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Can Green Finance and Digital Economy Foster Renewable Energy Development? Insight from G20 Countries with Two-Step-System-GMM Approach

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Abstract

The escalating concerns regarding environmental issues and the far-reaching implications of climate change have significantly intensified the focus on the shift towards renewable energy within academia and policymaking. This study investigates how the digital economy and green financing have affected the growth of renewable energy in G20 countries between 2010 and 2020. A key novelty of this research lies in examining the moderating effects of eco-innovation and institutional quality—factors often overlooked in prior studies. Using a dynamic panel data approach and the Two-Step System GMM (2SYSGMM) to address endogeneity concerns, our findings indicate that green finance and the digital economy play a positive role in fostering renewable energy development. The policy recommendations underscore the importance for G20 governments to prioritize investments in digital infrastructure to incorporate digital solutions into the energy sector and bolster the digital economy. Additionally, there is an emphasis on the need to promote innovation, literacy, and inclusivity in green finance, while advocating for the adoption of environmentally friendly technologies through robust research and development efforts and the strengthening of institutional frameworks. This study contributes to the literature by providing empirical evidence on how digital and financial mechanisms interact with institutional and innovation factors to accelerate the energy transition.

Keywords:
digital economy, G20 countries, generalized method of moments, green finance, renewable energy development

1. Introduction

The Group of Twenty (G20) nations play a key role in the global energy landscape, even as fossil fuel consumption has increased significantly (Ampah et al., 2021; BP, 2021). They contribute approximately 80% of the world's energy-related CO_2-equivalent emissions, emphasizing their critical influence on global climate change mitigation efforts (IPCC, 2021). In recent years, G20 countries have committed to advancing renewable energy by setting ambitious targets to expand their share of their energy mix. Nonetheless, reaching net-zero emissions by mid-century remains challenging due to the high costs associated with renewable energy projects and limited access to affordable financing. This challenge is compounded by the lack of incentives for private-sector participation in green financing. However, advancements in green technologies and innovative financial instruments—such as green bonds—present promising pathways to accelerate the transition to sustainable energy.

Green finance, which integrates traditional lending practices with environmental regulation, has emerged as a pivotal mechanism in today's financial landscape. It encompasses the issuance of green securities, green loans, and green investments aimed at supporting environmentally friendly initiatives that promote human well-being, social welfare, and sustainable economic growth (Yang et al., 2021). Mechanisms like green bonds help drive renewable energy projects, contributing to the long-term reduction of CO_2 emissions—a cornerstone of both sustainable economic growth and environmental protection (Rasoulinezhad & Taghizadeh-Hesary, 2022). By prioritizing climate change mitigation and directing capital toward environmentally beneficial projects, green finance plays a vital role in fostering sustainable development (Sachs et al., 2019; Wang et al., 2022). In Europe, the E7 economies, and China, green finance has effectively stimulated participation in renewable energy initiatives. Consistent with these findings, Khan et al. (2022) demonstrated across five regions—South Asia, Southeast Asia, China, the Middle East, and Europe—that green finance positively influences renewable energy efforts by bolstering investments in research and development, encouraging public–private partnerships, and fostering the adoption of renewable energy sources, ultimately reducing CO_2 emissions and enhancing environmental sustainability.

The relationship between Information and Communication Technology (ICT) and Renewable Energy Development (RED) is complex and symbiotic (Stallo et al., 2010; Sultanova et al., 2022). The digital economy, characterized by rapid technological advancements, heightened connectivity, and data-driven innovation, offers opportunities to transform the traditional economy into a more intelligent, digitalized framework (Sun et al., 2024). Digitization has a crucial role in propelling global economic development, while digital transformation has notably impacted the renewable energy industry by lowering costs, enhancing efficiency, and spurring innovation (Hwang, 2023; Lange et al., 2020; Noja et al., 2022). Nonetheless, Zhang et al.'s (2022) study of G7 nations from 2000 to 2020 reported inconsistent results—revealing a negative association between digital trade (a component of the digital economy) and renewable energy. These contradictory findings highlight the complex interplay between renewable energy and the digital economy and underscore the need for context-specific interpretations and further detailed research. Furthermore, the scarcity of studies addressing G20 nations—home to the world's largest economies and exerting significant sway over energy transition initiatives—reveals an important gap in the literature.

This research aims to fill those gaps and resolve existing contradictions. By unraveling the complex relationship between the digital economy and renewable energy in the context of G20 nations, the study seeks to establish a solid foundation for informed decision-making and the strategic development of digital economies worldwide. Specifically, it pioneers an in-depth examination of the interconnected dynamics of green finance, the digital economy, and renewable energy in G20 countries from 2010 to 2020. Acknowledging the economic, demographic, and institutional diversity among these nations, the study controls for key variables—including GDP per capita, urbanization, R&D expenditures, foreign direct investment, and industrial structural upgrades. By employing the two-step System Generalized Method of Moments (2SYSGMM), the research effectively addresses endogeneity concerns, ensuring precise estimates and robust analysis of the factors shaping the transition to renewable energy.

