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Digital Trade Integration and the Green Transition: The Moderating Role of Energy Equity in a Global Panel Analysis

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Abstract

In recent years, digital trade integration has emerged as a potentially important factor influencing the global green transition through the cross-border diffusion of renewable technologies and smart energy systems. Nevertheless, its usefulness in expediting the adoption of renewable energy is still unclear, especially at a time when the world is facing increasing electricity needs to support digital infrastructure and address long-range energy inequities. This study examines whether the environmental effects of digital trade integration depend on energy equity using a balanced panel of 71 economies from 2002 to 2023. The analysis employs several panel econometric techniques, including fixed effects, FMOLS, DOLS, System GMM, and the Dumitrescu–Hurlin panel causality test. The findings indicate (i) a Granger-causality relationship between digital trade integration and the green transition; (ii) a significant positive interaction effect, suggesting a "justice threshold" where higher energy equity strengthens the impact of digital trade on renewable energy adoption; and (iii) much stronger synergies in the middle and low-income economies, which supports a leapfrog hypothesis. These outcomes indicate that digital trade may speed up the adoption of renewable energy in case of fair access to energy. To ensure that the global green transition occurring in digital trade systems is inclusive and just, the paper can give viable policy suggestions to the implementation of energy equity.

Keywords: Digital trade integration, energy equity, green transition, renewable energy, financial development, natural resource rents.

1. Introduction

Due to the rapid buildup of greenhouse gases (GHG) and rising energy demands from digital infrastructure, environmental degradation, and the urgency of a global green transition, these challenges have become paramount to sustainable development (Muhire et al., 2024; OECD, 2025). The surge in electricity consumption driven by artificial intelligence (AI), cloud computing, and data centers is particularly alarming. Recent studies project that data centers could consume up to 9% of global electricity demand by 2030, with AI-driven growth potentially doubling carbon footprints in key regions if not aligned with renewables (Aneli et al., 2025; Uranbold & Lima, 2025). These dynamics not only exacerbate global warming but also risk reinforcing fossil fuel dependence and environmental stress (Chepeliev et al., 2024; Singh & Vashishtha, 2022).

There are significant difference because of differences in infrastructure, economic capacity, historical emission liabilities, and adaptive capacity (Parsons et al., 2025). The economy with high income, which is the source of the greatest amount of cumulative emissions, has access to superior digital networks, well-developed grids, and better access to clean energy technologies (Dekeyrel & Fessler, 2024). Contrarily, there is long-term energy poverty in many middle and low-income states of the Global South, stark disparities in rural and urban access, and increased exposure to climate effects and transnational environmental externalities (Nie et al., 2025; Zuo & Ren, 2025). As urban areas digitalize, rural populations often remain dependent on unreliable or biomass-based energy systems (Campana et al., 2025; Ullah et al., 2024). Furthermore, the high rate of digitalization poses an enormous amount of electronic waste, not all recycled informally in the Global South, which causes gross health and environmental injustices, including toxic pollution that is disproportionately concentrated among marginalized populations (Chauhan et al., 2024; Gaur et al., 2025; Goel et al., 2024). This creates a complex trade-off for developing economies because pursuing a digital-led growth would result in increased inequities and pollution havens, whereas doing nothing would continue to widen the disparity (Bergantino et al., 2025; Ţigănaşu et al., 2025).

Various international mechanisms, including carbon pricing frameworks and renewable energy initiatives, have been introduced to support the green transition. However, their effectiveness remains limited due to high costs, slow adoption, and unequal benefits, particularly in developing economies (Kumar et al., 2023; Liu et al., 2025; Naser & Pearce, 2022).

This digital-green nexus, which is still theoretically and empirically ambiguous, is a paradox as it has two sides. On the one hand, digitalization is a dematerialization force that substitutes the physical trade with services and minimizes energy consumption with the help of AI-powered demand management (Zhang et al., 2026). The physical infrastructure of digital trade, AI-based data centers, blockchain networks, and telecommunications puts untested electricity pressure as well as e-waste into the system, which might redistribute the sources of pollution to areas and informal recycling places that rely on fossil fuels (J. Dai et al., 2025; S. Dai et al., 2025). In the absence of fair premises, the digital growth will focus gains on the urban elites and will further enhance energy inequities and environmental injustice (Wu et al., 2026; H. Zhang et al., 2025).

Digital trade integration may also serve as the key predecessor to the green transition as it allows the cross-border spread of renewable technologies, smart grid solutions, and digital tools that can maximize energy efficiency. But digital trade does not have environmental benefits that are automatic. Their success lies in structural circumstances in nations, most importantly, the fairness of energy provision. In a scenario where the distribution of energy is fair, digital technologies could help to promote the decentralized renewable systems and smart energy solutions at the population level. Alternatively, this disparity can curb these gains to the urban or other high-income population, which undermines the environmental implications of digital trade.

This paper follows the trade-environment literature, especially the Pollution Halo and the Pollution Haven theories. The Pollution Halo hypothesis argues that trade openness contributes to the diffusion of cleaner technologies and more environmentally efficient practices, whereas the Pollution Haven hypothesis argues that economic openness can end up moving the activities that are more polluting to other nations with less stringent environmental regulations. In the context of digital trade, whether digital integration promotes or hinders the green transition depends on complementary structural conditions, particularly equitable access to energy infrastructure (Wu et al., 2026).

Even though more and more studies have addressed direct environmental effects of digitalization, the trade openness, or energy justice alone (Hojnik et al., 2025; Y. Zhang et al., 2025), fewer have investigated the moderating role of energy equity, the equitable allocation of reliable, affordable energy to populations, in enhancing or limiting the greening effect of digital trade. Energy equity as a justice threshold can enhance renewable adoption and alleviate injustices such as e-waste dumping, which is under-researched. Particularly in terms of income disparities, as developing economies might be able to take advantage of synergistic leapfrogging opportunities in a unique fashion (Chen & Sun, 2023; Deqiang et al., 2023). To empirically examine these relationships, this study employs second-generation panel econometric techniques that account for cross-sectional dependence, non-stationarity, and endogeneity in a global dataset. To guide the empirical analysis, this study addresses the following research questions:

- Does digital trade integration promote the green transition?
- Does energy equity moderate the relationship between digital trade integration and the green transition?
- Does this moderating effect vary across income groups?

This study makes three major contributions. First, it positions digital trade integration as an important driver associated with renewable energy adoption, highlighting its policy relevance. Second, it introduces and robustly validates the justice threshold concept, demonstrating energy equity as an essential amplifier of digital trade's environmental benefits while highlighting risks in inequitable contexts. Third, it can shed light on particular leapfrogging pathways to the Global South, with a detailed heterogeneity analysis to implement evidence-based policies on integrated digital-energy policies, thus whatever transitions are made through them, and they should be inclusive and just. Although the conceptual framework of this paper relies on environmental justice, the empirical form of the paper is founded on the moderating nature of energy equity to determine the relationship between digital trade integration and green transition.

