energy. The technological developments can be translated into an increase in energy efficiency by means of advanced metering, digital load balancing, and industrial energy analytics.

Lastly, residual diagnostics indicate that the ARDL estimates are statistically valid, i.e., these directions of policy are based on strong empirical evidence. The failure of heteroskedasticity, close to normal residual, and reasonable serial dependence are evidence that the identified relationships between digitalization, productivity, and energy management are structurally plausible and can be used to design long-term policies in the framework of the technological transition in Vietnam.

6. Conclusion

The empirical results affirm that modern technology is a key driver of labor productivity and energy management dynamics in Vietnam, although its effects emerge through delayed structural transmission rather than immediate adjustment. The sharp rise in internet penetration alongside steady productivity growth reflects the parallel evolution of digital transformation and economic restructuring over the past three decades. However, the declining share of renewable energy consumption suggests that the energy transition has not progressed uniformly with technological expansion. The ARDL estimates indicate strong productivity persistence, with the first lag (0.9929) showing that current performance is largely determined by past levels. GDP growth exerts the strongest short-run influence through positive contemporaneous and lagged effects, while internet penetration shows a delayed positive impact, implying that digital benefits depend on institutional adaptation and complementary investments. The long-run coefficients suggest stable directional associations between digitalization, economic growth, and productivity, supported by positive lag effects and gradual adjustment dynamics. However, the error correction term is positive and insignificant (0.1681), indicating the absence of a stable equilibrium mechanism and implying that the system evolves through persistent short-run dynamics rather than convergence. Overall, productivity gains in Vietnam are driven by the combined effects of digital expansion, sustained economic growth, and gradual structural transformation, highlighting the need for coordinated policies that integrate digital infrastructure, macroeconomic stability, and technology-enabled energy governance.

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