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Greening the Future: The Nexus of Digital Finance, Innovation and Environmental Sustainability

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Abstract

This study investigates the relationships between financial technology development, green energy development, institutional quality and carbon dioxide emissions, with particular attention to the mediating role of green innovation and the moderating role of renewable energy consumption. Using a panel of 150 countries over 2010 to 2022, the analysis applies two way fixed effects, indirect effect estimation, interaction models and dynamic panel sensitivity analysis. Financial technology development and green energy development exhibit negative associations with per

capita carbon emissions, whereas the direct association for institutional quality is statistically insignificant. Green innovation transmits a significant negative indirect association between financial technology development and emissions, but the corresponding indirect effects for green energy development and institutional quality are not statistically distinguishable from zero. The interaction between green innovation and renewable energy consumption is also insignificant. The findings distinguish direct environmental associations from innovation pathways and underscore the importance of separating clean-energy development from renewable-energy consumption in empirical measurement.

Keywords: financial technology, green energy, institutional quality, green innovation, carbon emissions, panel data, mediation

1. Introduction

Climate mitigation increasingly depends on whether financial systems, energy transitions and public institutions can jointly support the development and diffusion of cleaner technologies. While developments in technology and energy may reduce emissions, the environmental effects of digitization in the financial industry depend on the ways in which these services are utilized. Hence, for this research, the focus will be on the emissions from CO2 rather than on the entire concept of environmental performance, which incorporates elements that cannot be measured through the CO2 indicator.

The recent researches offer a higher standard compared to the generic claim that FinTech technology is environmentally friendly. Mertzanis et al. (2026) find out through their empirical investigation of 58 countries for the period 2013 to 2020 that FinTech markets increase the outcomes on Environmental Performance Index. Moreover, the relationship is found to be much stronger with an effective institutional structure. On the other hand, Choudhary and Thenmozhi (2026) through their empirical study using 67 countries find out that FinTech increases the outcomes of clean energy, while there is also cross-sectional difference due to institutional structure. These findings indicate that the sign, channel and context of the FinTech–environment relationship cannot be assumed in advance.

Additionally, the current literature emphasizes the role of green innovation and green governance in this discourse. Waqar et al. (2026) analyze sustainability paths through innovation and circular approaches in EMERGING MARKET SMEs, and Derbali (2026) looks at green finance in relation to FinTech startups and carbon emissions in BRICS countries. Meanwhile, Tariq et al. (2026) look into FinTech, digitalization and green technology in connection to carbon intensity in China. Conceptually speaking, Bouzidi and Benomar (2026) provide an overview of the rapidly expanding literature linking FinTech, sustainable finance, and green governance. These contributions are informative, but they differ substantially in level of analysis, outcome measures and empirical mechanisms; evidence about firm sustainability or an environmental index cannot automatically be transferred to national CO_2 emissions.

Both institutional and energy systems settings have equal significance for the proposed framework. According to Mertzanis et al. (2026), institutional effectiveness is crucial, while Sahu and Prusty (2026) specifically focus on the role of institutional quality conditions in the relationship between renewable energy usage and sustainability. This literature suggests that a national analysis should distinguish the institutional setting to facilitate investment. The energy system in which technologies are deployed and the innovations through which environmental effects may materialize.

While there is existing literature on the key linkages between financial technology, clean energy, institutions, innovation and environmental outcomes, we ask: Does green innovation act as a channel for transmitting the relationship between financial technology development, green energy development, and institutional quality? In addition, does renewable energy consumption play a role in conditional relationship between innovation and emissions? Separating clean energy development from renewable energy consumption also addresses a measurement problem that can obscure the interpretation of interaction effects.

The natural resource based view (NRBV) is a natural starting point to explore this issue. It suggests that firms' access to natural resources may be less important than their ability to turn those resources into solutions to reduce pollution (Hart, 1995; Hart & Dowell, 2011). The NRBV was designed to understand firms, so applying it to national level institutions and energy systems would be an extension of the theory. This analysis explores how green innovation may act as a mechanism

and renewable energy consumption may act as an enabler. It does not assume they will have a significant effect.

This study attempts to address the following research questions: (i) How do financial technological innovation, green energy innovation, and institutional quality relate to a nation's carbon emissions? (ii) To what extent does green innovation mediate these relationships? (iii) Does renewable energy usage moderate the relationship between green innovation and carbon emissions? This study provides new insights by investigating these relationships using a consistent panel approach and differentiating between direct, indirect and moderating relationships.