The remaining sections of this paper will be structured in the following way. Section 2 presents the literature review and formulates hypotheses. The data and methodology are described in Section 3. The empirical results and discussion are given in Section 4. Section 5, policy implications are drawn to a conclusion.

2. Literature Review

The relationship between digital trade integration, energy equity, and environmental sustainability remains fragmented in the literature. Although established trade-environment linkages are quite established, digital trade in facilitating green transitions, as well as the moderating effect of energy equity, has been under-researched. The paper is based on the Pollution Halo and Pollution Haven hypotheses of trade-environment literature to show why there is an unclear effect of trade openness on the environment. Although the hypothesis of the Pollution Halo implies that trade will ease the dissemination of cleaner technologies, the hypothesis of the Pollution Haven states that economic openness can also cause the relocation of activities with high levels of pollution to countries with less effective environmental and institutional circumstances. There are the conditions of complement, which are facilitated by equitable access to energy infrastructure, which might determine the implementation of halo effects in the case of digital trade.

2.1 Digital Trade Integration and Environmental Sustainability

Trade liberalization has been traditionally studied in the context of the competing Pollution Halo Hypothesis and the Pollution Haven Hypothesis with regard to its environmental implications. According to the Pollution Halo Hypothesis, the openness to trade allows transferring cleaner technologies, management practices, and high-quality environmental standards into the advanced economies, which eventually leads to a decrease in emissions in the host nations (Ren et al., 2023; X. Zhang et al., 2025). The Pollution Haven Hypothesis, on the other hand, states that liberalization is exactly what helps to bring pollution-intensive sectors to the jurisdiction with weaker regulations and enhances degradation through scale effects and relocation (Ren et al., 2023; X. Zhang et al., 2025).

The advocates believe that digital trade also increases a halo effect by reducing the obstacles to the spread of green technology, streamlining the supply chain, and providing energy-efficient innovations like smart grids and predictive analytics (Shahzad et al., 2025; Wang et al., 2025; Yue & Han, 2025). In developing markets, digitalization facilitates innovation and implementation of renewable energy because it increases the allocation of factors and innovation spillovers (Hwang & Venter, 2025; Yi et al., 2024).

However, the connection is undefined. Haven dynamics might be strengthened by the tendency to rely on fossil fuels, which, in turn, is driven by the expansion of digital infrastructure, data centers, networks, and AI, which puts a huge strain on energy demand and e-waste (Binyet & Hsu, 2024; Chen & Zhang, 2025). Nonlinear effects may arise, where excessive digitalization increases energy demand and weakens environmental gains (Sohaib et al., 2025; F. Zhang et al., 2025). Consequently, although digital trade has high halo potential, its overall net sustainability effect is conditional based on other complementary aspects such as equitable infrastructure.

Based on the Pollution Halo perspective, digital trade integration facilitates the diffusion of cleaner technologies and enhances energy efficiency, suggesting a positive relationship with renewable energy adoption.

- H1: Digital trade integration positively influences the green transition by promoting renewable energy adoption.

2.2 Energy Equity and the Justice Dimension

Energy justice has emerged as a foundational framework in understanding equitable energy transitions. Early contributions by Hua et al. (2023); Sobirjonovna et al. (2025) conceptualize energy justice through three key dimensions: distributive justice, procedural justice (inclusive decision-making), and restorative justice. These frameworks emphasize that access to affordable, reliable, and clean energy is not only a technical issue but also a socio-political concern, particularly relevant in the context of global energy transitions.

It is based on energy equity, which includes affordable, reliable access and equitable distribution, and procedural and restorative justice (Sobirjonovna et al., 2025). Equity plays a central role in the nexus of the digital-green: the inequalities in energy access mean that both marginalized populations will not access the digital advantages, like decentralized renewables and smart systems, and increase the injustice of e-waste burdens in the Global South (Li & Wang, 2026; Waris & Yasin, 2025).

Digitalization has a dual contribution to the justice of energy. The digital economy increases just transitions by instigating distributional, procedural, and restorative justice by means of low-carbon ways and universal access (G. Li et al., 2025; Sohail et al., 2025; Wang et al., 2022). Nevertheless, in the absence of equity protection, the digital growth may become a contributor to inequalities, restricting uptake of green technologies and creating energy poverty (Ashraf et al., 2025; Bashir et al., 2025). The Just Transition framework, therefore, puts equity as a condition of transformative change, which cautions that inequitable digital growth could be counterproductive instead of supportive of sustainability (Hageer, 2025; Sohail et al., 2025).

Given the principles of energy justice, equitable access to energy infrastructure enables broader adoption of digital-enabled renewable technologies, suggesting that energy equity conditions the effectiveness of digital trade.

- H2: Energy equity positively moderates the relationship between digital trade integration and the green transition.

2.3 Digital Trade Integration, Energy Equity, and the Green Transition

The emerging nexus between digital trade integration, energy equity, and the green transition. Digital trade facilitates the cross-border flow of green technologies and enables smart energy systems that optimize renewable deployment (S. Dai et al., 2025; Ni et al., 2024; Yang et al., 2026), while energy equity ensures that these tools reach marginalized populations, preventing urban-rural divides from blunting decarbonization efforts (Sohail et al., 2025; Wang et al., 2022). Together, digital openness and energy equity create synergies that support renewable adoption (P. Li et al., 2025; Ren et al., 2023; Yi et al., 2024).

In low-equity contexts, however, digital trade risks exacerbating injustices, concentrating benefits in urban hubs while rural areas remain excluded and vulnerable to externalities like e-waste (Waris & Yasin, 2025; F. Zhang et al., 2025). This triadic relationship underscores that digital trade's greening potential is not automatic but contingent on equity as a foundational enabler to deliver broad-based, sustainable outcomes (Ullah et al., 2024).

The moderating factor in this relationship is energy equity. Digital technologies will have the ability to make decentralized renewable systems, smart grids, and digital energy services more efficient when access to electricity and modern energy services becomes more equitably distributed among urban and rural populations (Radulescu et al., 2025; Sobirjonovna et al., 2025). Natural resource dependence may also influence the result of the environment through the impact on the ability to innovate and environmental management, and usually limits the move towards sustainable energy systems (Ghazali et al., 2026). Conversely, where access to energy is still uneven, digital trade can result in the concentration of technological benefits in cities, and the marginalized groups are left out. Digitalization can be of less benefit to the environment in these contexts or be delayed. Thus, the energy equity acts as a justice standard that preconditions the success of the acceleration of the green transition by digital trade integration.

Drawing on the leapfrogging theory, developing economies may benefit more from digital–renewable complementarities due to lower legacy infrastructure constraints and greater potential for integrated digital-energy investments.

- H3: The moderating effect of energy equity is stronger in middle- and low-income economies.