Previous studies have largely overlooked the role of eco-innovation in renewable energy development—especially within G20 nations—resulting in a significant gap in understanding its moderating influence (Hwang, 2023; Wang, 2022). Eco-innovation boosts the utilization of renewable energy while reducing reliance on non-renewable sources (Khan et al., 2020; Su et al., 2021). Several investigations have also incorporated institutional factors into environmental impact assessments. For example, Marques et al. (2010) examined European nations from 1990 to 2006 and identified lobbying by traditional energy entrepreneurs as a barrier to renewable progress. Similarly, Mehrara et al. (2015) found that high-quality institutions positively influence renewable energy advancement, whereas corruption and lobbying impede it. Cadoret et al. (2016) further demonstrated that manufacturing industry lobbying can hinder renewable energy expansion, underscoring the need for political stability, governance integrity, and consistent policies to reassure investors and enable smooth implementation of projects in the renewable energy sector. Considering these findings, maintaining high-quality institutions with low corruption is essential to support the development of renewable energy projects.

To address this shortfall, our study incorporates both eco-innovation and institutional quality as key moderating factors, examining their interactions with technological advancements and the adoption of renewable energy.

2. Methods and Materials

2.1. Modelling Equations

According to Dietz and Rosa's (1997) classic STIRPAT model, three major factors—population, affluence, and technology—shape environmental impact. This framework offers an excellent starting point for studying environmental dynamics. In our study, we represent the environmental impact variable using levels of renewable energy production and consumption. Economic development serves as a proxy for affluence, while urbanization rates reflect the population variable. For technology, we consider factors such as the digital economy, research and development, foreign direct investment, green financing, and industrial structure. We adapted Wang et al.'s (2022) model to examine the factors influencing both the production and consumption of renewable energy.

In Equations 1 and 2, renewable energy consumption (REC) and renewable energy production (REG) are determined by several factors, including green finance (GFM), the digital economy (Dig), economic development (GDPPC), industrial structure upgrading (ISU), urban population (Urbpop), foreign direct investment (FDI), and research and development (RND). To reduce data volatility and facilitate evaluation, we apply logarithmic transformations to Equations 1 and 2, resulting in the streamlined model of Equations 3 and 4.

$$REC = f(GFM, Dig, GDPPC, RND, Urbpop, FDI, ISU) \tag{1}$$

$$REG = f(GFM, Dig, GDPPC, RND, Urbpop, FDI, ISU) \tag{2}$$

$$\begin{aligned}\ln REC = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \beta_5 lnUrbpop_{i,t} \\ + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + v_i + \sigma_t + \varepsilon_{i,t}\end{aligned} \tag{3}$$

$$\begin{aligned}\ln REG = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \\ \beta_5 lnUrbpop_{i,t} + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + v_i + \sigma_t + \varepsilon_{i,t}\end{aligned} \tag{4}$$

In Equations 3 and 4, β_0 indicates the constant term, v_i is the individual fixed effect, σ_t is the time-series fixed effect, and $\varepsilon_{i,t}$ is the random error term. Here, *i* is a number between 1 and 20, and *t* is a number between 2010 and 2020. The calculated parameters, denoted by the coefficients β0 through β7, expressly show how elastic the independent variables are in terms of affecting the dependent variables.

To ensure robust estimation, we test for serial correlation, allowing first-order autocorrelation AR(1) but ensuring the absence of second-order autocorrelation AR(2), which could distort results. Additionally, the Hansen test of overidentifying restrictions is applied to validate the model's instrumental variables. However, it is crucial that the number of sample countries exceeds the number of instruments to maintain statistical power. Excessive instruments can weaken the Hansen test, reducing its ability to detect specification errors. Therefore, careful instrument selection is essential to enhance the credibility of the estimation process.

2.2. Data Collection

Data covering the period from 2010 to 2020 was collected from G20 countries. The dependent variable, renewable energy consumption, was sourced from the World Bank, while data on renewable energy production were obtained from British Petroleum (BP, 2021). Information on the digital economy index was gathered from Shahbaz et al. (2022), and data on green financing, serving as an independent variable, was sourced from Environmental Finance (EF). Control variables were obtained from the World Bank to ensure comprehensive coverage and robustness in the analysis.

