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Green Finance, Innovation and the Energy-Environment-Climate Nexus

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After the Paris Climate Conference (COP21), carbon neutrality and environmental sustainability have become the consensus of many countries. Technological innovation and green finance are the essential factors that can help to realize clean energy transition, carbon emission reduction and climate change mitigation. To investigate the pathways for sustainable development, this study includes innovation and green finance into simultaneous equations models within energy-environment-climate nexus. We examine the dynamic relationships for a sample of 49 countries with green bonds issued for the period 2007–2019. The results confirm that there are bidirectional relationships among renewable energy consumption, environmental pollution and climate change. Innovation can significantly promote renewable energy consumption, reduce CO_2 emissions and mitigate climate change. Green finance can effectively alleviate environmental pollution and climate change. Accelerating the development of green finance is the primary motivation for sustainable development. Green finance moderates the relationship between innovation and energy-environment-climate nexus. The positive impact of innovation on renewable energy consumption is enhanced by higher level of green finance. When the development of green finance is high, innovation has a greater negative influence on CO2 emissions, and the impact of innovation on climate change is weakened.

Keywords: green finance, innovation, renewable energy consumption, environmental pollution, climate change

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INTRODUCTION

The role of energy consumption is highly correlative with both environmental protection and climate change. The high emission level of CO_2 has become a serious global issue (Bekun et al., 2019). The BP statistics indicated that the global fossil energy-related CO_2 emission increased from 11.190 billion tonnes in 1965 to 34.356 billion tonnes in 2019, with a threefold increase. The Intergovernmental Panel on Climate Change (IPCC) predicted that energy-related carbon dioxide emissions will rise to 40–110% by 2030. Many countries are actively seeking the solutions to guarantee energy sustainability and reduce greenhouse gas emissions, with the increasingly serious problems of environmental pollution and climate change. Renewable energy has become a key element in the "fast zero" and "net zero" schemes, which can promote energy structure transition, protect ecological environment and mitigate climate change crisis. Assessing the impact of energy consumption on carbon emissions and climate change requires take into consideration not only fossil energy but also renewable energy (Brini, 2021; Usman and Balsalobre-Lorente, 2022). Thus, the new perspective on renewable energy does allow for building a rational theoretical base for the energy-environment-climate nexus.

Technological innovation acts as a catalyst for improving energy efficiency and reducing energy intensity. High value products can be obtained by advanced technology innovation with low energy consumption (Sohag, 2015). Energy innovation is an internal driving force for low-carbon economy, which lead to optimize energy consumption structure and accelerate the application of renewable energy. Government agencies have turned their attention to encourage substantial investment in technological innovation to reach solutions for environmental disruption and global warming, and achieve sustainable development (Ahmad et al., 2021). Technological innovation can promote energy conservation and emission reduction. Both low-carbon utilization of traditional fossil energy and large-scale utilization of renewable energy at low cost are highly dependent on technological innovation. Additionally, tackling global warming and other environmental threats requires a well-coordinated innovation program to curb high carbon dioxide emissions. Investments in technological innovation as an effective strategy is essential to sustainable improvements in energy security (Erdoğan et al., 2020; Zheng et al., 2021), carbon emission mitigation (Uluak et al., 2020; Jahanger et al., 2022), and climate change problems reduction (Lin and Zhu, 2019; Wang et al., 2020). Thus, technological innovation is a critical factor that can influence the energy-environment-climate nexus, deciding whether to achieve the goals of the Paris Conference Climate Change (COP21).

Green finance aims to reduce greenhouse gas emissions and protect environment by providing investment, financing and financial service for environmentally-friendly projects (Dogan and Seker, 2016; Dafermos and Nikolaidi, 2021; Sun, 2021). For example, the Equator Principles were designed to deal with environmental and social issues related to financing, and the climate finance provides financial assistance for green projects to mitigate and adapt to climate change. On the one hand, green finance can transfer financial resources from high-pollution and high-energy-consuming industries to green industries through structural effects, and reduce greenhouse gas emissions. It also can optimize the allocation of financial resources and promote the optimization and upgrade of green industrial structure (Gu et al., 2021). Various types of central banks have issued financial regulation tools to guide capital flows, such as climate-related financial disclosures (Campiglio et al., 2018). On the other hand, many countries have actively set out to change the extensive mode of economic growth, and realize high-quality economic development through emission reduction and ecological conservation (Ren et al., 2020). Green finance can relieve financing constraints on green activities, encourage enterprises to re-allocate various resources, and achieve the purpose of sustainable development (Yu et al., 2021).

In summary, the important position of innovation and green finance on sustainable development has moved from the margins to the mainstream. Innovation often faces financing constraints due to technological uncertainty and long R&D cycles. Green financial development may provide sufficient funds for activities of green technology innovation, which leads to improve energy efficiency, decrease carbon emission and reduce extreme weather risks. Technological innovation with rational financial support can stimulate the environmentally-friendly industrial scale, which result in environmental sustainability. The interaction of innovation and green finance has served as a potential solution to problems of energy structure transformation, environmental pollution reduction and climate change mitigation. This study integrates innovation and green finance into the framework of energy-environment-climate nexus. Simultaneous equations model is used to explain bidirectional causality between variables and the way in which they are endogenously determined within the same framework, which systematically examines the driving factors of the sustainable development.

This study contributes the previous studies in the following respects. First, this study introduces energy-environment-climate nexus in simultaneous equations model. Systematic and simultaneous discusses the bidirectional causality between energy consumption, environmental pollution and climate change. Providing a more comprehensive narrative of energy-environment-climate relative to previous studies. Second, this study has included innovation and green finance as explanatory variables into models within the energy-environment-climate dimensions. Evaluating the moderating effects of innovation index and green bonds on the analytical framework of energy-environment-climate nexus, which sets up a new perspective for the improvement of the theories and methodologies. Third, this study focuses on renewable energy consumption in the nexus, which can better explain the effects of renewable energy on carbon emission reduction and climate change mitigation from the perspective of energy structure transition. Fourth, this study applied simultaneous equations and system GMM models for examining the relationship among innovation, green finance and energy-environment-climate nexus. A dynamic three-equations set-up can relieve omitted variables bias and endogeneity problem, and the equation estimations are more efficient.