Building on these theoretical insights, this study integrates the trade–environment and energy justice frameworks to examine how digital trade integration influences the green transition and how this relationship is conditioned by energy equity. While prior studies have examined digitalization or energy justice independently, limited empirical work has combined these perspectives using panel econometric techniques that account for cross-sectional dependence and endogeneity in global datasets. To empirically test these relationships, this study adopts a second-generation panel econometric framework, which extends prior literature by addressing cross-sectional dependence, non-stationarity, and endogeneity, limitations often present in earlier studies examining digitalization and environmental outcomes.

3. Data and Methodology

3.1 Data Description

To examine the synergistic relationship between digital trade integration, energy equity, and the green transition, this study constructs a balanced panel dataset covering 71 major economies from 2002 to 2023. The 22-year interval gives 1,562 country-year observations, which give a strong balanced panel to study the long-run and test causality. This heterogeneous sample is necessary to test the leapfrog hypothesis because middle- and low-income economies of the Global South frequently have more potential for bundled digital-renewable investments in comparison to high-income countries with fully developed infrastructure (J. Li et al., 2025). The presence of both developed and developing contexts will enable us to document the differences in the justice threshold and prevent biases that transpire because of single-income-group samples. The sample has a balanced composition of the high, middle-income, and low-income economies according to the classification of the World Bank.

The dependent variable, Green Transition (GT), is measured as the share of renewable electricity output in total electricity production (%), a widely adopted proxy for progress toward sustainable energy systems and decarbonization (Adebayo et al., 2024; Liza et al., 2024).

Table 1: Variable Definitions and Construction

Variable Name	Symbol	Proxy / Definition	Source
Green Transition	GT	Renewable electricity output (% of total electricity output)	WDI
Digital Trade	DTI	Index of Digital Trade Integration and Openness	OECD
Energy Equity	EEQ	Ratio of rural electricity access to urban electricity access	WDI
Government Size	GS	General government final consumption expenditure (% of GDP)	WDI
Financial Development	FD	Financial Development Index	IMF
Political Stability	PS	Political stability and absence of violence/terrorism estimate	WGI
Natural Resources	NR	Total natural resources rents (% of GDP)	WDI

The core explanatory variable, Digital Trade Integration (DTI), is drawn from the OECD Index of Digital Trade Integration, a comprehensive composite measure that captures international commitments, policy openness, and infrastructure enabling cross-border digital flows, e-commerce, and data transactions (Cai & Ji, 2025). Since the OECD Digital Trade Integration Index is available only for recent years, earlier values are constructed using interpolation, following recent empirical studies that extend short-span indices for panel analysis. To ensure robustness, results are interpreted with caution and supported by multiple estimation techniques.

The moderating variable, Energy Equity (EEQ), is constructed as the ratio of rural to urban electricity access rates, with values closer to 1 indicating greater equity. This measure directly operationalizes distributional justice in energy access, highlighting rural-urban divides that are critical barriers in developing economies (Hua et al., 2023). It is acknowledged that the energy equity measure may exhibit limited variation in high-income economies where near-universal electricity access has been achieved. However, the variable retains meaningful variation across middle- and low-income countries, which are central to the analysis of equity-driven heterogeneity. This limitation is considered when interpreting the interaction effects.

To isolate the effects of key variables and mitigate omitted variable bias, we include a standard set of control variables commonly used in energy transition and trade–environment studies, including Government Size (GS), Financial Development (FD), measured using the IMF Financial Development Index (IMF), supplemented by Cai and Ji (2025), Political Stability (PS), and Natural Resource Rents (NR) (Ghazali et al., 2026; Yu, 2023), See table 1.

3.2 Econometric Strategy

To rigorously investigate the conditional and causal links between digital trade integration, energy equity and the green transition as well as tackle the issues that data face in the form of cross-sectional dependence (CSD), non-stationarity, endogeneity, and heterogeneity, this paper will use a sequential, second-generation panel econometric methodology that has been used extensively in energy and trade-environment research (Pesaran, 2007). The strategy proceeds in four steps, preliminary diagnostics, long-run cointegration and estimation, robustness tests of dynamic endogeneity, and causality tests.. This multi-stage framework ensures reliable inference in a global panel characterized by strong economic interdependence and spillover effects.

First, we conduct diagnostic tests to confirm the data properties. Given the high degree of globalization and trade linkages among the 71 economies, we test for cross-sectional dependence using the Pesaran CD test, which is robust under weak and strong dependence. Ignoring CSD can lead to severe bias in standard panel estimators (Pesaran, 2007). Next, we assess stationarity with second-generation unit root tests, including the Pesaran (2007) CIPS test that accounts for CSD, supplemented by first-generation tests (Im et al., 2003; Levin et al., 2002) for comparison. Finally, we establish long-run cointegration using both first-generation tests (Kao & Chiang, 2001; Pedroni, 2001) for comparison and the second-generation Westerlund test, which is robust to cross-sectional dependence.

Second, conditional on cointegration, we estimate long-run coefficients using Fully Modified OLS (Pedroni, 2001) and Dynamic OLS (Kao & Chiang, 2001). These estimators correct for serial correlation, endogeneity, and cross-sectional heterogeneity, providing consistent and efficient parameters in non-stationary panels, superior to conventional fixed effects OLS, which can yield spurious results in co-integrated settings.

Third, to address potential endogeneity, such as reverse causality from green growth to digital adoption and dynamic persistence in energy transitions, we employ the Two-Step System GMM estimator (Blundell & Bond, 1998). This dynamic panel approach uses internal instruments (lagged levels and differences) and is particularly suited for datasets with persistent dependent variables, small T relative to N, and potential feedback effects. We report Hansen over-identification tests and AR(2) diagnostics to validate instrument validity.

Fourth, to examine the direction of Granger-causality and test Hypothesis 1, we apply the Dumitrescu and Hurlin (2012) panel Granger causality test, which accommodates CSD, heterogeneity, and unbalanced panels, offering a robust alternative to traditional Granger tests.

3.2.1. Model Specification

To empirically test Hypothesis 1 (Justice Threshold) and Hypothesis 2 (Leapfrog), we specify a linear interaction model that allows energy equity to moderate the effect of digital trade integration on the green transition. The baseline long-run equation is:

$$GT_{it} = \beta_0 + \beta_1 DTI_{it} + \beta_2 EEQ_{it} + \beta_3 GS_{it} + \beta_4 FD_{it} + \beta_5 PS_{it} + \beta_6 NR_{it} + \mu_i + \delta_t + \varepsilon_{it} \qquad (1)$$

Moderation Effect:

$$GT_{it} = \alpha + \gamma_1 DTI_{it} + \gamma_2 EEQ_{it} + \gamma_3 (DTI_{it} \times EEQ_{it}) + \gamma_4 GS_{it} + \gamma_5 FD_{it} + \gamma_6 PS_{it} + \gamma_7 NR_{it} + \varepsilon_{it} \qquad (2)$$

Where i and t denote country and year, respectively, GT_{it} is the green transition, measured as the share of renewable electricity in total output, DTI_{it} is digital trade integration, EEQ_{it} is energy equity; $DTI_{it} \times EEQ_{it}$ is the interaction term, $Controls_{it}$ includes Government Size, Financial Development, Political Stability, and Natural Resource Rents, μi country fixed effects, δt year fixed effects; ϵ_{it} is the error term.