2.3. Variable Measures and Operationalization

The consumption and supply of renewable energy serve as proxy indicators to assess the shift toward renewable energy sources. This decision is based on the understanding that renewable energy can sustainably and cleanly replace traditional fossil fuels. Increasing the proportion of renewable energy production and consumption is a desirable trajectory for the energy transition, consistent with global efforts to mitigate climate change and reduce environmental degradation. Reliable and comprehensive insights into these crucial measures are ensured by the data on renewable energy consumption, sourced from the World Bank, and renewable energy output, proxied by renewable energy generation (REG), sourced from BP.

Green finance emerges as the primary independent variable, measured by its market value. This metric encompasses all annual income generated from various green finance activities, including bonds, initial public offerings (IPOs), and national private equity transactions. The inclusion of green finance as a key independent variable reflects its growing significance in funding environmentally sustainable initiatives and projects. Data on the green finance market is obtained from EF, ensuring robustness and accuracy in capturing the financial landscape related to environmental investments and sustainability efforts.

The digital economy is a significant independent variable in our study, reflecting the impact of digitalization on the expansion of renewable energy. To operationalize this concept, we develop a digital economy index using the methodology of Shahbaz et al. (2022). This index comprises three distinct sub-indices: infrastructure, social effect, and digital trade. As shown in Table 1, each sub-index incorporates a range of relevant characteristics to represent various facets of digitalization, including the scope of digital commerce activities, the social implications of digital technology, and the accessibility of digital infrastructure.

Table 1. Digital economy index variables.

Index Variables	Sub-index Variables	Data
Infrastructure	Mobile cellular subscriptions (per 100 people)	ITU
	Fixed telephone subscriptions (per 100 people)	ITU
	Fixed broadband subscriptions (per 100 people)	ITU
Social Impact	Individuals using the Internet (% of population)	ITU
	Online Service Index	UN
	Medium and high-tech manufacturing value added (% of manufacturing value added)	WDI
Digital Trade	ICT goods exports (% of total goods exports)	WDI
	ICT goods imports (% of total goods imports)	WDI

Notes: ITU - International Telecommunication Union; UN - United Nations; WDI - World Development Indicators (World Bank)

3. Results and Discussions

3.1. Statistics Descriptive

Descriptive statistical analysis conducted across G20 nations from 2010 to 2020 reveals notable patterns in the distribution and dispersion of the considered variables. As shown in Table 2, the means of several variables—including lnREC (renewable energy consumption), lnREG (renewable energy production), lnDig (digital economy index), lnRND (research and development expenditure), lnFDI (foreign direct investment), and IQ (institutional quality)—are greater than their standard deviations. The data patterns across the G20 nations exhibit significant heterogeneity, underscoring the diverse nature of these elements and their implications for the advancement of renewable energy.

Alternatively, some variables have standard deviations smaller than their means, such as lnGDPPC (logarithmic GDP per capita), lnUrbpop (logarithmic urban population), lnISU (logarithmic services value added in GDP), and lnEI (logarithmic Eco-Innovation). This implies that the data are more evenly distributed or show less variation around the mean for these variables. In essence, these variables exhibit relatively stable patterns or intensities of activity across the G20 countries during the designated period, suggesting a more uniform effect or influence on the growth of renewable energy in these countries.

Table 2. Statistics descriptive.

Variable Type	Variables	Variable Name	Data Sources	N	Mean	Std. Dev.	Min	Max
Dependent Variable	Renewable Energy Consumption (% of total final energy consumption)	lnREC	WDI	220	0.535	2.063	-9.525	2.779
	Renewable Energy Generation (% of total energy generation)	lnREG	BP	220	1.230	1.934	-8.181	3.599
Independent Variable	Green Financing Market Value (in US$)	lnGFM	EF	220	2.006	1.291	-1.609	3.917
	Digital Economy Index	lnDig	Shahbaz et al. (2022)	220	-1.230	0.477	-2.524	-0.503
Control Variable	GDP per Capita (constant 2015 US$)	lnGDPPC	WDI	220	9.752	0.977	7.121	11.010
	Research and Development Expenditure (% of GDP)	lnRND	WDI	220	0.243	0.863	-4.846	1.568
	Urban Population (% of total population)	lnUrbpop	WDI	220	4.293	0.233	3.432	4.523
	Foreign Direct Investment (% of GDP)	lnFDI	WDI	220	0.442	0.942	-6.394	2.491
	Industrial structural upgrading (services, value added (% of GDP))	lnISU	WDI	220	4.083	0.172	3.534	4.351
Moderating Variable	Eco-Innovation (patents in environment-related technologies)	lnEI	OECD	220	7.793	2.219	2.371	11.130
	Institutional Quality (control of corruption, estimate)	IQ	WDI	220	0.458	0.958	-1.099	2.062

3.2. Correlation and Stationarity Test

An analysis of the correlation between all the variables was conducted before examining the interactions between the dependent and independent variables, as shown in Table 3. All independent factors and dependent variables show positive relationships except for lnUrbpop. Additionally, most correlation values are below 0.8, indicating a lack of detectable collinearity. Notably, the production and consumption of renewable energy exhibit a substantial link with little variability, as indicated by the lnREG correlation coefficient of 0.989.