The framework of this study is revealed as follows. Section shows the *Introduction*. Section presents the *Literature review*. Section provides the *Data and methodology*. Section presents the *Results and discussions*. Section shows the *Conclusions and policy implications*.

LITERATURE REVIEW

Energy-Environment-Climate Dimension

There is a complex relationship among energy consumption, environmental pollution and climate change. Global warming is mainly caused by greenhouse gas emissions, which is due to widespread consumption and dependence on fossil energy to promote economic development (Chiu, 2017; Salari et al., 2021). Global communities are collaborating to find renewable energy as alternative energy sources for achieving environmental and economic sustainability (Pavlović et al., 2021). Usman and Balsalobre-Lorente (2022) revealed that investment in clean energy may reduce ecological footprint and mitigate climate-related extreme events for the top ten newly industrialized countries from 1990 to 2019. Dong et al. (2017) investigated the relationship between the renewable and natural gas energy sources and carbon dioxide emissions use via the augmented mean group estimator. They found that 1% increase in the level of renewable energy and natural gas consumption will reduce carbon dioxide emissions by 0.2601 and 0.1641% in BRICS countries. Bölük and Mert (2014) showed that clean energy emits about half as much carbon as fossil energy using the sample of 16 European Union countries in the period 1990–2008. In addition, Nyambuu and Semmler (2020) proved that renewable energy can effectively deal with climate change problems with a dynamic growth model. Rahman and Velayutham (2020) predicted the greenhouse gas emissions and investment costs caused by meeting electricity demand under different energy consumption condition. The results showed that clean energy is a vital way to mitigate global warming, and the cost of renewable energy is lower than that of non-renewable energy. Brini (2021) applied the autoregressive distributed lag model and granger causality tests to investigate the relationship between renewable energy generation and climate change for African countries from 1980 to 2014. The results revealed that renewable energy can effectively ameliorate greenhouse gas emissions in the long term, and increase in the proportion of clean energy consumption in total energy will help mitigate climate change.

Climate change seem to play an important role in energy consumption and carbon dioxide emissions. On the one hand, climate change can increase energy consumption. Liu et al. (2021) proved that climate change may have a punishing effect on environmental quality, global warming will accelerate the deterioration of air quality. The current global climate change shows a trend of increasing temperature year by year, which makes urban areas require a lot of energy, especially electricity to be consumed for cooling buildings (Javanroodi et al., 2018). On the other hand, climate change will threaten the safety of electricity generation (Sharifi and Yamagata, 2016). Extreme temperatures will destroy electricity generation equipment and decrease confidence in clean energy. Insufficient investment in clean energy will inhibit the development of renewable power generation, especially solar power generation (Chen et al., 2021). Zhao and Huang, (2020) expected that climate change has a negative impact on the potential of photovoltaic energy, and it may experience a slight decline of up to 6% in most regions of China.

Innovation and Energy-Environment-Climate Dimension

Technological innovation is the key factor of global energy pattern and low-carbon economic development. Innovation contributes to reducing energy consumption and optimizing energy structure. On the one hand, technological innovation helps to reduce emissions by improving energy efficiency (Sohag, 2015; Pradhan and Ghosh, 2022). Technological innovation can raise the efficiency of traditional fossil energy, achieve the target of energy conservation and emission reduction by decarbonization in the production process. It also can improve green total factor productivity, hoist technological capability of renewable energy, and accelerate development of clean energy industry. Jahanger et al. (2022) applied that technology innovation can mitigate carbon footprint and environmental pollution by providing energy efficiency in 73 developing countries during the period from 1990 to 2016. On the other hand, Innovation can promote energy consumption to shift from pollution-intensive fossil fuels consumption to renewable energy consumption, which contributes to the reduction of carbon emissions (Anwar et al., 2020). In fact, technological innovation can improve the supply capacity of renewable energy as well as optimize the energy mix (Chen and Lei, 2018). Tang and Tan (2013) applied that the main reason for reduction in fossil energy consumption is renewable energy innovation. Cheng et al. (2019) indicated that energy innovation stimulates renewable energy consumption in countries with low oil reserves. Geng and Ji (2016) found that technology innovation has a long-run equilibrium relationship with renewable energy consumption in United States, Germany, and other six developed countries from 1980 to 2010. Zheng et al. (2021) found that innovation also promotes renewable energy power generation in China. They applied that a 1% increase in the level of renewable energy innovation will lead to an increase of 0.411% in the province's renewable energy power generation. However, the contribution of energy innovation to economic growth will inevitably increase energy demand, which may totally or partially offset reduction in energy consumption (Ganda, 2019).

The innovation-environment link has revealed that many countries have focused on investing in research and development to achieve environmental sustainability and low-carbon development (Cantner and Dettmann., 2019). Technological innovation may be a cost-effective way to build low-carbon society (Bayer et al., 2013). Danish and Ulucak (2021) applied the dynamic auto-regressive distributive lag simulation method to prove that technology innovation is conducive to a significant reduction in carbon dioxide emissions in the United States in the short-run and long-run. Sæther (2021) underlined that decarbonization of the power sector is key to the global energy consumption transition from fossil fuels to renewables. They applied that technological innovation policies can enhance the efficiency of carbon emission reduction in wind power generation using the sample of 34 OECD countries and 5 BRICS countries in the period 2001–2018. Su and Moaniba (2017) explored that whether technology innovation can cope with environmental pollution. They implied that innovation responds positively to the deteriorating environment, and increasing greenhouse gas emissions from liquid and gas fuel will compel technology innovation with data from 70 countries.