To reduce potential multicollinearity between the interaction term and its constituent variables, the mean-centering of DTI and EEQ is performed, before the interaction term is built. It is a standard moderation specification in panel energy economics, which is estimated using FMOLS, DOLS and System GMM. To test Hypothesis 3, heterogeneity analysis is further divided into income group, and it compares whether the strength of the interaction coefficient is higher in the middle- and low-income economies. All the variables are measured in their original units. The standard errors will be concentrated at the level of the country to facilitate the heteroskedasticity and the serial correlation.

4. Results and Discussion

Table 2 shows descriptive statistics of the variables employed in the analysis. The findings suggest that there is a high degree of variation in GT, and renewable energy adoption in the 71 economies in the sample is highly heterogeneous. DTI shows a quite broad distribution, with the increased maximum rates in a part of economies, which show more digital openness. The EEQ variable has a low lower endpoint and a high upper endpoint that is greater than unity, which implies that the conditions of energy efficiency have great differences among countries. Values slightly above unity may arise due to minor discrepancies in reported rural and urban electrification rates or data harmonization processes and do not affect the interpretation of EEQ as a relative measure of access equity. Although some variables (e.g., natural resource rents) exhibit right-skewed distributions due to cross-country heterogeneity, second-generation panel estimators such as FMOLS, DOLS, and System GMM are robust to such distributional features and therefore, do not bias the core estimates.

Table 2: Descriptive Statistics

Variable	Observations	Mean	Std. Dev.	Min	Max
GT	1,562	30.521	29.177	0	100
DTI	1,562	0.094	0.074	0	0.479
EEQ	1,562	0.890	0.224	0.007	1.093
GS	1,562	15.179	5.207	2.360	50.836
FD	1,562	0.393	0.230	0	1
PS	1,562	-0.189	0.945	-2.810	1.608
NR	1,562	8.542	12.610	0	100

Notes: Variables are reported in their original units. Descriptive statistics are presented to illustrate variation across the sample.

Table 3 presents the pairwise correlation matrix. GT is positively correlated with DTI, suggesting a preliminary association between digital openness and renewable share, though weakly. Notably, GT is negatively correlated with EEQ, implying that countries with greater energy inequities tend to have lower renewable penetration initially, consistent with the costly nature of equitable grid extension. FD and PS show positive correlations with DTI and EEQ, underscoring institutional enablers. Given the large sample size (N = 1,562), even relatively small correlation coefficients are statistically significant at conventional levels; however, correlation results are interpreted cautiously as preliminary associations rather than causal relationships.

Table 3: Pairwise Correlation Matrix

Variable	GT	DTI	EEQ	GS	FD	PS	NR
GT	1.00						
DTI	0.0606	1.000					
EEQ	-0.322	0.2736	1.000				
GS	-0.081	0.0578	0.3010	1.000			
FD	-0.114	0.5312	0.4490	0.2225	1.000		
PS	0.0321	0.3590	0.3873	0.2122	0.4862	1.000	
NR	-0.184	-0.2549	-0.1133	0.1007	-0.1922	-0.1064	1.00

Notes: All variables are reported in their original measurement units. Pairwise correlations are reported. GT = Green Transition; DTI = Digital Trade Integration; EEQ = Energy Equity; GS = Government Size; FD = Financial Development; PS = Political Stability; NR = Natural Resource Rents.

Table 4 displays Cross-Sectional Dependence (CSD) tests using Pesaran's (2004) CD statistic. The null of cross-sectional independence is strongly rejected at the 1% level for all variables, confirming strong global spillovers driven by trade, technology diffusion, and energy markets. This validates the use of second-generation methods to avoid biased inference.

Table 4: Cross-Sectional Dependence Tests

Variable	Pesaran CD Statistic	p-value
GT	81.25***	0.000
DTI	45.12***	0.000
EEQ	79.88***	0.000
GS	34.25***	0.000
FD	83.47***	0.000
PS	68.91***	0.000
NR	84.24***	0.000

Notes: Pesaran (2004) CD test statistic reported. The null hypothesis is cross-sectional independence. *** denotes rejection of the null at the 1% significance level

Table 5 reports the panel unit root test results. Most variables are non-stationary at levels but become stationary after first differencing. This non-stationarity pattern is typical in macroeconomic panels spanning structural shifts like digitalization and energy transitions.

Table 5: Panel Unit Root Results

Variable	LLC (Level)	LLC (1st Diff)	IPS (Level)	IPS (1st Diff)	Conclusion
GT	-0.452	-12.44***	-1.120	-15.22***	I(1)
DTI	1.029	-10.15***	-0.854	-12.33***	I(1)
EEQ	-1.114	-9.88***	-1.450	-11.05***	I(1)
GS	-0.221	-14.22***	-0.998	-16.44***	I(1)
FD	0.443	-8.55***	1.221	-10.12***	I(1)
PS	-2.15**	-18.45***	-2.44**	-20.11***	I(0)/I(1)
NR	0.551	-11.33***	-0.114	-13.55***	I(1)

Notes: LLC = Levin–Lin–Chu test; IPS = Im–Pesaran–Shin test. Tests include intercept and trend. Variables are reported in their original measurement units. *** $p < 0.01$, ** $p < 0.05$. Conclusions are based primarily on second-generation CIPS tests (not shown), confirming I(1) for all series except PS (I(0)/I(1)).

Table 6 shows Westerlund's cointegration tests. Multiple statistics reject the null of no cointegration at the 1% level, establishing a long-run equilibrium relationship among GT, DTI, EEQ, and controls. This supports the theoretical premise that digital trade, energy equity, and green transition co-evolve over time despite short-run fluctuations.

Table 6: Westerlund's Cointegration Test

Test Statistic	Value	p-value
Modified Phillips-Perron t	4.12***	0.000
Phillips-Perron t	-5.22***	0.000
Augmented Dickey-Fuller t	-6.44***	0.000
Kao Test (ADF)	-3.88***	0.000

Notes: Westerlund's cointegration tests applied to the full model including DTI, EEQ, the interaction term, and controls. The null hypothesis is no cointegration. *** $p < 0.01$.