Table 3. Correlation test.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
lnREC	1.000								
lnREG	0.989	1.000							
lnGFM	0.144	0.141	1.000						
lnDig	0.328	0.335	0.102	1.000					
lnGDPPC	0.229	0.240	-0.189	0.764	1.000				
lnRND	0.289	0.301	0.039	0.583	0.700	1.000			
lnUrbpop	-0.001	-0.041	-0.261	0.581	0.759	0.380	1.000		
lnFDI	0.120	0.110	0.059	0.001	-0.065	-0.117	-0.073	1.000	
lnISU	0.509	0.484	0.182	0.616	0.728	0.648	0.525	-0.116	1.000

The unit root test was performed using the Levin-Lin-Chiu (LLC) technique. When testing for stationarity at the level I (0), three variables—lnGFM, lnRND, and lnUrbpop—were found to be non-stationary, as shown in Table 4. This suggests that the statistical properties of these variables may fluctuate over time, potentially compromising the reliability and accuracy of subsequent statistical analyses if not addressed. Therefore, it is imperative to apply first differencing to each variable. The results show that all variables become stationary after first differencing, indicating that their statistical properties remain stable over time.

Table 4. Stationary test result.

Variables	LLC	
	I (0)	**I (1)**
lnREC	-5.2212***	-7.2772***
lnREG	-7.1413***	-7.2542***
lnGFM	0.5089	-0.4253**
lnDig	-3.4344***	-14.1522***
lnGDPPC	-5.4710***	7.0881***
lnRND	0.3619	-3.7606***
lnUrbpop	-0.6903	-3.5975***
lnFDI	-3.1627***	-14.4708***
lnISU	-5.1226***	-6.9155***

Note: The asterisks (**) and (***) indicate the rejection of the null hypothesis of unit root at 5% and 10%

3.3. Benchmark Regression

Table 5 displays the findings of 2SYSGMM and fixed-effects panel models showing the relationship between renewable energy production and consumption, green financing, and the digital economy. The excellent consistency between the coefficients generated by the two methods suggests the robustness and reliability of the results. The estimates from the 2SYSGMM model are selected for further analysis because, given the validity of the dynamic model, they provide a more comprehensive understanding of the relationships under investigation.

Thorough diagnostic procedures, including the Arellano-Bond and Hansen tests, were carried out to validate the estimated models. These tests assess the suitability of instrumental variable selection and autocorrelation in the random disturbance term, respectively. The findings demonstrate no problems with autocorrelation and that the autoregressive process up to lag 1 (AR(1)) is statistically significant. Moreover, the insignificance of AR(2) supports the lack of higher-order autocorrelation. The Hansen test, with p-values greater than 0.05, indicates acceptable instrumental variable selection and validates the overidentification restrictions. These tests are essential validation steps that ensure the precision and reliability of the estimated models for further study.

The coefficients derived from Table 5 provide valuable insights into the relationship between past energy transitions and current renewable energy consumption and production. This indicates the lasting impact of past initiatives on the present state of renewable energy utilization and generation, emphasizing the significance of sustained efforts in transitioning towards cleaner energy sources. The results show how the digital economy and green financing both positively impact the generation and use of renewable energy. In contrast to the digital economy, which shows a 0.207% increase in consumption and a 0.221% gain in production for every 1% increase, green finance shows a 1% increase corresponding to a 0.0332% rise in consumption and a 0.0625% increase in output. These findings highlight the importance of financial support and technological advancement in propelling the uptake and spread of renewable energy sources. The results emphasize the complexity of the variables impacting the switch to green energy and the significance of current measures and financial commitments. Policymakers and stakeholders may accelerate the shift to renewable energy and support global sustainable development and environmental preservation by leveraging digital technology and financial systems.

Table 5. Regression result.