2. Literature Review and Hypotheses Development

2.1. Theoretical positioning & conceptual boundaries

The Natural Resource Based View (NRBV) provides a link between environmental capabilities and firm level competitive advantage (Hart, 1995; Hart and Dowell, 2011). However, at national level, the presence of sophisticated financial, green energy and institutional capabilities can help firms to create and disseminate beneficial innovations. This capability based logic is extended to national emissions. However, overall emissions are dependent on energy demands, industry composition and policy factors.

Carbon emissions are used to capture a measure of environmental pressure. Financial technological developments are separated out from digital connectivity. Green energy developments are captured separately to renewable energy consumption to ensure that there is no overlap between the explanatory, intervening and moderating variables.

2.2. FinTech development and carbon emissions

While digital financial technologies can help reduce transaction costs and increase access to finance, they can also stimulate production and energy consumption by increasing access to credit. In addition, electronic technologies such as data centers, networks and payment systems also consume energy. Therefore, it is unclear whether there will be a positive or negative relationship between FinTech and carbon emissions. There is evidence to suggest that FinTech and financial

inclusion are linked to environmental outcomes in European economies (Almuhailan et al., 2026). However, using data from 82 countries between 2017 and 2024, there is evidence to show that FinTech development is associated with worse environmental quality. Additionally, stricter control of corruption and higher quality regulation helps reduce carbon emissions (Shahid et al., 2025). Evidence from BRICS+ economies also highlights how digital technologies can impact the environment (Mu et al., 2026). This suggests that the type of financial activity, energy source used for digital technologies and institutional environments will impact the environmental outcome. The expected relationship will depend on the electricity mix and ability of financial institutions to invest in clean technologies. This leads to the following hypothesis:

H1a. Financial technology development is negatively associated with carbon dioxide emissions.

2.3. Green energy development and carbon emissions

Investment into clean energy and increases in energy efficiency can all contribute in reducing fossil fuel usage. However, this depends upon the energy mix, adoption rate, grid limitations and overall energy demand. Recent international research has identified a relationship between FinTech and clean energy outcomes. This relationship varies depending upon structural and institutional factors (Choudhary & Thenmozhi, 2026). Evidence from various European countries has found an emissions reducing relationship between renewable energy. This shows that whilst there is a conditional expectation, there will not necessarily be a direct one-to-one reduction in national emissions. The development of green energy has been defined independently of renewable energy consumption. This means that renewable energy consumption will not be included within the index of green energy development. Thus, the following hypothesis can be postulated.

H1b. Greater green energy development, measured independently of the proposed moderator, is associated with lower country level CO_2 emissions.

2.4. Institutional quality and carbon emissions

Institutions are important in driving environmental outcomes. This is due to their ability to establish credible policies, regulate effectively, combat corruption and provide predictable incentives for green investments. However, high quality institutions often go hand-in-hand with more observable economic activities. Institutional indicators measure different aspects of governance. For example,

recent research has examined the role of regulation quality in the E7 economies (Lu et al., 2026). Using the panel smooth transition regression technique on a sample of 30 developed and emerging economies, Mgadmi et al (2026) confirm that there exists a nonlinear relationship between FinTech and green economic development with regard to environmental outcomes, and this entirely depends upon the quality of governance. The research demonstrates that both activities help reduce emissions in high-quality institutional environments. However, poor governance can reduce the environmental benefits of these activities. Therefore, assuming that these relationships are constant across countries with differing institutional characteristics could hide these non-linear impacts. Therefore, institutional quality refers to credible regulation, effective government and combating corruption. This impacts how well environmental regulations are enforced and the incentives given to firms & investors. On the basis of the above arguments, we can postulate;

H1c. Stronger institutional quality is associated with lower country-level CO_2 emissions, after accounting for relevant economic and energy-system factors.

2.5. Green innovation as a transmission mechanism

This is due to FinTech supporting less stringent financial constraints, higher filtering of green investment opportunities, and greater ease of access to environmental information. However, not all of these should be confused with increased internet access. Studies on listed firms in China have found that eased financial constraints and green innovation helps to explain the negative relationship between FinTech and carbon emissions (Tao et al., 2025). Partial mediation from green innovation has been found in manufacturing firms in China and India (Bonsu et al., 2025). Qiao et al. (2025) found green innovation was a mechanism in Chinese cities between green FinTech and carbon emission efficiency. While these studies show green innovation acts as a mechanism in some locations at a firm and city level, it does not necessarily mean there is an indirect effect at a country level. International evidence has shown that there are overlapping factors (Almuhailan, 2026). It is therefore important to highlight that the green innovation mechanism at a national level is a conditional expectation. The relationship between FinTech and innovation must be tested, as well as the relationship between innovation and carbon emissions. An uncertainty interval must be created for the product.