Technology innovation is often regarded as a most effective approach to mitigate climate change. In order to deal with the problems of global warming and other threats to the environment, a series of technological innovation programs are made to control high greenhouse gas emissions. Promoting technological innovation will help achieve the climate change goals set by the Paris Agreement at COP21 (Wang et al., 2020). Investments in R&D as an effective strategy to reduce carbon emissions due to improve innovation capability and promote sustainable development. Lin and Zhu (2019) discussed the driving factors of renewable energy technology innovation. The intensive greenhouse gas emissions force governments to promote the level of renewable energy technological innovation, signifying that innovation processes respond positively to climate change.

Green Finance and Energy-Environment-Climate Dimension

The G20 defines green finance as investment and financing of environmentally sustainable development. Green finance stimulates a shift in energy consumption from fossil fuel resources to renewable resources by encouraging investment in clean energy projects. A more direct approach would be to impose quantitative limits on loans for carbon-intensive activities, reduce the proportion of bank credit to the fossil fuel sectors. Dafermos and Nikolaidi (2021) found that green differentiated capital influences the transmission channels of credit supply and loan spreads within a dynamic framework. Green funds can slow the pace of global warming by supporting environmentally friendly projects, and reduce financing restriction of enterprises. Muganyi et al. (2021) employed the semi-parametric difference-in-differences method to explain that green finance has significantly reduced industrial waste gas emissions in 290 Chinese cities during the period from 2011 to 2018. They emphasized that governments should accelerate the innovation of green financial products and services, and improve the green credit capacity of financial institutions. In addition, green finance and clean energy consumption will help reduce carbon intensity. Ren et al. (2020) implied that clean energy consumption is mainly affected by carbon intensity, which development lacks independent driving ability and mainly depends on green financial support in the long term. Reboredo (2018) found that the positive environmental externalities generated by green bonds trading contribute to the execution and proliferation of renewable energy solutions across countries. Li et al. (2022) further analyzed the relationship between green bonds and renewable energy index during the period from 2011 to 2019. The results showed that OECD countries raise 31 percent of green bond financing into the construction of the renewable energy index, the per unit energy efficiency of renewable energy will increase by 9.4 percent.

As green bonds and climate bonds are aligned with the sustainable development goals, more and more countries are beginning to recognize the potential of green finance in addressing environmental pollution and climate change. Climate finance aims to provide financial support for climate change mitigation and adaptation activities, which provide financial assistance to mitigate risks of environmental pollution and extreme weather change. Zerbib (2019) adopted a matching method to estimate the relationship between environmental preferences and green bonds, and found that the growing demand for environmental quality is the main driver of demand for green bonds. Flammer (2020) analyzed that the market mechanism of green bond financing in environmental sustainability. The results emphasized that the significance of green bonds in shaping environmentally responsible enterprises and pointed to the use of green bond as a financing policy tool to complete environmental protection targets.

Innovation, Green Finance and Energy-Environment-Climate Dimension

Many countries are trying to promote the development of green innovation and green finance to realize long-term climate targets (Li and Liao., 2018). Green innovation often forms financing constraints due to technological uncertainty and long R&D cycles (Andersen, 2017). The promotion effect of green finance on investments and loans for environmental sustainability, which has become a global consensus on environmental protection action (Acheampong et al., 2020). Green financial development can promote green technologies, improve energy efficiency, and thereby reduce carbon dioxide emissions per unit of output (Pan et al., 2019). Hu et al. (2021) proved that green technology innovation of enterprises needs to invest a lot of capital, which cannot be achieved by relying solely on traditional financing channels. Green finance can provide enterprises with comprehensive financial support on preferential terms, which can meet the needs of clean technology transformation and advanced production relations, effectively reduce carbon emissions. In fact, green financing seems to guarantee the effectiveness of environmental protection actions by a massive investment in technical human capital and technological innovation. Adequate and sustained funds can promote low-carbon technology innovation, and ultimately reduce environmental degradation and climate risks (Tamazian et al., 2009). Bird et al. (2011) analyzed that carbon finance can also promote the expansion of renewable energy scale through energy substitution effect, and the indirect effect of scale can further trigger the innovation of renewable energy technology by stimulating investment. Yu et al. (2021) proved that green finance policy alleviates financing constraints of green innovation. When companies face higher financing constraints, green innovation capacity will be impaired. Governments should design a comprehensive evaluation mechanism for green performance to ensure that funds flow to green innovation.

However, financial development can promote business activities by reducing the costs of credit for enterprise technological progress. The expansion of business activities and infrastructure projects will lead to an increase in energy consumption and greenhouse gas emissions (Sadorsky, 2011). Increased carbon dioxide emissions may result from the promotion effect of financial development on technology innovation. Productive technology can obtain financial support through green finance development, so as to further expand the production scale of enterprises. Energy-efficiency technological innovations lead to an increase in total actual energy consumption, a phenomenon known as the rebound effect of technology. Aluko and Obalade (2020) proved that financial development has an adverse impact on environmental quality through technology innovation, using the sample of 35 sub-Saharan African countries for the period 1985–2014.

TABLE 1 | Countries description.