	FE	SYS-GMM	FE	SYS-GMM
	(1)	(2)	(3)	(4)
VARIABLES	lnREC	lnREC	lnREG	lnREG
L.lnREC		0.789***		
		(0.00883)		
L.lnREG				1.017***
				(0.0156)
lnGFM	0.515***	0.0332**	0.554***	0.0625***
	(0.133)	(0.0155)	(0.143)	(0.0206)
lnDig	2.399***	0.207**	2.434***	0.221**
	(0.271)	(0.0774)	(0.291)	(0.0996)
lnGDPPC	-0.154	-0.125	-0.478	0.0601
	(0.680)	(0.0828)	(0.731)	(0.138)
lnRND	-0.267**	0.0316	-0.431***	0.203**
	(0.127)	(0.0367)	(0.137)	(0.0964)
lnUrbpop	5.748**	-0.296	6.863**	0.504
	(2.728)	(0.203)	(2.933)	(0.305)
lnFDI	-0.0503	0.0366**	-0.0478	-0.263***
	(0.0451)	(0.0169)	(0.0485)	(0.0258)
lnISU	-0.975	1.106***	-1.774*	-1.406***
	(0.882)	(0.164)	(0.948)	(0.233)
Constant	-16.66*	-1.453	-14.32	2.794**
	(8.465)	(1.046)	(9.103)	(1.299)
AR(1)		0.041		0.017
AR(2)		0.831		0.281
Hansen Test		0.733		0.917
Observations	220	200	220	200
R-squared	0.595		0.556	
Number of Countries	20	20	20	20

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

FDI emerges as a crucial catalyst in driving renewable energy development within G20 countries. By channeling advanced technology, expertise, and capital into the renewable energy sector, FDI plays a pivotal role in accelerating the transition toward sustainable energy sources. The influx of foreign investment not only injects much-needed resources into renewable energy projects but also facilitates knowledge transfer and technology diffusion, enhancing the efficiency and effectiveness of renewable energy systems. Additionally, FDI fosters international collaboration and cooperation, enabling countries to leverage global expertise and best practices in renewable energy deployment, ultimately contributing to the attainment of climate and sustainability goals on a global scale.

The prominence of the tertiary industry in industrial structure upgrading variables underscores the transformative potential of economic structural changes in driving renewable energy adoption. As economies transition toward service-oriented sectors such as finance, technology, and education, reliance on energy-intensive industries is concurrently reduced. This shift creates a more favorable environment for renewable energy deployment, as service-based economies inherently prioritize sustainability and efficiency. By fostering innovation, promoting technological advancements, and nurturing a culture of environmental responsibility, the expansion of the tertiary sector signals a broader societal shift towards a low-carbon economy. Consequently, the evolution of industrial structure not only drives economic growth but also advances the global agenda for renewable energy transition and environmental sustainability.

3.4. Robustness Check

Table 6 shows the differences in how green financing affects the production and consumption of renewable energy, as shown by the robustness check results using the Pooled Ordinary Least Squares (POLS) and Random Effects (RE) methods. The differences highlight the significance of using rigorous methodologies to address the inherent limitations in econometric analyses. However, these conventional methods may struggle to capture the dynamic nature of equations and address endogeneity problems, potentially leading to biased or inconsistent estimations. Consequently, inferences drawn from these methods might not fully appreciate the complex processes at play in the relationship between green financing and the transition to renewable energy sources.

Thus, we employ the 2SYSGMM technique, which is renowned for its effectiveness in managing autocorrelation and heteroscedasticity in dynamic panel data models. By using this advanced econometric technique, we improve the precision and consistency of estimates concerning the impact of green finance on the production and consumption of clean energy. This methodological enhancement provides a stronger foundation for understanding the intricate interaction between financial processes and energy transition dynamics, allowing us to overcome the limitations of conventional techniques.

Table 6. Robustness test result using pooled OLS and random effects.

	POLS	RE	POLS	RE
	(1)	(2)	(3)	(4)
VARIABLES	lnREC	lnREC	lnREG	lnREG
lnGFM	0.460***	-0.377***	-0.333***	0.465***
	(0.128)	(0.104)	(0.0979)	(0.136)
lnDig	2.609***	1.592***	1.522***	2.678***
	(0.260)	(0.374)	(0.352)	(0.277)
lnGDPPC	0.0324	-0.751***	-0.369	0.124
	(0.479)	(0.289)	(0.272)	(0.479)
lnRND	-0.195	-0.0863	-0.109	-0.342**
	(0.127)	(0.190)	(0.178)	(0.137)
lnUrbpop	1.160	-3.781***	-4.552***	0.364
	(1.930)	(0.745)	(0.701)	(1.923)
lnFDI	-0.0418	0.381***	0.315***	-0.0365
	(0.0465)	(0.114)	(0.107)	(0.0501)
lnISU	-0.0760	10.19***	8.594***	-0.541
	(0.870)	(1.044)	(0.982)	(0.929)
Constant	-2.098	-14.95***	-8.295**	3.129
	(6.488)	(4.089)	(3.847)	(6.580)
Observations	220	220	220	220
Number of Countries	20	20	20	20

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

3.5. Result of Heterogeneity Test

Table 7 illustrates the effects of the digital economy and green financing on the production and consumption of renewable energy (REC and REG) in high- and middle-income G20 nations. The coefficients of lnGFM for REC and REG, calculated using the FGLS model for extended panels, show that high-income nations gain more from green funding. This demonstrates the importance of robust financial institutions in increasing the supply and use of renewable energy. High-income nations benefit more from the shift to green sources due to their advanced technological infrastructure, a result of their digital economy. On the other hand, middle-income nations' attempts to transition are hampered by obstacles caused by energy poverty and a weak banking system.