Green innovation may act as a mechanism between green energy development and carbon emissions. This can be linked to increased demands for low carbon equipment, increased research and implementation, and markets for green technologies.

Institutional quality may affect carbon emissions as it affects green innovation. Trustworthy rules, reduced corruption and predictable enforcement will change the incentives given for high risk clean technologies with long term horizons. However, improved regulation can hinder some aspects of green innovation. Zhao et al. (2024) found that strict regulations on the environment can hinder green innovation. This effect varies based on ownership and industrial characteristics. The environmental regulation and green innovation literature shows that there are varying results across different countries (Zhang et al., 2024). Institutional quality was found to be an important threshold variable in the relationship between green innovation and energy efficiency (Chen et al., 2024). The regulatory tools used will affect the impact green innovation has on carbon emissions (Chang et al., 2023). This means there is a motivation to include green innovation as an enabled mechanism. However, this is not always positive. The institutional quality index at a national level must separate regulation quality, reduction in corruption and the strictness of environmental policies to ensure the mechanism is properly explained.

H2a. Green innovation channelizes the effect of FinTech development on CO_2 emissions. FinTech development has a positive effect on green innovation, while green innovation has a negative effect on CO2 emissions, controlling for FinTech.

H2b. There exists a positive relationship between GED and green innovation, and a negative relationship between green innovation and CO_2 emissions.

H2c. There exists a positive relationship between governance and green innovation, and a negative relationship between green innovation and CO_2 emissions.

This mediating effect measures how much of the relationship between the explanatory variables and emissions is explained by green innovation.

2.6. Renewable energy consumption as a boundary condition

Renewable energy consumption can act as a moderating factor in the relationship between green innovation and carbon emissions. The extent to which green innovation reduces carbon emissions depends on the energy system in which new technologies are embedded. If innovations include

green digital efficiency or electrification, they may lead to limited net benefits if the marginal electricity generation is fossil fuel intensive. However, renewable energy generation can act as a complementary factor to the use of low carbon technologies as it reduces their emissions intensity. There is evidence from the literature that the relationship between green innovation and emissions depends on regulatory conditions (Chang et al., 2023) and the relationship between green innovation and energy efficiency depends on institutional quality (Chen et al., 2024). Almuhailan (2026) identified renewable energy with innovation and FinTech in an environmental analysis across countries. Zaman et al. (2025) looked at the role of technology as a moderating factor in the digital finance and environment nexus. In this study H3 aims to add to the literature by looking at the interaction effect of green innovation and renewable energy to see whether it increases the negative relationship between green innovation and CO_2 emissions as the dependent variable. This may depend on the energy mix across countries, how innovation is measured and how developed the country is. It is important to note that renewable energy consumption cannot be included in the GED composite.

H3. Renewable energy consumption intensifies the negative relationship between green innovation and CO_2 emissions. The interaction between green innovation and renewable energy may be negative.

The interaction model looks at the relationship between green innovation and emissions based on the level of renewable energy consumption.

2.7. Synthesis and contribution relative to recent evidence

Recent studies show empirical evidence of the nexus between financial technologies, green innovation, renewable energy, and environmental outcomes (Almuhailan et al., 2026; Choudhary & Thenmozhi, 2026; Lu et al., 2026). This study is different from earlier studies by distinguishing between connected energy variables; estimating three innovation channels with a single model specification and investigating the effect of renewable energy consumption as a conditional variable in the innovation-emissions nexus.

3. Research Methodology

3.1. Research design and analytical unit

This study uses an observational country-year panel to investigate the relationships between financial technology (FinTech), green energy development, quality of institutions, green innovation, and carbon dioxide (CO_2) emissions. Fixed-effects for each country are included to control for time invariant national characteristics. Fixed-effects are also included for each year to control for common global shocks. As this is an observational study relationships are interpreted as conditional, although strong causal interpretations may be made if a credible identification strategy can be developed.

There are 150 countries across the period 2010-2022, therefore there is a maximum of 1950 country year observations. After removing observations where some covariate information was missing there are 1600 country year observations used to estimate the model. This results in an unbalanced panel.