Regions	Countries
Africa	Egypt, Morocco, South Africa
Asia	China, Indonesia, India, Japan, Malaysia, Philippines, Saudi Arabia, South Korea, Singapore, Thailand, Turkey, Vietnam
Europe	Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Russian Federation, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom
North America	Canada, Costa Rica, Mexico, United States
Oceania	Australia, New Zealand
South America	Argentina, Brazil, Chile, Colombia, Peru, Uruguay

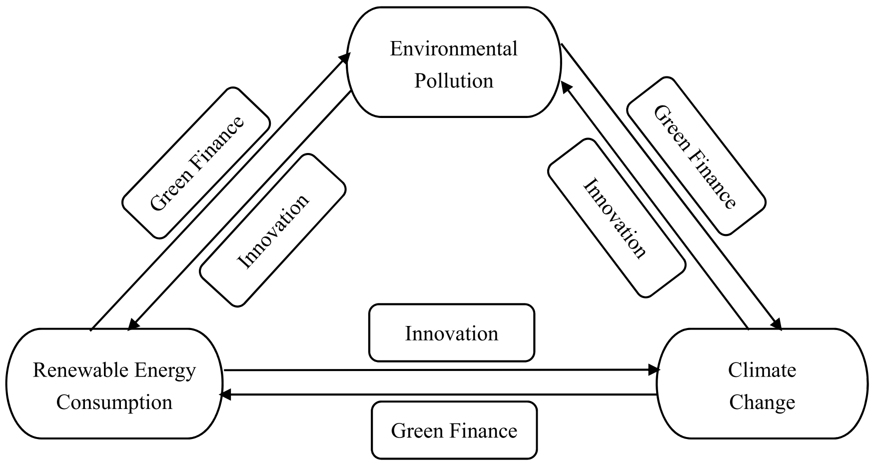

FIGURE 1 | Theoretical framework.

DATA AND METHODOLOGY

Data

The green bond market has grown dramatically in recent years, increased flows of capital flows into low-carbon economic activities. The global cumulative issuance of green bonds reached USD754bn by 2019, since its inception in 2007. The volume of green bonds issued was primarily driven by the European market, with 45 percent of global market. It is followed by the Asia-Pacific market (25 percent) and North American market (23 percent). United States leading with USD171.5bn, followed by China (USD107.3bn) and France (USD86.7bn).

The total number of countries with green bonds issued to 62 in 2019. The main countries from six continents, including Africa, Asia, Europe, North America, Oceania, and South America. In consideration of the typicality and availability of data, this study excluded the sample of countries with small volume of green bond issuance and incomplete data. We employed annual and unbalanced panel data of 49 countries over the period 2007–2019. The countries are described in **Table 1**.

This study included technology innovation and green finance as core variables into the simultaneous equations model of energy-environment-climate nexus. The theoretical framework is showed in **Figure 1**. The main variables include innovation, green finance, energy consumption, environmental pollution, climate change and other control variables. The innovation is measured by global innovation index, green finance is calculated as yearly green bond volume, energy consumption is calculated as a percentage of renewable energy to total energy consumption, environmental pollution is based on CO2 emissions, and climate change is measured by the variations of average temperatures. All variables come from the database of World Bank, World Intellectual Property Organization, Penn World Table and Climate Bonds Initiative. The variables are showed in detail in **Table 2**.

Methodology

Simultaneous Equations Model

The energy-environment-climate nexus is devoted to discuss the causal relationship among energy consumption, environmental pollution and climate change. The simultaneous equations model can not only allow the three independent variables are simultaneous determination, but also the reverse causality between the variables is permitted. Simultaneous estimation is more systematic and efficient than single-equation estimation (Tiba and Frikha, 2018). In addition, the method is straightforward to include new variables in simultaneous equations models, which can avert the omitted variables bias

TABLE 2 | Variables description.

	Variable	Symbol	Description
Dependent variables	Renewable energy consumption	RE	Renewable energy consumption/Total energy consumption (%)
	Environmental pollution	ENVIR	CO_2 emissions per capita (metric tons per capita)
	Climate change	CLIMA	Climate change is measured by the variations of average temperatures based on the year 2000 (°C) The average temperatures are evaluated by mean temperatures during the summer months (June, July and August) for countries with the capitals in the Northern Hemisphere; mean temperatures during the months (January, February and December) for countries with the capitals in the Northern Hemisphere
Independent variables	Innovation	INO	Ln (Global innovation index)
	Green finance	GF	Yearly green bond volume by currency (in USD, billion)
Control variables	Economic development	GDP	Ln (Real GDP per capita) (in USD)
	Climate Policy	CP	Joining of the Paris Agreement, if member state is 1, non-member state is 0
	Industrialization	Indus	Industry value added/GDP (%)
	Capital	CS	Ln (Capital stock at constant national prices) (in USD)
	Urbanization	Urban	Urban population/Total population (%)

(Arminen and Menegaki, 2019). Thus, this study employs the simultaneous equations model to analyze energy-environment-climate nexus, the traditional equations can be estimated based on previous literature as follows.

$$Energy_{i,t} = \alpha_0 + \alpha_1 ENVIR_{i,t} + \alpha_2 CLIMA_{i,t} + \alpha_3 GDP_{i,t} + \alpha_4 Indus_{i,t} + +\varepsilon_{it} \quad (1)$$

$$ENVIR_{i,t} = \beta_0 + \beta_1 Energy_{i,t} + \beta_2 CLIMA_{i,t} + \beta_3 GDP_{i,t} + \beta_4 GDP^2_{i,t} + \beta_5 Urban_{i,t} + \varepsilon_{it} \quad (2)$$

$$CLIMA_{i,t} = \gamma_0 + \gamma_1 Energy_{i,t} + \gamma_2 ENVIR_{i,t} + \gamma_3 GDP_{i,t} + +\varepsilon_{it} \quad (3)$$

Where $Energy_{i,t}$ is total energy consumption; $ENVIR_{i,t}$ is environmental pollution; $CLIMA_{i,t}$ is climate change; $GDP_{i,t}$ is economic development; $Indus_{i,t}$ is industrialization; $Urban_{i,t}$ is urbanization; ε_{it} is the error term; $t = 1, 2, \ldots,$ T time periods; and $i = 1, 2, 3 \ldots,$ N countries.