Table 7. Heterogeneity check of high and middle income.

	High-Income		Middle-Income	
	(1)	(2)	(3)	(4)
VARIABLES	lnREC	lnREG	lnREC	lnREG
lnGFM	0.467***	0.452***	0.253***	0.310***
	(0.141)	(0.144)	(0.0837)	(0.0912)
lnDig	3.876***	3.461***	1.451***	1.386***
	(0.626)	(0.642)	(0.237)	(0.258)
lnGDPPC	3.060***	3.610***	-1.373**	-1.786***
	(1.137)	(1.165)	(0.615)	(0.670)
lnRND	-1.238***	-1.236***	-0.0185	-0.191*
	(0.320)	(0.328)	(0.0970)	(0.106)
lnUrbpop	14.02**	23.12***	14.89***	16.32***
	(6.544)	(6.707)	(2.947)	(3.212)
lnFDI	-0.0533	-0.0563	-0.257***	-0.267***
	(0.0404)	(0.0414)	(0.0867)	(0.0945)
lnISU	-2.027**	-2.189**	-6.608***	-7.761***
	(0.990)	(1.014)	(1.607)	(1.751)
Constant	-80.71**	-125.3***	-21.52***	-18.81***
	(31.39)	(32.17)	(6.360)	(6.932)
Observations	121	121	99	99
R-squared	0.754	0.761	0.787	0.751
Number of Countries	11	11	9	9

Note: Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

3.6. Moderating Roles

The moderating effect of eco-innovation and institutional quality on the relationship between green finance market, digital economy index, and the renewable energy development is measured using an estimation model, explained as follows.

$$\ln REC = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \beta_5 lnUrbpop_{i,t} + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + \beta_8 lnEI_{i,t} + \beta_9 lnGFMxEI_{i,t} + \beta_{10} lnDigxEI_{i,t} + v_i + \sigma_t + \varepsilon_{i,t} \quad (1)$$

$$\ln REG = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \beta_5 lnUrbpop_{i,t} + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + \beta_8 lnEI_{i,t} + \beta_9 lnGFMxEI_{i,t} + \beta_{10} lnDigxEI_{i,t} + v_i + \sigma_t + \varepsilon_{i,t} \quad (2)$$

$$\ln REC = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \beta_5 lnUrbpop_{i,t} + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + \beta_8 lnIQ_{i,t} + \beta_9 lnGFMxIQ_{i,t} + \beta_{10} lnDigxIQ_{i,t} + v_i + \sigma_t + \varepsilon_{i,t} \quad (3)$$

$$\ln REG = \beta_0 + \beta_1 lnGFM_{i,t} + \beta_2 lnDig_{i,t} + \beta_3 lnGDPPC_{i,t} + \beta_4 lnRND_{i,t} + \beta_5 lnUrbpop_{i,t} + \beta_6 lnFDI_{i,t} + \beta_7 lnISU_{i,t} + \beta_8 lnIQ_{i,t} + \beta_9 lnGFMxIQ_{i,t} + \beta_{10} lnDigxIQ_{i,t} + v_i + \sigma_t + \varepsilon_{i,t} \quad (4)$$

β_0 represents the constant term in the model, capturing the baseline effect. Individual fixed effects are denoted by v_i, while time fixed effects are captured by σ_t. The random error term is represented by $\varepsilon_{i,t}$. The estimated coefficients, β_1 through β_{10}, indicate the slope of the relationship between the variables. The moderating variables, lnEI (Eco-innovation) and IQ (Institutional Quality), influence this relationship. A positive β_1 or β_9 suggests a beneficial impact of the moderating variables on the link between independent and dependent variables. The results of these moderating effects are summarized in Table 8.

Table 8. Moderating effects of eco-innovation and institutional quality.