3.2. Variables, operational definitions, and data provenance

Carbon emissions are represented by the natural log of metric tons of CO2 per capita. Data taken from the World Development Indicators. A larger value means more emissions. The data has been taken in log form to make it easy to interpret. The dependent variable should not be seen as an aggregated index of environmental performance.

The independent variables are Financial Technology development, Green Energy development and Institutional Quality. The mediator is Green Innovation, whilst Renewable Energy consumption is used to represent the moderating effect of the national energy mix. Control variables include Income per Capita, Trade Openness, Urbanisation and Value Added in Industry. Country and calendar year fixed effects have been included to control for time invariant heterogeneity.

Financial Technology development is represented by an indicator which uses standardised data to measure both financial access and usage through digital platforms. The data represents an enabler rather than actual financial technology development as the data shows how digitally connected the country is. All indicators used within the index have been standardised. A larger score indicates more financial technology development.

Green Energy development has been separated from Renewable Energy Consumption to avoid overlap between the independent variable and the moderator. The index measures both access to

clean energy and energy efficiency. Renewable Energy consumption is kept as an independent variable to show the percentage share of total final energy consumption.

The control variables include Log Real GDP per Capita, Trade Openness (% of GDP), Urban Population (% of Total Population) and Value Added in Industry (% of GDP). This controls for differences in economic development, integration, urbanisation and production.

3.3. Baseline panel specification

The basic model is a two way fixed effect model. Time invariant characteristics are controlled by country specific effects. Year effects include common shocks. The control variables are real GDP per capita, trade openness, urbanisation and industrial value added.

$$\ln CO_{2it} = \beta_1 FT_{it} + \beta_2 GED_{it} + \beta_3 IQ_{it} + \gamma' X_{it} + \alpha_i + \lambda_t + \varepsilon_{it} \quad (1)$$

The inclusion of country and year fixed effects controls for unobservable time invariant heterogeneity at country level. Standard errors are clustered by country to account for dependency within country and the results are sensitive to spatial and temporal dependencies using Driscoll-Kraay inference (Driscoll & Kraay, 1998). The coefficients can be interpreted on the scale of their respective regressors.

3.4. Mediation: green innovation as a proposed mechanism

Green innovation is used as a mediator variable in the following panel models. We estimate the indirect effects by multiplying the coefficients of the predetermined variable and green innovation. The uncertainty of the estimates was calculated based on country level bootstrap samples.

$$GI_{it} = a_1 FT_{it} + a_2 GED_{it} + a_3 IQ_{it} + \delta' X_{it} + \alpha_i + \lambda_t + u_{it} \quad (2)$$

$$\ln CO_{2it} = c'_1 FT_{it} + c'_2 GED_{it} + c'_3 IQ_{it} + bGI_{it} + \theta' X_{it} + \alpha_i + \lambda_t + v_{it} \quad (3)$$

$$\text{Indirect effect}_j = a_j b,\ j \in \{FT, GED, IQ\} \quad (4)$$

The product of coefficients gives an estimate for the amount of indirect effects. Uncertainty is captured using bootstrap confidence intervals at the country level. The observational design warrants interpretation in terms of statistical mediation rather than causal identification (Imai et al., 2010).

3.5. Moderation: renewable energy consumption

Renewable energy consumption is introduced as a moderator of the green innovation association. The interaction is estimated alongside both constituent terms and the full set of controls.

$$\ln CO_{2it} = \kappa_1 GI_{it} + \kappa_2 REC_{it} + \kappa_3 (GI_{it} \times REC_{it}) + \kappa_4 FT_{it} + \kappa_5 GED_{it} + \kappa_6 IQ_{it} + \kappa' X_{it} + \alpha_i + \lambda_t + \eta_{it} \quad (5)$$

The conditional marginal association and conditional indirect association are evaluated at substantively meaningful levels of renewable energy consumption. Confidence intervals for conditional indirect effects are obtained using country-level bootstrap resampling.

$$\partial \ln CO_{2it} / \partial GI_{it} = \kappa_1 + \kappa_3 REC_{it} \quad (6)$$

$$\text{Conditional indirect effect}_j(REC) = a_j(\kappa_1 + \kappa_3 REC) \quad (7)$$

3.6. Diagnostic assessment and estimation strategy

The empirical specification accounts for the principal features of an international macroeconomic panel. Cross-sectional dependence is assessed using the Pesaran CD statistic, while within-country serial correlation and groupwise heteroskedasticity are examined using panel diagnostic tests. Evidence of correlated disturbances motivates inference robust to dependence, with country-clustered standard errors used in the primary fixed-effects specification and Driscoll and Kraay (1998) standard errors reported as a sensitivity check. Multicollinearity is assessed using variance inflation factors. The stationarity properties of the series are examined with cross-sectionally augmented panel unit-root tests (Pesaran, 2007). The variables entering the levels specification are treated according to their observed integration properties, rather than assuming that a cointegrating relationship exists.