Based on the above equations, the model is improved as follows. First, this study has established a three-dimensional simultaneous equation framework for discussing the relationship among energy-environment-climate by including innovation and green finance as major variables. We also introduce the interaction term of innovation and green finance to further explore the moderating effect. Exploring the key role of global innovation index and green bonds in energy-environment-climate nexus. Second, accurately assessing the influence of energy consumption on climate change need to consider more than just the aggregate energy consumption, and the energy consumption structure should be taken into the framework. We used the renewable energy consumption instead of total energy consumption in the traditional model, which is helpful to explain the green transition of energy structure. Third, the models include new control variables (e.g., economic development, industrialization, urbanization, climate policy and capital stock) in simultaneous equations models to avoid the omitted variables bias and control for country-specific effects. Thus, the three main simultaneous equations can be estimated as follows.

Energy consumption equation

$$RE_{i,t} = \alpha_0 + \alpha_1 ENVIR_{i,t} + \alpha_2 CLIMA_{i,t} + \alpha_3 INO_{i,t} + \alpha_4 GF_{i,t} + \alpha_5 INO_{i,t} * GF_{i,t} + \alpha_6 GDP_{i,t} + \alpha_7 Indus_{i,t} + \alpha_8 Urban_{i,t} + \alpha_9 CP_{i,t} + \alpha_{10} CS_{i,t} + \varepsilon_{it} \quad (4)$$

Environmental pollution equation

$$ENVIR_{i,t} = \beta_0 + \beta_1 RE_{i,t} + \beta_2 CLIMA_{i,t} + \beta_3 INO_{i,t} + \beta_4 GF_{i,t} + \beta_5 INO_{i,t} * GF_{i,t} + \beta_6 GDP_{i,t} + \beta_7 GDP^2_{i,t} + \beta_8 Indus_{i,t} + \beta_9 Urban_{i,t} + \beta_{10} CP_{i,t} + \beta_{11} CS_{i,t} + \varepsilon_{it} \quad (5)$$

Climate change equation

$$CLIMA_{i,t} = \gamma_0 + \gamma_1 RE_{i,t} + \gamma_2 ENVIR_{i,t} + \gamma_3 INO_{i,t} + \gamma_4 GF_{i,t} + \gamma_5 INO_{i,t} * GF_{i,t} + \gamma_6 GDP_{i,t} + \gamma_7 Urban_{i,t} + \gamma_8 CP_{i,t} + \gamma_9 CS_{i,t} + \varepsilon_{it} \quad (6)$$

Where $RE_{i,t}$ is renewable energy consumption; $ENVIR_{i,t}$ is environmental pollution; $CLIMA_{i,t}$ is climate change; $INO_{i,t}$ is innovation; $GF_{i,t}$ is green finance; $INO_{i,t}*GF_{i,t}$ is interaction term of innovation and green finance; $GDP_{i,t}$ is economic development; $Indus_{i,t}$ is industrialization; $Urban_{i,t}$ is urbanization; $CP_{i,t}$ is climate policy; $CS_{i,t}$ is capital; ε_{it} is the error term; $t = 1, 2, \ldots,$ T time periods; and $i = 1, 2, 3 \ldots,$ N countries.

Estimation Methods

Endogenous problems are inevitable due to the complex relationship among energy consumption, environmental pollution and climate change. Endogeneity means that one or more explanatory variables are related to the random error term in the model. There are three main reasons for endogeneity problem, first, the omission of associated variables caused by the lack of comprehensive consideration. Second, the error generated in the process of selecting and measuring variables weakens the explanatory

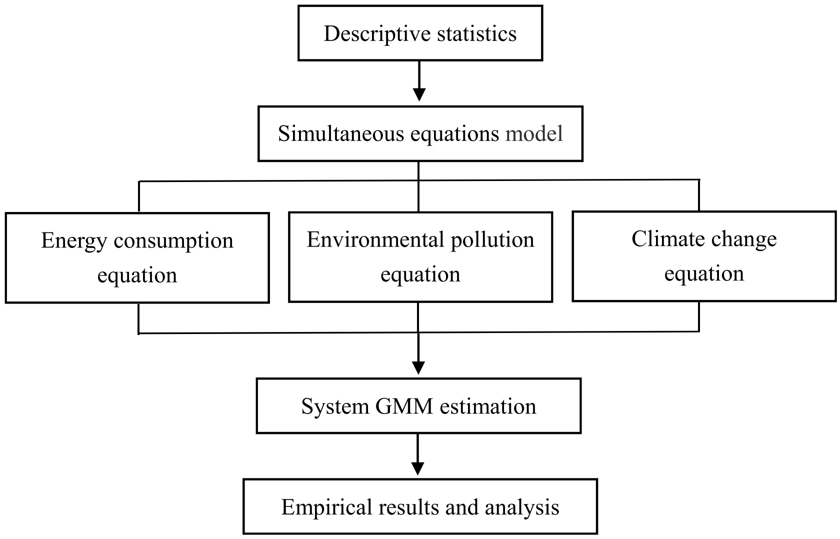

FIGURE 2 | Methodological framework.

degree. Third, the explanatory variable and the explained variable are mutually causal.

To estimate and measure energy-environment-climate phenomenon over time to address endogeneity issues more precisely. In this paper, the generalized method of moments estimation (GMM) is used for endogeneity correction (Arellano and Bond, 1991; Arellano and Bover, 1995). The dynamic panel model includes Difference GMM and System GMM. When there is a weak correlation between instrumental variable and the first difference of disturbance term, it is easy to form a weak instrumental variable, and the difference GMM estimator will produce a large error. Therefore, Blundell and Bond (1998) proposed the system GMM to solve the problem that the instrumental variable might be weakly correlated with the disturbance term in the first-order difference moment estimation. The system GMM estimator combines the difference equation and the level equation into the system of first-differenced equations to improve estimation efficiency. An explanatory variable may include the lagged dependent variable as its instrumental variable.

In order to ensure the effectiveness of the system GMM, the following two tests should be passed. First, Arellano-Bond test is used to test the autocorrelation, the results should not reject the null hypothesis that there is no second-order autocorrelation of the model, that is, the p-value of second-order serial correlations is greater than 0.05, indicating that the estimators were consistent. Second, Sargan test is used to examine validity of the instruments, the p-value of Sargan test of models is greater than 0.05, indicating that there is no over-recognition problem of model instrumental variables, and the regression results maintain a certain accuracy. The methodological framework is showed in **Figure 2**.