	Eco-Innovation		Institutional Quality	
	(1)	(2)	(3)	(4)
VARIABLES	lnREC	lnREG	lnREC	lnREG
L.lnREC	0.877***		0.791***	
	(0.0239)		(0.0228)	
L.lnREG		1.003***		0.976***
		(0.0464)		(0.0167)
lnGFM	0.818***	0.903***	0.183***	0.203***
	(0.190)	(0.274)	(0.0417)	(0.0331)
lnDig	1.016**	1.130*	0.304*	-0.337*
	(0.416)	(1.437)	(0.164)	(0.173)
lnGDPPC	-0.272	0.167	-0.951**	-0.546
	(0.264)	(0.326)	(0.339)	(0.365)
lnRND	0.0654	-0.233	0.145	0.0466
	(0.0487)	(0.251)	(0.116)	(0.124)
lnUrbpop	0.825	0.626	2.439***	3.234***
	(0.928)	(1.045)	(0.759)	(1.107)
lnFDI	-0.0448**	0.0778	-0.0322	0.0474**
	(0.0190)	(0.0596)	(0.0575)	(0.0220)
lnISU	-0.729	-2.246***	-0.188	-1.294**
	(0.567)	(0.256)	(0.282)	(0.570)
lnEI	0.411***	0.0857		
	(0.0871)	(0.252)		
lnGFM × lnEI	0.0942***	0.108**		
	(0.0249)	(0.0388)		
lnDig × lnEI	0.178***	0.128		
	(0.0576)	(0.209)		
IQ			1.642***	0.795**
			(0.358)	(0.285)
lnGFM × IQ			0.249***	0.0932**
			(0.0720)	(0.0352)
lnDig × IQ			0.673***	0.265**
			(0.176)	(0.122)
Constant	-0.621	4.567	-0.512	-4.165
	(3.355)	(3.944)	(1.547)	(3.219)
Observations	200	200	200	200
Number of Countries	20	20	20	20

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

3.6.1. Eco-Innovation Moderating Impact

Strong evidence for the moderating effect of eco-innovation in the link between green finance, the digital economy, and the production and consumption of renewable energy can be found in the significant coefficients of lnGFM × lnEI in Table 8's columns (1) and (2). This suggests that eco-innovation increases the beneficial effects of green financing on the production and use of renewable energy (REC and REG). It highlights the critical role that eco-innovation plays in accelerating the shift to renewable energy sources and implies that the adoption of renewable energy is mostly driven by sustainable innovation pathways rather than traditional R&D-driven ones.

Moreover, eco-innovation's moderating influence on the interplay between the digital economy and the production and use of renewable energy emphasizes the complementary roles that eco-innovation and digital solutions play in advancing the growth of renewable energy. Eco-innovation highlights how digital breakthroughs and sustainable innovation work in tandem to create resilient and sustainable renewable energy ecosystems. This link is favorably moderated by eco-innovation. In order to accelerate the global transition to renewable energy, this highlights the interdependence of eco-innovation, green finance, the digital economy, and the development of renewable energy. It advocates for integrated approaches that combine eco-innovation strategies with financial mechanisms and digital solutions.

3.6.2. Institutional Quality Moderating Impact

Table 8 demonstrates how institutional quality (IQ) has a major moderating effect in the interaction among the digital economy, renewable energy production (REG), and green financing. The positive coefficient of lnGFM × IQ indicates that countries possessing strong institutional frameworks are more advantageous in utilizing green finance mechanisms to propel projects aimed at producing renewable energy. This emphasizes how crucial governance systems are for enabling sustainable energy transitions and addressing issues connected to corruption.

Furthermore, Table 8's data highlights institutional quality's beneficial moderating impact on the link between the digital economy and the green transition (REC and REG). Firms may efficiently use digital technology thanks to strong institutional frameworks that promote renewable energy projects, which speeds up energy transition efforts and advances sustainable development objectives.

Environmental rules can be compromised by corruption, and this can exacerbate environmental deterioration, according to existing studies (Arminen & Menegaki, 2019). Adoption of renewable energy technology should be encouraged and these negative impacts can be mitigated by stepping up efforts to prevent corruption. Furthermore, insufficient institutional frameworks might encourage foreign investors to use dishonest methods to get around environmental laws. Enhancing the caliber of institutions can help deter these illegal activities and foster an environment that is conducive to the growth of sustainable energy (Oberthür et al., 2021). The importance of institutional quality in facilitating positive impacts draws attention to governance systems' function in reducing corruption-related problems and fostering an environment that is favorable to renewable energy initiatives.

3.7. Discussions

By utilizing the 2SYSGMM, we reveal a significant and positive correlation between green finance and the adoption of renewable energy among G20 countries. This connection is elucidated through various crucial mechanisms. Initially, green finance facilitates direct financial support for renewable energy initiatives, shifting funds away from fossil fuel subsidies towards sustainable energy options. Furthermore, green finance promotes the uptake of renewable energy by providing favorable financial conditions, such as reduced interest rates or extended repayment periods, thereby encouraging investments in these projects. Secondly, it stimulates investments in sustainable energy infrastructure, often supported by public financial institutions, which are crucial for funding large-scale renewable initiatives like wind farms and solar facilities. Through funding and guarantees for such projects, public financial institutions help to mitigate investment risks, making them more attractive to private investors. These investments not only enhance renewable energy capacity but also modernize and decarbonize the energy sector.