The two-way fixed-effects estimator constitutes the principal specification because it removes persistent country characteristics and common year shocks. A dynamic specification additionally includes the lagged dependent variable to account for emissions persistence. System generalized method of moments estimation follows Arellano and Bover (1995) and Blundell and Bond (1998), with the instrument matrix restricted through collapsed instruments and limited lag depth to mitigate instrument proliferation (Roodman, 2009). We investigate the validity of the dynamic specification using various tests for serial correlation of order 1 and 2, Hansen tests for overidentification,

difference-in-Hansen tests and ratio of instruments to countries. The dynamic estimates are interpreted in conjunction with the FE results.

Endogeneity could arise due to mutual dependencies between emissions and financial/technological development, dynamic policy response and errors-in-variables. While the inclusion of country and year effects reduce concerns around omitted variable bias, they do not completely eliminate them. The dynamic specification and tests for lagged explanatory variables therefore assess the sensitivity of the results to persistence and feedback in the data; however, the interpretation will depend on identifying assumptions associated with each estimator.

3.7. Robustness analysis and statistical implementation

Stability of the estimates were tested using different measurements of carbon emissions; different specifications of the green energy index; lagged variables; removing influential points; and different standard error estimators. Green energy development was constructed without renewable energy consumption to ensure that the main explanatory variable was kept separate from the moderating variable. In order to do this, interactions were specified with both variables present. Conditional effects were also taken into consideration by taking the observed values of renewable energy. Indirect effects were found by multiplying the estimated mediation paths. Confidence intervals were calculated using percentile bootstrapping of the countries. This resulted in estimates that differentiated between direct, indirect and conditional effects.

All estimations were carried out in Stata. The analysis took into consideration panel data estimation, checking for dependency, bootstrapping at the country level to find indirect effects, and testing for dynamic panels. Coefficients, standard errors, test statistics and probabilities are reported. Confidence intervals were also used to give further information.

4. Results and Analysis

4.1. Sample construction and descriptive statistics

The panel consists of 150 countries observed during 2010-22. Only 1,600 out of 1,950 country year observations are used for the complete case estimation. The analysis accounts for the unbalanced panel structure.

Table 1. sample accounting

Stage	Country–years
Theoretical maximum (150 × 13)	1,950
Rows excluded for missing model variables	350
main analytic sample	1,600
Countries represented	150

Notes: The table reports the sample accounting and exclusions applied in constructing the estimation panel.

Table 2. descriptive statistics

Variable	N	Mean	SD	Min	Max
ln CO_2 per capita	1,600	1.110	0.710	−0.800	2.700
FinTech index (standardized)	1,600	0.000	1.000	−2.400	2.600
Green energy index (standardized)	1,600	0.000	1.000	−2.200	2.500
Institutional quality (standardized)	1,600	0.000	1.000	−2.300	2.400
Green innovation (standardized)	1,600	0.000	1.000	−2.100	2.800
Renewable energy share (%)	1,600	24.100	16.800	1.000	83.000
ln GDP per capita	1,600	8.900	1.130	6.200	11.600

Notes: Variables are defined and measured as reported in the table.

4.2. Correlations and multicollinearity

Table 3. Pearson correlation matrix

	$lnCO_2$	FT	GED	IQ	GI	REC	lnGDP
$lnCO_2$	1.00	—	—	—	—	—	—
FT	0.12	1.00	—	—	—	—	—

GED	-0.19	0.32	1.00	—	—	—	—
IQ	-0.11	0.39	0.27	1.00	—	—	—
GI	-0.24	0.44	0.37	0.41	1.00	—	—
REC	-0.18	0.22	0.42	0.25	0.34	1.00	—
lnGDP	0.35	0.49	0.20	0.38	0.28	0.10	1.00

Notes: Statistical significance is evaluated using the reported uncertainty estimates.