TABLE 3 | Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
ENVIR	6.6416	4.2328	0.4810	18.9708
RE	20.9078	17.3612	0.0059	88.8318
CLIMA	0.6725	1.2903	−3.31	6.7
INO	1.4769	1.0408	0.0165	4.9512
GF	13.0283	26.3432	0.001	108
GDP	11.5804	2.2023	6.8093	17.8846
Indus	27.8473	7.9934	13.6822	70.2203
Urban	70.9202	16.1919	24.374	98.156
CP	0.9558	0.2056	0	1
CS	15.0807	1.3662	11.2618	18.2188

RESULTS AND ANALYSIS

Descriptive Statistics

This study employs annual and unbalanced panel data of 49 countries over the period 2007–2019. The energy-environment-climate nexus simultaneous equations model includes five core variables (renewable energy consumption, environmental pollution, climate change, innovation and green finance), and control variables (GDP, industrialization, urbanization, climate policy and capital stock). **Table 3** provides descriptive statistics on each of variables.

In order to deal with the problems associated with the existence of unobtainable heterogeneity, a system GMM estimator with two-step robust standard error was employed in this study. All the models (energy consumption model, environmental pollution model and climate change model) passed the AR (2) test (p value >0.05) and Sargan test (p value >0.05), it shows that the statistical model does not have the problem of autocorrelation in second-order serial correlations and

TABLE 4 | Energy consumption model.

RE Model	(1)	(2)	(3)	(4)	(5)
$RE_{(t-1)}$	0.9162*** (0.0080)	0.8737*** (0.0065)	0.7794*** (0.0133)	0.7554*** (0.0308)	0.7692*** (0.0366)
ENVIR	−0.0479* (0.0248)	−0.0990*** (0.0262)	−0.5260*** (0.0559)	−0.6514*** (0.0446)	−0.6167*** (0.0306)
CLIMA	−0.0209 (0.0139)	−0.0207 (0.0130)	−0.0668*** (0.0072)	−0.0443*** (0.0156)	−0.0262* (0.0149)
INO	—	0.5492*** (0.0539)	—	0.7950*** (0.0650)	0.8140*** (0.0582)
GF	—	—	−0.0069* (0.0038)	−0.0114*** (0.0038)	−0.0883*** (0.0153)
INO*GF	—	—	—	—	0.0406*** (0.0056)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−3.3916	−3.3024	−2.5447	−2.466	−2.3652
p-value	0.0007	0.0010	0.0109	0.0137	0.0180
AR (2)[a]	−1.3837	−1.3586	−1.6175	−1.5626	−1.629
p-value	0.1771	0.1783	0.1058	0.1181	0.1033
Sargan test[b]	38.6263	35.2121	19.6358	25.4764	22.1789
p-value	0.2684	0.4106	0.9683	0.8222	0.9235

Note: Standard errors are showed in brackets. All models include control variables.
[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*
[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*
***: $p < 0.01$.
**: $p < 0.05$.
*: $p < 0.1$.

over-identifying restrictions in instrumental variables. Thus, the regression results are accurate and reasonable.

Energy Consumption Function

For the energy consumption model given in **Table 4**. ENVIR has a significantly negative influence on RE, which is supported by Pavlović et al. (2021) and Ahmed et al. (2021). Areas with high carbon dioxide emissions are more dependent on fossil fuel consumption, which hinders the transformation of energy structure and inhibits the consumption of clean energy. Environmental degradation has not effectively formed a coercive mechanism for the governments to regulate greenhouse gas emissions.

CLIMA has a statistically significant and negative impact on RE. The evidence is consistent with work by Chen et al. (2021) and Zhao and Huang., 2020. Extreme temperatures will hinder the use of clean energy such as solar and wind, damage equipment and reduce the efficiency of power generation in the short term. Climate change also can arouse public concern, forcing governments and enterprises to transform energy structure and improve the utilization rate of clean energy. In fact, the influence of the former is more obvious at this stage.

INO has statistically significant and positive impact on RE, which is supported by Anwar et al. (2020) and Zheng et al. (2021). Technological innovation satisfies the target of energy conservation and improves clean energy consumption. Technological innovation can effectively alleviate the contradiction between supply and demand in energy market, and enterprises will embark on more efficient renewable energy innovation actions with a higher energy demand.

GF has statistically significant and negative impact on RE, which is not supported by Ren et al. (2020) and Li et al. (2022). Green bonds have failed to create incentives for renewable energy consumption. With an increasing green bonds investment in the buildings and transport sectors year by year, it has a crowding out effect on the clean energy sector, and inhibits the investments of renewable energy projects. In addition, greenwashing behavior may also make green bonds no different from ordinary financing methods, failing to effectively form special funds for green projects.

The interaction term INO*GF is positively correlated with RE. The positive effect of innovation on renewable consumption will increase as green finance is enhanced. The evidence is similar to finding by Bird et al. (2011) and Hu et al. (2021). Green finance may increase investment in clean technologies innovation, which lead to a shift in the energy structure from fossil-fuel resources to renewable resources. Sufficient funds will reduce uncertainty and financing constraints of green innovation, and encourage governments and enterprises to promote innovations and patents to promote high-quality development of renewable energy sectors.

Environmental Pollution Function

For the environmental pollution model given in **Table 5**. RE has a negative influence on ENVIR, which is supported by Rahman and Velayutham, (2020) and Usman and Balsalobre-Lorente, (2022). Excessive use of fossil energy is the primary cause of greenhouse gas emissions. Carbon dioxide emissions can be significantly reduced by using renewable energy sources, such as solar, nuclear and wind energy. When more renewable energy is used in power generation, carbon dioxide emissions are significantly reduced. And ultimately achieve the goals of environmental quality improvement.