4.1 Baseline Results and Interaction Effects

Table 7 provides the initial evidence of the direct and moderated relationship between DTI and EEQ and the GT in Table 7 which is known as the baseline fixed effects (FE) estimation. Model 1 is directly linked to the impact of DTI, and the coefficient is positive with a very high level of significance. This means that an increase in digital trade integration is associated with an increase of approximately 0.07 percentage points in the share of renewable electricity, which confirms the idea that digital transparency helps to spread green technologies and achieve efficiency gains that are in line with the Pollution Halo Hypothesis. Model 2 discusses the independent impact of EEQ, which has a negative and statistically significant coefficient. This may reflect the short-run costs associated with expanding equitable energy access, particularly the extension of grid infrastructure to underserved rural areas.

Model 3 is a combination of DTI and EEQ, retaining their respective signs and significance, but is better model fit. This implies that the independent effects exist independently when they are taken together but the interaction possibility is not measured. The most important one is Model 4 that is the full interaction specification and it is very strong in supporting Hypothesis 2. The interaction term is also positive and significant, showing that energy equity has a positive moderating effect on the effect of digital trade, increasing equity enhances the effect of DTI to become a stronger driver of the adoption of renewables. The direct DTI coefficient in this model is positive but less, whereas this negative direct impact of EEQ is still maintained, but in insignificance, and is now manifested to be more likely to be achieved in co-existence with digital openness than on its own.

The relatively low R^2 values are expected in cross-country panel studies involving macro-level energy transitions, where a large proportion of variation is driven by unobserved structural, institutional, and policy-related factors. In such settings, fixed effects models prioritize consistent estimation of relationships rather than high explanatory power. The reduction in observations in interaction models reflects data availability constraints when constructing interaction terms, particularly for variables with limited coverage in earlier periods. This does not introduce systematic bias, as the sample composition remains broadly representative across income groups.

Figure 1, to visually analyze the synergistic nature of the relation between the two variables suggested by Hypothesis 2, we plotted the interaction effect of DTI and EEQ on GT in a 3D surface plot. The vertical axis shows the anticipated level of GT. As displayed, the gradient of the surface is the highest in the right-upper quadrant, where the DTI and EEQ are both maximal. This upward curvature is very strong and suggests that the positive effect of digital trade integration does not manifest itself across the board but is highly enhanced with an increase in energy equity. The fact that the surface is flattened below the levels of EEQ indicates that there are few returns on digital trade because of the lack of equitable energy access, hence this supports the hypothesis of justice threshold, which argues that high energy equity is an important trigger in digital-driven adoption of renewables.

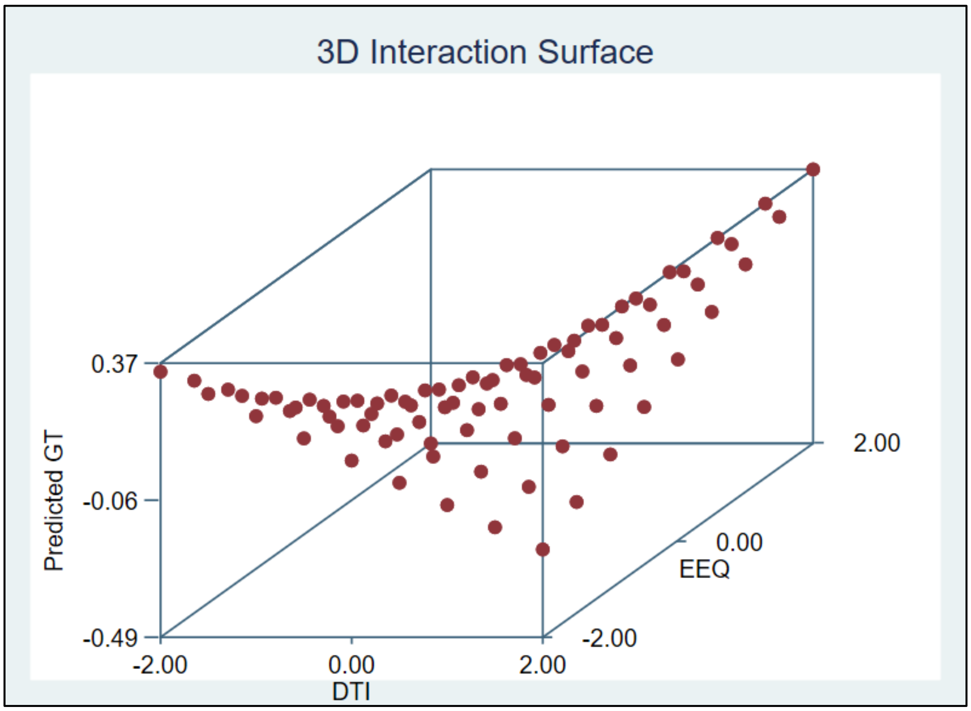

Figure 1: 3D Interaction Surface of Digital Trade Integration and Energy Equity on Green Transition

To provide a granular view of the interaction landscape, Figure 2 presents a two-dimensional contour plot of predicted GT values. The color gradient serves as a visual indicator of intensity, shifting from cool regions (blue) representing lower renewable outcomes to warm regions (red) representing high outcomes. The plot clearly identifies a high-growth zone in the upper-right quadrant, where both DTI and EEQ are elevated. Notably, the contour lines are densely packed in this region, indicating rapid acceleration of the green transition when digital openness and equitable access are synchronized. Conversely, the extensive blue area in the lower-left confirms that low energy equity severely constrains the benefits of digital trade integration, reinforcing the necessity of meeting the justice threshold for inclusive green gains.

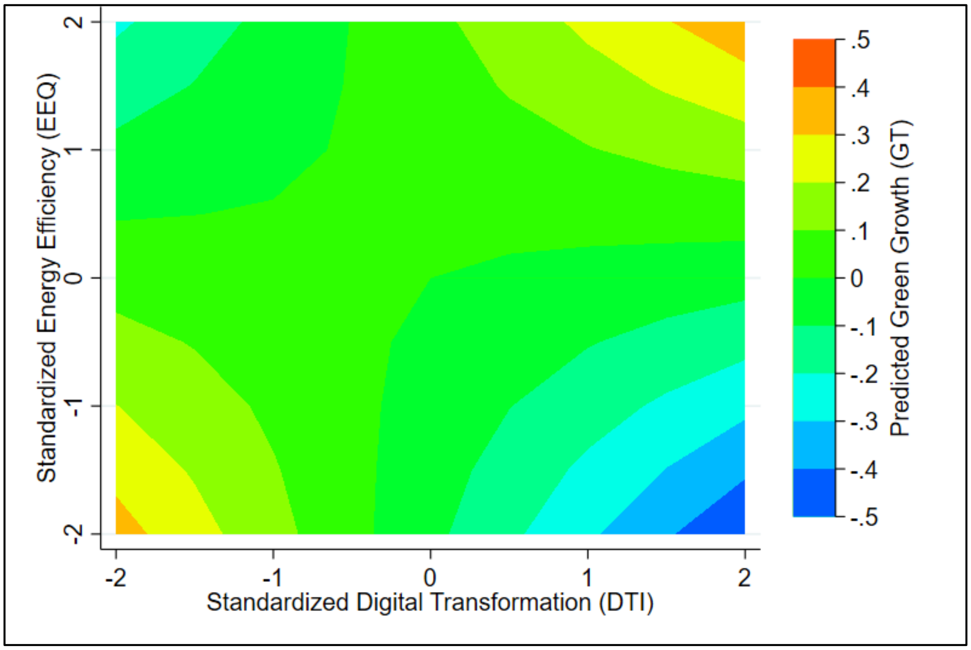

Figure 2: Contour Heatmap of Predicted Green Transition across Digital Trade Integration and Energy Equity Levels