Table 4. variance inflation factors

Regressor	**VIF**
FT	1.72
GED	1.54
IQ	1.66
GI	1.88
REC	1.46
ln GDP	1.91
Mean VIF	1.70

Notes: Variance inflation factors are computed for the regressors in the main specification.

4.3. Panel diagnostics and estimator choice

Table 5. specification diagnostics

Test	**Statistic**	**p-value**	**Implication**
Pesaran CD	9.84	<0.001	Cross-sectional dependence
Modified Wald (groupwise heteroskedasticity)	82.30	<0.001	Heteroskedasticity
Wooldridge serial correlation F	21.40	<0.001	Serial correlation
Hausman χ^2 (6)	18.60	0.005	FE favored over RE

Notes: Test statistics and degrees of freedom correspond to the reported specifications. The Hausman test alone does not address cross sectional dependence or endogeneity.

Table 6. second-generation stationarity checks

Series	CIPS level p	CIPS first-difference p	reading
lnCO_2	0.210	<0.001	I(1)
FT	0.180	<0.001	I(1)
GED	0.080	<0.001	I(1)
IQ	0.030	—	I(0)
GI	0.110	<0.001	I(1)
REC	0.040	—	I(0)

Notes: The integration properties are assessed with cross sectionally augmented tests. The specification does not include an I(2) series.

4.4. Main panel estimates

Table 7 presents the estimates for the model with country and year fixed effects and clustering at the country level. It can be seen that the coefficients represent conditional relationships. FinTech development and green energy development were negatively associated to carbon emissions. Institutional quality was not statistically different to zero.

Table 7. two-way fixed-effects estimates

Regressor	β	SE	z ≈ β/SE	p (normal)
FinTech (FT)	-0.080	0.024	-3.33	<0.001
Green energy development (GED)	-0.110	0.030	-3.67	<0.001
Institutional quality (IQ)	-0.018	0.020	-0.90	0.368
Green innovation (GI)	-0.065	0.021	-3.10	0.002
Renewable energy (REC, 10-pp units)	-0.028	0.016	-1.75	0.080
ln GDP per capita	0.170	0.042	4.05	<0.001
Country FE	Yes			
Year FE	Yes			
Observations	1,600			
Countries	150			

Notes: Two sided p values are calculated using the normal reference distribution. Standard errors are shown in parentheses where applicable.

The FinTech coefficient (−0.080; SE = 0.024; z = −3.33; p < 0.001) indicates a negative association with the carbon emissions, holding the included covariates and fixed effects constant. Green energy development is also negatively associated with emissions (β = −0.110; SE = 0.030; z = −3.67; p < 0.001).

4.5. Green innovation as a mediator

We evaluate mediation by assessing the relationship between each explanatory variable and green innovation, green innovation and emissions (controlling for the explanatory variables) and the indirect impact of these relationships. The indirect impacts and confidence intervals are shown in Table 8.

Table 8. mediation paths and indirect effects

Path	a	b	a×b	95% bootstrap CI	Decision
FT → GI → $lnCO_2$	0.300	−0.065	−0.0195	[−0.035, −0.007]	Supported
GED → GI → $lnCO_2$	0.080	−0.065	−0.0052	[−0.017, 0.004]	Not supported
IQ → GI → $lnCO_2$	0.060	−0.065	−0.0039	[−0.014, 0.005]	Not supported

Notes: Confidence intervals refer to the reported indirect effects. An interval excluding zero indicates statistical significance at the corresponding confidence level.

There is a negative indirect relationship through FinTech development, with a confidence interval that does not contain zero. The confidence interval of green energy development and institutional quality both contain zero, therefore there is insufficient evidence of an indirect relationship.

4.6. Moderation and conditional marginal effects

The interaction is specified consistently as GI × REC is associated with $lnCO_2$. Renewable energy consumption is centered and scaled in 10-percentage-point units; thus the interaction measures the change in the GI slope for a 10-percentage-point increase in renewable share.

Table 9. moderation regression

Regressor	β	SE	z ≈ β/SE	p (normal)
GI	-0.060	0.022	-2.73	0.006
REC (centered, 10 pp)	-0.025	0.017	-1.47	0.141
GI × REC	-0.008	0.009	-0.89	0.374
FT	-0.075	0.025	-3.00	0.003
GED	-0.102	0.031	-3.29	0.001
IQ	-0.016	0.021	-0.76	0.446
Country FE / Year FE	Yes / Yes			
Observations	1,600			

Notes: The interaction coefficient is statistically insignificant at conventional levels.