CLIMA has a significantly positive impact on ENVIR. The evidence is consistent with work by Javanroodi et al. (2018) and Liu et al. (2021). Extreme weather events may frequently destroy electricity generation equipment, the investment of clean energy power generation will be curbed, especially solar and wind power sectors. Extreme temperatures can also make urban areas require a lot of energy, especially electricity to be consumed for cooling buildings. Thus, climate change will increase the probability of environmental pollution.

TABLE 5 | Environmental pollution model.

ENVIR Model	(1)	(2)	(3)	(4)	(5)
$ENVIR_{(t-1)}$	0.6470*** (0.0119)	0.6739*** (0.0147)	0.3900*** (0.0470)	0.3351*** (0.0356)	0.3388*** (0.0452)
RE	−0.1042*** (0.0068)	−0.0878*** (0.0075)	−0.1056*** (0.0085)	−0.1009*** (0.0095)	−0.1026*** (0.0095)
CLIMA	0.1441*** (0.0076)	0.1521*** (0.0076)	0.0768*** (0.0150)	0.0644*** (0.0092)	0.0641*** (0.0114)
INO	—	−0.3116*** (0.0704)	—	−0.6632*** (0.0542)	−0.6442*** (0.0759)
GF	—	—	−0.0328*** (0.0027)	−0.0316*** (0.0013)	−0.0424*** (0.0038)
INO*GF	—	—	—	—	0.0059** (0.0023)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−2.9521	−2.9655	−1.3897	−0.8444	−0.9384
p-value	0.0032	0.0030	0.1646	0.3984	0.3480
AR (2)[a]	0.9259	0.8313	−1.5965	−1.4730	−1.4422
p-value	0.3545	0.4058	0.1104	0.1382	0.1322
Sargan test[b]	41.8280	39.3825	25.3515	24.5007	24.1990
p-value	0.1674	0.2416	0.8269	0.8573	0.8674

Note: Standard errors are showed in brackets. All models include control variables.

[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*

[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*

***: $p < 0.01$.

**: $p < 0.05$.

*: $p < 0.1$.

TABLE 6 | Climate change model.

CLIMA Model	(1)	(2)	(3)	(4)	(5)
$CLIMA_{(t-1)}$	0.0951*** (0.0223)	0.0838*** (0.0233)	0.0471 (0.0291)	0.0952*** (0.0269)	0.0814*** (0.0193)
ENVIR	0.2742*** (0.0404)	0.3011*** (0.0431)	0.3944*** (0.0387)	0.3474*** (0.0765)	0.3398*** (0.0756)
RE	−0.0637*** (0.0094)	−0.0636*** (0.0093)	−0.0666*** (0.0234)	−0.0976*** (0.0241)	−0.0740** (0.0287)
INO	—	−0.1926* (0.1168)	—	−0.3906** (0.1534)	−0.2820** (0.1312)
GF	—	—	−0.0103*** (0.0025)	−0.0074** (0.0034)	−0.0281*** (0.0268)
INO*GF	—	—	—	—	−0.0211* (0.0119)
Control variables	Yes	Yes	Yes	Yes	Yes
AR (1)[a]	−3.3154	−3.3017	−1.7323	−1.7705	−1.8403
p-value	0.0009	0.0010	0.0832	0.0766	0.0657
AR (2)[a]	−1.2953	−1.3677	−0.4452	−0.7242	−0.8595
p-value	0.1952	0.1714	0.6562	0.4689	0.3900
Sargan test[b]	37.9629	37.7709	23.9615	22.7399	21.9403
p-value	0.2935	0.3010	0.8749	0.9098	0.9289

Note: Standard errors are showed in brackets. All models include control variables.

[a]*The Arellano-Bond test for zero autocorrelation, null hypothesis (H0): the disturbance terms have no autocorrelation (Arellano and Bover, 1995).*

[b]*The Sargan test for overidentifying restrictions, null hypothesis (H0): all putative instrumental variables are valid.*

***: $p < 0.01$.

**: $p < 0.05$.

*: $p < 0.1$.

INO has a statistically significant and negative influence on ENVIR, which is supported by Sæther, (2021) and Jahanger et al. (2022). Green technology innovation facilitates the transition of the energy matrix from fossil energy consumption to the renewable energy sector due to its environmentally friendly character. Urgent investment in green technology innovation can meet energy demand at low carbon emissions level. Innovation may improve energy efficiency, reducing greenhouse gas emissions per unit of energy consumption.

GF has a significantly negative impact on ENVIR, which is supported by Flammer (2020) and Muganyi et al. (2021). Green financial development can encourage companies to improve energy efficiency by constantly upgrading equipment, and achieve targets of energy conservation and emission reduction. Green finance guides capital flow to low-carbon industries and restrains the flow to high-carbon sectors, and lead to carbon emissions reduction.

The interaction term INO*GF is positively correlated with ENVIR at the 5% significance level. The negative effect of technology innovation on CO_2 emissions is enhanced by higher levels of green finance, which is supported by Pan et al. (2019) and Acheampong et al. (2020). Financial development can encourage a higher level of R&D, decarbonization technology innovation is more favored by green finance due to carbon emissions reduction. Green bonds mode is suitable for low-carbon technology innovation, which has the characteristics of long cycle and large capital demand. Green financial policies can improve green innovation by effectively dissolving the impact of corporate financing constraints to achieve carbon emissions reduction. Thus, development of green finance can help improve environmental quality by supporting technological innovation.

Climate Change Function

For the climate change model given in **Table 6**. RE has a statistically significant and negative effect on CLIMA, which is supported by Nyambuu and Semmler (2020) and Brini (2021). Renewable energy is the main way to alleviate global warming as a virtually carbon-free energy resource. Governments take serious action on climate change mitigation by increasing clean energy consumption in the energy sector and optimizing the energy structure, and reduce unacceptable climate risks and extreme weather events.