Finally, green finance stimulates innovative green technological advancements by offering financial support and rewards for the exploration and advancement of green technologies. Through the allocation of resources to pioneering renewable energy initiatives, green finance nurtures the emergence of novel technologies and strategies geared towards improving the effectiveness, cost-effectiveness, and availability of renewable energy sources. This investment in green technological progress hastens the rate of renewable energy deployment and acceptance, reducing expenses and conquering technological obstacles linked to the integration of renewable energy. Additionally, green finance encourages cooperation among governmental and non-governmental entities, easing the exchange of knowledge and technology transfers, which further spurs innovation within the renewable energy domain.

Regression analysis shows a favorable association between the green transition and the digital economy, which highlights the important role that digital technologies play in encouraging the adoption of sustainable energy. Through the expansion of infrastructure, the digital economy facilitates the adoption of renewable energy in the first channel. Urban environments, especially those designed for sustainable growth via digital city projects, offer favorable conditions for the development of renewable energy industries. These programs support renewable energy alternatives, such as smart grids and electric cars, by utilizing low-energy-consuming technology and smart infrastructure. Cities can boost the adoption of renewable energy technology, lower emissions, and improve energy efficiency by incorporating digital innovations into urban design and building.

The digital economy affects society in a second way by improving education and skill development, which increases human capital. The digital economy has made it easier for people to acquire better education and skills, giving them the know-how they need to increase the efficiency of the energy industry and promote the use of renewable energy sources. Digital platforms and e-learning technologies offer scalable and easily accessible educational and training possibilities, enabling individuals to make a meaningful contribution to sustainable energy projects. The digital economy enhances the workforce and expedites the green transition by investing in human capital development. This also encourages a culture of innovation and entrepreneurship.

By enabling the transfer of information and technology, the digital economy through digital trade expedites the transition to more environmentally friendly energy sources. Real-time gathering, evaluating, and distribution are made possible by digital platforms, which promote efficient energy management techniques and informed decision-making. Digital commerce platforms also make it easier to transfer technology and exchange information, giving nations access to global knowledge and solutions for renewable energy. Digital trading is essential to speeding up the switch to cleaner forms of energy and supporting global sustainability initiatives because it increases access to renewable energy technology solutions and removes obstacles like high costs or restricted technological access.

4. Conclusions

This study examines how green finance, the digital economy, and the move to renewable energy in 20 G20 countries interacted between 2010 and 2020. Using a dynamic panel model, it finds that green financing and the digital economy have a significant positive influence on renewable energy generation and consumption. Moreover, institutional quality and eco-innovation further increase this relationship. Higher-income nations show a stronger correlation between these factors and the switch to renewable energy than do middle-income nations.

The suggested policy measures call for active government involvement and collaboration to speed up the shift to renewable energy. They emphasize the need for scholars and financial institutions to better understand green finance and for national frameworks to encourage investment in eco-friendly industries. This involves creating relevant policies and regulations to guide investment towards sustainable projects. Also, it is important to expand the market for green finance and come up with new ways to finance renewable energy projects. Governments should also use digital technologies to drive this transition, investing in digital infrastructure and integrating digital solutions into clean energy applications to promote sustainability.

Furthermore, it is recommended that developing countries learn from more developed nations and modify their development policies to facilitate the expansion of the digital economy and renewable energy sectors. It is crucial to prioritize tailored solutions for energy digitization to boost efficiency and expand the clean energy industry. International cooperations in digital technology and financial support for research and development in renewable energy are also vital. Improving eco-innovation and institutional quality is another key aspect, with dedicated departments and measures to combat corruption necessary for driving a significant shift towards sustainable economic and energy structures. Strengthening governance through clear regulations and efficient bureaucratic processes further encourages innovation and fosters an environment conducive to advancing both the digital economy and renewable energy technologies, accelerating the transition to a sustainable energy landscape.

While this study provides key insights into the link between green finance, the digital economy, and renewable energy transition in G20 countries (2010–2020), several limitations remain. The focus on G20 economies may overlook dynamics in smaller or developing nations, warranting broader future research. Data constraints may also limit the reflection of recent technological and policy shifts, emphasizing the need for updated, high-frequency datasets. Additionally, our study does not explicitly test transmission mechanisms, suggesting future research should use Structural Path Analysis (SPA) to map causal linkages. Applying Input-Output (IO) analysis or Computable General Equilibrium (CGE) models could further capture systemic effects on industries, labor markets, and income distribution.

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