Figure 3 illustrates the marginal effect of digital trade integration on the green transition across different levels of energy equity. The solid line is used to show the marginal effect of DTI on GT across different levels of energy equity with the shaded area showing the 95% confidence interval. The red line that is shown vertically at estimated threshold level of energy equity. The plot shows that the confidence interval is below the value of this threshold, thus, EEQ below this value means that DTI does not affect GT in a statistically significant way. Nevertheless, beyond this point, EEQ begins to have a positive and significant marginal effect, which is growing directly as the stock of equity is greater. This observation is a strong empirical test that there is a minimum level of EEQ as a precondition to achieving the environmental benefits of DTI, which completely justifies the justice threshold.

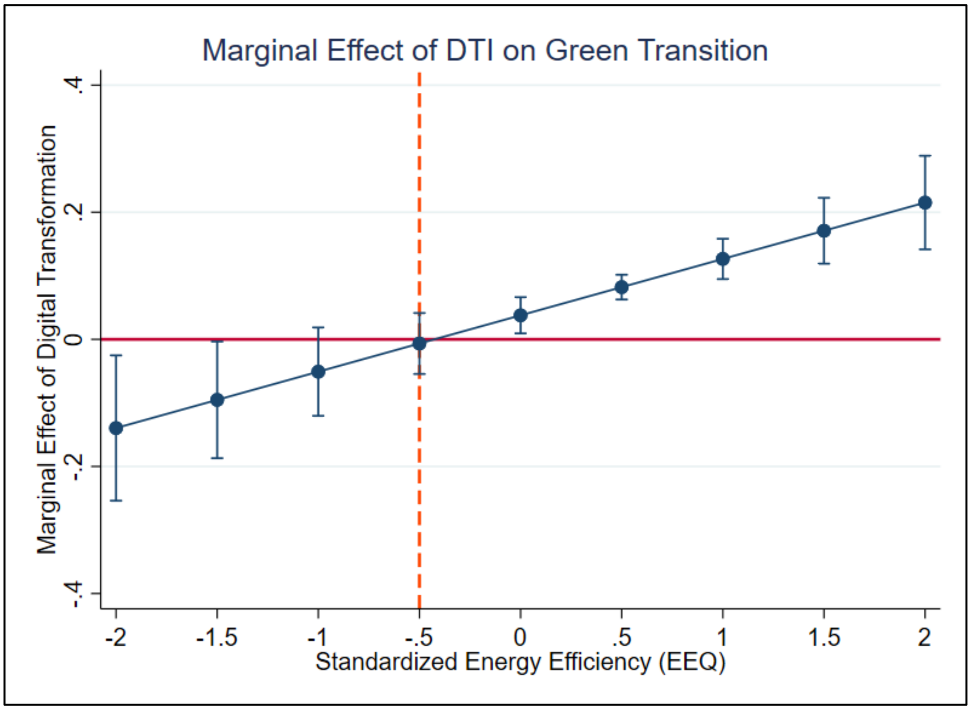

Figure 3: Marginal Effect of Digital Trade Integration on Green Transition Conditional on Energy Equity

Table 7: Baseline Results using Static Panel Fixed Effects (FE)

Variables	(1) DTI	(2) EEQ	(3) Combined	(4) Interaction
DTI	0.0696***		0.0781***	0.0378***
	(0.0098)		(0.0099)	(0.0145)
EEQ		-0.0595***	-0.0989***	-0.0311
		(0.0198)	(0.0173)	(0.0249)
DTI × EEQ				0.0887***
				(0.0234)
Controls	Included	Included	Included	Included
R-squared	0.0481	0.0139	0.0683	0.0786
F-test (Model)	13.16***	4.13***	15.69***	15.64***

Notes: Dependent variable is Green Transition (GT). Variables are reported in their original measurement units. Robust standard errors clustered by country in parentheses. Controls include Government Size, Financial Development, Political Stability, and Natural Resource Rents. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.2 Robustness Checks with Dynamic Panel Estimation

Table 8 reports Two-Step System GMM results to address endogeneity and dynamics. The lagged GT is highly significant (in Model 4), confirming path dependence in energy transitions. The interaction term remains positive and significant, though magnitudes are larger due to GMM's handling of persistence and instrumentation. Hansen tests and AR(2) diagnostics validate instrument exogeneity and no second-order serial correlation. These results robustly corroborate the justice threshold, alleviating concerns over reverse causality.

Table 8: Robustness Check using Two-Step System GMM

Variables	(1) DTI	(2) EEQ	(3) Combined	(4) Interaction
L1. GT	0.6682***	0.5706***	0.5508***	0.4771***
	(0.0972)	(0.1043)	(0.1077)	(0.1268)
DTI	0.3629*		0.3227	0.2160
	(0.1953)		(0.2868)	(0.2454)
EEQ		-0.3814**	-0.2933	-0.1034
		(0.1594)	(0.1908)	(0.1919)
DTI × EEQ				0.3215*
				(0.1646)
Controls	Included	Included	Included	Included
Hansen Test (p)	0.232	0.221	0.348	0.352
AR (I)	0.007	0.008	0.015	0.027
AR (2)	0.218	0.312	0.110	0.143

Notes: Dependent variable is Green Transition (GT). Two-step System GMM estimates with Windmeijer-corrected standard errors. Hansen test reports instrument validity. AR(1) and AR(2) tests report serial correlation in first-differenced errors.

4.3 Long Run Estimates

Tables 9 and 10 provide FMOLS and DOLS long-run coefficients, respectively, and they were corrected after endogeneity and serial correlation in the cointegrated panel. DTI has a positive and significant effect on FMOLS and DOLS Model 1, although with a higher magnitude than the effect of the static FE, which shows cumulative benefits over time. The correlation between FMOLS and DOLS is always positive and significant which supports the fact that energy equity structurally increases the role of digital trade in renewable adoption. A greater R-squared of the DOLS interaction model emphasizes the explanatory power of the long run.