ENVIR has a positive influence on CLIMA. The evidence is similar to finding by Chiu, (2017) and Salari et al. (2021). Carbon dioxide emissions are the main reason for global warming, an increasing greenhouse gas emissions will cause extreme climate problems. Reducing greenhouse gas emissions worldwide by decarbonizing of energy sector, which can ensure global temperatures change at reasonable levels.

INO has a significantly negative impact on CLIMA. Technological innovation is an effective way to mitigate climate change, which is supported by Lin and Zhu (2019) and Wang et al. (2020). The improvement of green technology innovation may reduce greenhouse gas emissions and mitigate global warming risks by increasing energy efficiency and upgrading low-carbon equipment. Offsetting carbon emissions through technologies of carbon capture and storage, which will achieve "net zero" emissions of greenhouse gases.

GF is negatively related to CLIMA, which is supported by Dafermos and Nikolaidi (2021). Green bonds are issued to alleviate financing constraints for the solutions of environmental and climate problems. Green bonds improve climate change adaptation through targeted funding, including improving infrastructure resilience to climate change impacts, and building climate observation and warning systems.

The interaction term INO*GF is negatively correlated with CLIMA at the 5% significance level. The negative effect of technological innovation on climate change will decrease as green finance is enhanced. The evidence is consistent with work by Sadorsky (2011) and Aluko and Obalade (2020). Although green financial development may relieve financing constraints and provide adequate and sustainable financing for innovation, the development of green finance will inevitably drive economic expansion, and expanded production scale may weaken the emission reduction effects of innovation.

CONCLUSIONS AND POLICY IMPLICATIONS

Conclusion

This study introduced innovation and green finance as explanatory variables into simultaneous equations models within the energy-environment-climate dimensions. We found that the promotion effect of technological innovation on renewable energy consumption. Innovation significantly reduces CO_2 emissions and climate change by improving renewable energy efficiency. The governance effect of green finance on environmental pollution and climate change indicates that green financial development will provide important impetus for sustainable development. Green bonds mitigate renewable energy consumption, the funds mainly flow to the field of energy conservation, green buildings and transport, which has a crowding out effect on renewable energy.

In the interaction term aspect, the positive effect of innovation on renewable energy consumption is enhanced by higher level of green finance. The negative relationship between innovation and CO_2 emissions are strengthen when level of green finance is high. The negative impact of innovation on climate change is weakened as green finance is enhanced. The green financial development will support adequate and sustained funding for innovation to promote renewable energy structure transformation and ameliorate environmental pollution.

In the energy-environment-climate nexus, there is bidirectional causality between renewable energy consumption and carbon dioxide emissions. The development of clean energy will support the low-carbon sustainable development. Deteriorating environment will in turn inhibit the development of renewable energy. There is a bidirectional causality between CO_2 emissions and climate change. Carbon dioxide emissions will lead to global warming and frequent climate extremes. Global warming in turn appears to increase carbon dioxide emissions and diffusion. There is a bidirectional relationship between climate change and renewable energy consumption. Extreme weather will inhibit the development of renewable energy sources by reducing the efficiency of energy generation and increasing maintenance costs. Renewable energy consumption will in turn cut down greenhouse gas emissions, and mitigate climate change.

This research has limitations that can serve as directions for further studies. First, we employed green bonds as a proxy for green finance, which could not reflect the whole picture of green finance. The further research can build a multi-dimensional finance index, including green investment, green credit, green securities and green insurance, and explore the financing mechanism of heterogeneous green finance. Secord, the sample involved the countries with green bonds issued as a whole. The further studies can subdivide countries into regions and characteristics, and offer country-specific policy implications.

Policy Implications

The policy implications are as follows.

First, governments should encourage clean energy development and make a more scientific and rational energy structure. Government agencies should attempt to shift from fossil fuels to clean and renewable energy so that CO_2 would be reduced at the global level. Countries should actively adjust energy systems to achieve the goal of carbon neutrality. The European Union set up a "20-20-20" goal, which is to raise the renewable energy consumption ratio to 20%, increase the energy efficiency by 20%, and decrease carbon emissions by 20% before

2020. China promised a "30-60" target, that is to realize emission peak before 2030 and achieve carbon neutrality by 2060. Governments should focus on developing green industries, such as energy conservation and environmental protection industry, cleaner production industry, ecological environment industry, clean energy industry and green building industry. It is necessary to remove the entry barriers for renewable energy sources, and ensure renewable energy products can access to generate electricity market competitively.

Second, governments should develop environment-related technologies as a priority item. They should strengthen international partnerships to improve global environmental standards, increase policy support for environmental-friendly innovation and decarbonization technologies. For example, China has proposed to establish a green development alliance of the "Belt and Road" countries, which is committed to promoting green investment, sharing technical knowledge and resolving environmental problems. In addition, countries should build inter-regional platforms for innovation cooperation to promote the technology upgrading, and shorten the time for new technologies commercialization.

Third, a comprehensive green financing system should be established. Governments should set up a whole industrial chain and large-scale green finance to ensure the development of low-carbon economy. They should emphasize the important status of the securities market in green financing, and raise funds via IPOs and secondary placements for eligible green enterprises. It is necessary to encourage the development of green bond index and green stock index, and gradually establish a compulsory environmental information disclosure mechanism for bond issuers and listed companies. Governments should stimulate the vitality of carbon assets by asset securitization, which can promote the allocative efficiency of carbon assets. In addition, it is necessary to promote the innovation of green financial products and tools to provide financial support for sustainable development. Flexible and diversified financial services should be applied in clean energy sectors.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://data.worldbank.org/.

AUTHOR CONTRIBUTIONS

KZ: Conceptualization; Data curation; Methodology; Analysis; Project administration. HC: Investigation; Project administration; Resources; Software. LT: Investigation; Data curation; Resources. SQ: Formal analysis; Project administration; Review and editing.

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