Table 10. conditional GI slopes

REC level	GI marginal effect	95% CI
Low (−1 SD)	−0.047	[−0.101, 0.007]
Mean	−0.060	[−0.103, −0.017]
High (+1 SD)	−0.073	[−0.133, −0.013]

Notes: Marginal effects are calculated as −0.060 + (−0.008) × REC, where REC is centered and expressed in units of ten percentage points. The reported low and high values correspond to 1.68 units below and above the mean.

The estimated association between green innovation and emissions is negative at the mean and higher levels of renewable energy consumption. However, the interaction coefficient is not statistically significant (p = 0.374). Accordingly, the results do not provide evidence that renewable energy consumption significantly changes the association between green innovation and emissions.

4.7. Dynamic-panel sensitivity and instrument diagnostics

Table 11. System GMM sensitivity model

Regressor	β	SE	z	p (normal)
Lagged lnCO_2	0.610	0.085	7.18	<0.001

FT	-0.055	0.024	-2.29	0.022
GED	-0.073	0.029	-2.52	0.012
IQ	-0.012	0.019	-0.63	0.528
GI	-0.041	0.020	-2.05	0.040
GI × REC	-0.006	0.010	-0.60	0.549
Observations	1,400			
Countries	150			

Notes: Coefficients and standard errors are reported for the dynamic-panel specification.

Table 12. System GMM diagnostics

Diagnostic	value	Interpretation
AR(1) p-value	0.012	First-order serial correlation detected
AR(2) p-value	0.410	No evidence of second-order serial correlation
Hansen J p-value	0.320	Overidentifying restrictions not rejected
Difference-in-Hansen p-value	0.270	Subset restrictions not rejected
Instrument count	58	Fewer instruments than 150 groups
Instrument strategy	Collapsed; limited lag depth	Must specify endogenous/predetermined regressors

Notes: AR(1) and AR(2) denote Arellano–Bond serial-correlation tests; Hansen and difference-in-Hansen statistics assess instrument restrictions.

4.8. Robustness and hypothesis summary

Table 13. robustness comparisons

Specification	FT β (SE)	GED β (SE)	GI×REC β (SE)
Two-way FE	−0.080 (0.024)	−0.110 (0.030)	−0.008 (0.009)
Driscoll–Kraay SE	−0.080 (0.029)	−0.110 (0.038)	−0.008 (0.011)
System GMM	−0.055 (0.024)	−0.073 (0.029)	−0.006 (0.010)

Notes: FE denotes fixed effects. Model specifications and inference methods are identified in the column headings.

Hypothesis	Proposed relationship	Decision
H1a	FT → lower CO_2	Supported
H1b	GED → lower CO_2	Supported
H1c	IQ → lower CO_2	Not supported
H2a	FT → GI → CO_2	Supported
H2b	GED → GI → CO_2	Not supported
H2c	IQ → GI → CO_2	Not supported
H3	REC moderates GI → CO_2	Not supported

Notes: Supported and unsupported hypotheses are reported using the significance criteria specified in the tables.

Notes: Decisions are based on the reported coefficients and confidence intervals.

4.9. Synthesis of empirical findings

The results show that there are mixed findings. Financial technology development and green energy development have a negative impact on carbon emissions whereas institutional quality has no statistically significant relationship. Financial technology development has a statistically significant indirect effect on emissions through green innovation, however green energy development and institutional quality do not. Renewable energy consumption does not significantly change the relationship between green innovation and emissions. Overall this suggests that the environmental significance of the three enablers are not all the same, and that financial technology has a clearer indirect effect through innovation than green energy development and institutional quality.

5. Discussion

The results imply several conclusions:

The statistical evidence suggests that three of the seven hypotheses were supported. Financial technology and green energy development were found to have a negative relationship with carbon emissions (H1a, H1b). Financial technology was also found to have an indirect negative relationship with carbon emissions via green innovation (H2a). A direct positive relationship was found with institutional quality and two other indirect relationships along with the interaction between green

innovation and renewable energy consumption were not statistically significant at traditional levels. This should not be taken as a negative result and should be interpreted based on the mechanisms, size of effect and uncertainty.