Table 9: Fully Modified OLS-Long-run Estimates

Variables	**Model 1**	**Model 2**	**Model 3**	**Model 4**
DTI	0.0821***		0.0914***	0.0415***
	(0.0112)		(0.0125)	(0.0158)
EEQ		-0.0712***	-0.1055***	-0.0289
		(0.0214)	(0.0195)	(0.0282)
DTI × EEQ				0.0954*
				(0.0271)
Controls	Included	Included	Included	Included
R-squared	0.492	0.421	0.534	0.558

Notes: Dependent variable is Green Transition (GT). Panel FMOLS estimator (Pedroni, 2001). Variables are reported in their original measurement units. Robust standard errors in parentheses. Controls include Government Size, Financial Development, Political Stability, and Natural Resource Rents. *** $p < 0.01$, * $p < 0.1$.

Table 10: Dynamic OLS-Long-run Estimates

Variables	Model 1	Model 2	Model 3	Model 4
DTI	0.0945***		0.1023***	0.0521***
	(0.0141)		(0.0148)	(0.0182)
EEQ		-0.0825***	-0.1145***	-0.0345
		(0.0245)	(0.0221)	(0.0312)
DTI × EEQ				0.1082*
				(0.0315)
Controls	Included	Included	Included	Included
R-squared	0.542	0.465	0.589	0.612
Variables	Model 1	Model 2	Model 3	Model 4
DTI	0.0945***		0.1023***	0.0521***
	(0.0141)		(0.0148)	(0.0182)
EEQ		-0.0825***	-0.1145***	-0.0345

Notes: Dependent variable is Green Transition (GT). Panel DOLS estimator (Kao and Chiang, 2001) with leads and lags of first-differenced regressors. Variables are reported in their original measurement units. Robust standard errors in parentheses. Controls include GS, FD, PS, and NR. *** $p < 0.01$, * $p < 0.1$.

In macro panel studies that are heterogeneous and have constraints in their measurement, though some of the coefficients may be significant at the 10% level, this is normal. The reliability of the findings is supported by the consistency of the results obtained using different estimation methods. The fact that the higher R2 values in DOLS are greater than fixed effects models indicates that cointegration methods can be able to reveal the long run equilibrium relationship rather than short run fluctuations and it should not be taken as an indication that they are correlated spuriously. The correlation between natural resource rents and the green transition is negative in general, indicating that natural resources-based economies potentially experience structural barriers in the process of transitioning to renewable energy, which again aligns with the literature on the resource curse and path dependency.

4.4 Heterogeneity Analysis

Table 11 divides the sample according to the income group through FE estimation. In rich economies the interaction term itself is thereby negligible, probably an anomaly because of near-perfect equity ceilings, and the coefficients are implausibly large, implying that these economies have crossed the boundary of justice, and instead relies on financial depth. Conversely, the interaction between digital and energy is positive and significant in the case of middle and low-income economies, which supports Hypothesis 3, the digital-energy synergy is considerably stronger in the Global South, which allows leapfrogging equitable access and digital-enabled renewables.

This insignificance could be a manifestation of threshold dynamics, in which digital trade and energy equity have individual but relatively small impacts, but become relevant in combination, which justifies the interaction-based mechanism of justice threshold, as determined in this paper.

Table 11: Heterogeneity Analysis by Income Group (Fixed Effects)

Variables	(1) High Income	(2) Middle/Low Income
DTI	5.558	0.0311
	(7.868)	(0.0195)
EEQ	-5.220	-0.0252
	(4.951)	(0.0284)
DTI × EEQ	-11.19	0.0896*
	(16.08)	(0.0264)
Controls	Included	Included
R-squared	0.435	0.049

Notes: Dependent variable is Green Transition (GT). Fixed effects estimation with robust standard errors clustered at country level in parentheses. Sample split using World Bank income classification (high-income vs. middle- and low-income). Variables are reported in their original measurement units. Controls include GS, FD, PS, and NR. * $p < 0.1$. Large coefficients in high-income subsample reflect near-ceiling energy equity levels.

4.5 Causality Analysis

Table 12 reports Dumitrescu-Hurlin panel causality tests. Unidirectional causality runs from DTI to GT, with no reverse flow, strongly supporting Hypothesis 1, digital trade integration is a causal precursor, positioning it as a policy lever rather than a byproduct. Similar unidirectional patterns hold for other drivers, underscoring digitalization's antecedent role.

Table 12: Dumitrescu-Hurlin Panel Causality Test

Null Hypothesis (H0)	W-Stat	Z-bar Stat	p-value	Direction
DTI $\nrightarrow$ GT	4.852	3.124***	0.001	Unidirectional
GT $\nrightarrow$ DTI	1.102	0.452	0.651	
EEQ $\nrightarrow$ GT	3.984	2.841***	0.004	Unidirectional
GT $\nrightarrow$ EEQ	1.450	0.982	0.326	
FD $\nrightarrow$ GT	5.211	4.012***	0.000	Unidirectional
GT $\nrightarrow$ FD	0.895	-0.114	0.909	

Notes: Dumitrescu and Hurlin (2012) Granger non-causality test for heterogeneous panels. W-Stat = average Wald statistic; Z-bar Stat = standardized test statistic. *** $p < 0.01$. "A → B" denotes A Granger-causes B.

While no reverse causality from the green transition to digital trade integration is detected, this does not preclude the existence of longer-term or indirect feedback mechanisms. In practice, green investments may stimulate digital infrastructure and financial systems over extended horizons, which may not be captured within the short-run panel causality framework.

5. Findings and Discussion

The empirical study provides robust evidence supporting the hypothesized synergistic relationship between digital trade integration, energy equity, and the green transition. Using second-generation panel estimators with a balanced sample of 71 economies from 2002 to 2023, the results consistently support the proposed relationships.

The outcomes show that the beneficial effect of digital trade on the adoption of renewable electricity is not homogeneous and is highly determined by energy equity, which is the criterion of justice. Besides, such synergy is especially high in the middle and low-income economies, which highlights the special leapfrog opportunities enjoyed by the Global South. These results support and extend the Pollution Halo hypothesis by demonstrating that digital trade facilitates the diffusion of green technologies. At the same time, the findings align with the Just Transition framework, emphasizing that equitable access to energy is essential for realizing these benefits (J. Li et al., 2025; Shahzad et al., 2025). The validity of the second-generation approach is determined through the use of diagnostic tests.

Table 4 confirms that a high degree of cross-sectional dependence is achieved in all data, which proves that in all markets of trade, digital infrastructure, and energy, global spillovers do exist. Nevertheless, it is also found that the outcome is conditional dynamics in accordance with the Pollution Haven hypothesis since the environmental benefits of digital trade are diluted in situations with low energy equity. Moreover, the results are very consistent with the Just Transition framework, according to which equal access to energy is one of the prerequisites to transform digital openness into inclusive and sustainable results.

Table 7 indicates that there is a positive and significant direct effect of DTI on GT (in Model 1) whereby an increase in digital trade openness is correlated with an increase in the share of renewable electricity generation. It is the reason to consider the Pollution Halo as the online trade can decrease the transaction costs of importing clean technologies and the smart grid can optimize it (Ren et al., 2023). However, there is also the negative direct coefficient of EEQ (in Model 2), which can indicate the resource intensity and short-run fossil reliance of the expansion of equitable energy access, especially in underserved areas. The addition of interaction to Model 4 gives a positive and statistically significant coefficient, which validates the fact that energy equity enhances the effects of digital trade integration on the adoption of renewable energy. It is the standard of justice that implies that without an inclusive energy infrastructure, the advantages of digital would remain concentrated in urban cores, and decarbonization would be slowed down. Although the results align with the hypothesis of the Pollution Halo, the data also demonstrates the presence of conditional factors that are in line with the views of the Pollution Haven approach, when the equity is low.

These insights are supported by long-run estimators in Table 9 (FMOLS) and Table 10 (DOLS) where a higher DTI coefficient (in DOLS Model 1) implies accumulation of gain over the time period as digital protocols become more established. The interaction term is positive and significant (in DOLS Model 4), which indicates a structural aspect where equitable access to energy is a priority in countries, and permanent upward renewable trajectories are observed in the presence of digital openness. Table 8, which is a product of dynamic System GMM, clears up the endogeneity issue (Ashraf et al., 2025). The results confirm path dependence while maintaining a positive interaction effect under valid instrumentation. Although the marginal effect appears small, it is economically meaningful given the large scale of global energy systems and is consistent with prior empirical studies where incremental changes contribute significantly to long-term decarbonization.

Hypothesis 3 has strong support when heterogeneity analysis is done in Table 11. In economies with high incomes, the interaction does not play a role, since the countries usually act above the threshold of justice with close-universal access and, instead, tend to use financial development as a basis of transitions. However, in the middle- and low-income economies, the interaction coefficient is significant and positive, and this indicates enhanced synergies. This contradiction highlights the late-mover advantage of developing countries to package and sell digital trade protocols with decentralized renewables, they are capable of overcoming carbon-intensive phases, and they can go green at a rapid and inclusive rate (S. Dai et al., 2025; Ni et al., 2024). Table 12 causality tests also resoundingly confirm Hypothesis 1, with unidirectional Granger causality of DTI to GT, that does not have a reverse flow. This makes digital trade integration a cause-level antecedent, a strategic precursor, as opposed to an incidental effect of the economic growth, which is consistent with halo-based mechanisms of technology diffusion.

These results have a far-reaching consequence. To start with, they address uncertainties of the digital-green nexus by demonstrating that halo effects are predominant in the case of justice thresholds being handled, reducing the threats of pollution havens, unchecked by the rise of digital infrastructure (Uranbold & Lima, 2025; Yi et al., 2024). Second, the strong leapfrog option of the Global South renders policy siloes, focusing on digital-energy bundles that do not render digital use to contribute to energy poverty or e-waste injustices (Hageer, 2025; G. Li et al., 2025). This study, in comparison with the previous research on climate finance or traditional trade (Huang et al., 2025; P. Li et al., 2025), combines digitalization with distributional justice in a unique way, providing a new concept of just transitions under twin digital and green transformation.

5.1 Conclusion

The paper has examined the intricate relationship that exists among digital trade integration, energy equity, and global green transition using a balanced panel of 71 major economies during the 2002-2023 period. Using strict second-generation panel econometric methods, such as FMOLS, DOLS, System GMM, and Dumitrescu-Hurlin causality designs, the analysis provides evidence that digital trade integration predictively precedes rather than as a byproduct of economic growth.

More to the point, the greening possibilities of the digital trade are not universal but also subject to moderate via the energy equity, and the justice threshold is confirmed. Equity in the physical access to energy in the form of rural-urban parity of electricity access are linked to high levels of equity, which in turn increase the positive impacts of digital openness on the share of renewable electricity, whereas inequities reduce or even eliminate such impacts. The heterogeneity analysis also indicates that this synergistic effect is especially high in middle and low-income economies, which confirms the leapfrog hypothesis and indicates a strategic opportunity of the Global South to jump into digital-renewable investments.

These results add three content valid contributions to the body of literature. To start with, the strong positive interaction term among estimators both introduces and empirically proves the existence of the concept of justice threshold to inclusive digital-green synergies that equitable energy distribution is a precondition of inclusive digital-green synergies (Sohail et al., 2025; Ullah et al., 2024). Second, the strong impacts in emerging economies highlight leapfrog processes, which provide a contrasting perspective to the siloed perceptions of digital and energy policies and provide a deeper insight into how late-movers can become rapidly decarbonized (Dekeyrel & Fessler, 2024; Ni et al., 2024).

Third, as it demonstrates unidirectional causality between digital trade integration and the green transition (Table 12), the paper is placing digitalization as a strategic policy lever, which invites the debate on whether digital trade is just an accompanying phenomenon or a driver of sustainability, the Pollution Halo Hypothesis is extended into the digital sphere (J. Li et al., 2025).

5.2 *Policy Implications*

The policy implications are significant, particularly in light of emerging trends in digitalization and the recent rise in AI-driven energy demand, which, although not fully captured in the study period (2002–2023), highlight the growing importance of aligning digital trade with sustainable energy systems. Policymakers should promote coordinated digital-energy strategies that align digital trade development with renewable energy expansion. Digital trade policies should be coordinated with climate policy frameworks, including national decarbonization strategies and international climate commitments. It is imperative to acknowledge that digital barriers are the environmental barriers of the first order, hindering the diffusion of renewable energy. In the case of the middle- and low-income economies, the evidence requires digital-energy bundling, which systematically combines the rural broadband, digital literacy and e-commerce investments with the decentralized renewable investments, such as solar microgrids, to reach the justice threshold, unlock the multiplier effect, and prevent the problem of the catastrophic digital consumption/energy poverty paradox that increases rural exclusion and e-waste liability. International trade negotiations could incorporate energy equity and environmental justice impact assessments, which should be a must in digital negotiations with the agreements on Global South digital exports should include specific funding; Green Digital Bonds and concessional loans, to finance equitably the infrastructure and prevent transboundary injustices, and digital trade should mainly drive an inclusive and fair green transition of the world.

Policymakers should promote coordinated digital–energy strategies through inter-ministerial alignment, ensuring that digital trade policies, energy planning, and climate objectives are mutually reinforcing. Rather than integrating directly into NDCs or WTO frameworks, targeted digital–green trade provisions can be incorporated into regional and bilateral trade agreements (e.g., ASEAN or EU frameworks) (Ashraf et al., 2025), where regulatory flexibility allows for better policy coordination.

Future research could extend this framework by incorporating broader indicators of environmental justice, including e-waste governance, transboundary pollution pressures, and participatory energy governance.

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Availability of Data

The dataset is available from the corresponding author upon reasonable request.

Declaration of AI Use

AI tools were used to improve the readability of this paper. No AI tool was used to generate ideas, theoretical arguments, data analysis, empirical results, or interpretations, etc.

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