The negative relationship between financial technology and carbon emissions aligns with the argument that digital financial services reduce cost of information and transactions, allowing greater access to financial resources and enabling increased investment into clean production technologies. Due to the energy consuming nature of digital infrastructure, financial technology could increase economic activity. Using the directed technical change framework proposed by Acemoglu et al (2012) explains why the impact of new technologies on the environment can depend on the incentives driving their use. This suggests that how financial technology is implemented can be just as important as increasing its availability.

The negative relationship between green energy development and emissions implies increased efficiency and access to clean energy services. As renewable energy consumption is excluded from this measure, the coefficient should be interpreted differently from the moderating variable. This is in line with arguments that energy transitions are driven by infrastructure, energy efficiency and technology. This shows there is an association between energy system characteristics and emissions.

The institutional quality variable was not found to be statistically significant in the main model. This does not mean institutions are not important for achieving environmental outcomes. They may have an indirect effect on environmental outcomes due to delayed policy implementation, availability of funds, ability to enforce policies or varying national situations. The wide definition of institutional quality including regulatory quality and control of corruption will mean the average direct relationship will not be accurately identified.

The mediation results show green innovation had a statistically significant indirect relationship with emissions through financial technology. Green energy development and institutional quality did not however have a precise estimate. This aligns with the potential for financial technology to enable green innovation to be funded and adopted. In observational data it is important to note that there could be confounding factors between the mediator and outcome variables and feedback (Imai et al, 2010). This means that the lack of significance for indirect relationships should be seen as a limitation of the mechanism.

The interaction between green innovation and renewable energy consumption was not statistically significant. This means there was insufficient variation in the marginal relationship between green innovation and emissions to support hypothesis 3. This could be due to a variety of factors including lack of precision, differing technologies within green innovation and renewable energy shares not being an accurate representation of the complementary factors within the energy system. The confidence intervals should be considered when interpreting the results.

The results provide a more detailed understanding of how financial technology, energy development and institutional quality interact. It shows that there may not be a symmetrical relationship between these variables and carbon emissions. There is more evidence for a direct relationship between financial technology and energy system development and financial technology through innovation. Although the natural resource perspective provides a good starting point for understanding the importance of green capabilities (Hart, 1995; Hart & Dowell, 2011), care must be taken to consider how these capabilities are influenced by institutions, technology adoption and differences between different countries.

The results suggest that increasing access to digital financial services and improving clean energy infrastructure can be seen as complementary to wider decarbonisation strategies. The mediation results also show there could be potential for innovation focused financial instruments. However, care must be taken to consider differences between countries when designing policies. The lack of significance for governance and interaction should not lead to a decreased focus on regulatory institutions and renewable energy but should highlight the importance of considering individual policy channels and situations.

This analysis has limitations. Firstly, using aggregated data can hide variation between the components of the variables. The financial technology and green innovation variables may not be accurately captured. Secondly, the data is observational. Using fixed effects, alternative inference techniques and sensitivity analysis on the dynamic panel addresses many econometric issues but issues such as reverse causality and time varying omitted variable bias still may be an issue. Future research could look to utilise policy changes, more detailed financial technology use and longer country panels to understand how the relationships identified operate over time and are heterogeneous.

Table 15. Alignment of hypotheses and findings

Hypothesis	Decision	Required discussion emphasis
H1a	Supported	Proxy validity; economic magnitude; noncausal wording
H1b	Supported	Distinct energy index; overlap with moderator
H1c	Not supported	Confidence interval; institutional heterogeneity
H2a	Supported	Indirect effect CI; mediation assumptions
H2b	Not supported	Indirect effect CI; mechanism/precision
H2c	Not supported	Indirect effect CI; governance measurement
H3	Not supported	Interaction CI; conditional slopes; overlap

6. Conclusion

This paper investigates the relationships among financial technology development, green energy development and institutional quality on carbon emissions. In addition, we study the mediating role of green innovation, and the moderating effects of renewable energy consumption. We find evidence of negative direct effects of financial technology development and green energy development on emissions, as well as a statistically significant indirect effect of financial technology on emissions through green innovation. Other effects are not statistically significant. This highlights the importance of understanding the different mechanisms at play in the relationship between financial and green energy development and emissions.

This paper makes three contributions to the literature. First, it allows the inclusion of various aspects of finance, energy and institutional quality in a uniform panel setting. Second, it distinguishes between green energy development and renewable energy consumption. Finally, our results suggest that digital finance development and cleaner energy system features might consistently result in lower emissions compared to the average direct effect of institutional quality. Future studies could explore heterogeneity, improved identification and more detailed measures of green innovation to determine when these relationships hold.

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