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Contact to corresponding author: Chun-Ping Chang, cpchang@g2.usc.edu.tw

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Mingbo Zheng
Chang'an University, China
orcid.org/0000-0002-0853-5195

Gen-Fu Feng
Xi'an Jiaotong University, China
orcid.org/0009-0003-6014-6562

Chun-Ping Chang
Shih Chien University, Taiwan
orcid.org/0000-0003-1782-4551

Is green finance capable of promoting renewable energy technology? Empirical investigation for 64 economies worldwide

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Abstract

Research background: As an outcome of a global consensus on combating climate change, green finance is expected to play an important role in promoting green growth and innovation progress. Some studies note that green credit policy yields a negative influence on green innovation, while how green finance affects renewable energy innovation has received scant

attention in academia. This study focuses on the impact of green finance on renewable energy innovation.
Purpose of the article: This research investigates the influence of green finance on an economy's renewable energy innovation by using green bond data from the Climate Bonds Initiative. This research further tests whether it varies for different kinds of energy types and economic development levels. Given that policies are key to renewable energy technology development, this research checks whether government stability changes the relationship between green finance and renewable energy innovation.
Methods: Using the panel fixed effects model and big-scale data from 64 economies worldwide during the period 2014–2019, we investigate green finance's impact on renewable energy innovation. In the robustness test, the dynamic panel model and the panel Tobit model are employed.
Findings & value added: This research finds that green finance has a positive effect on renewable energy innovation. This effect is prominent in non-OECD economies as well as middle-income and low-income economies. Government stability enhances the influence of green finance on renewable energy innovation. Moreover, the results indicate that green finance mainly promotes innovation progress for wind energy and produces little effect for other renewable energies. The subsample analysis also sheds light on the heterogeneity of the role of green finance in promoting renewable energy innovation.

Introduction

Environmental deterioration, air pollution, and resource exhaustion are serious challenges facing human beings (Sinha *et al*., 2021). Thus, how to pave the way for a sustainable transition toward a low-carbon future has attracted international attention (Tao *et al*., 2022; You *et al*., 2022). To fight the increasingly serious climate crisis and environmental challenges in human society (Zhang *et al*., 2022a), 195 countries signed the Paris Agreement in 2015 and reached a consensus to restrict the rise of global temperatures. Many countries hence started to lower their use of traditional fossil energy and began to promote renewable energy development (Wang & Lee, 2022), especially making efforts to facilitate technological innovation in renewable energy fields. Technology innovation is proven to be an effective approach to reducing CO2 emissions and environmental pollution (Zheng *et al*., 2021), but renewable energy innovation activities, with their high uncertainty and current low-cost competitiveness, face the problem of limited financial support (Zhang *et al*., 2022b), which hampers the pace and speed of innovation. As an outcome of a global consensus on combating climate change, green finance represents credit and investments allocated to environmental-friendly projects and sustainable development (Yu *et al*.,

2021) and is expected to play an important role in promoting green growth and innovation progress.

Green finance improves the information transparency of corporates and enhances the communication between corporates and financial institutions (Lee *et al*., 2021). At the same time, green finance is able to help financial institutions at avoiding environmental risk (Jin *et al*., 2023). From the firm level, researchers find that green finance including green credit boosts corporates' social and environmental responsibilities (Sinha *et al*., 2021) and renewable energy investment and facilitates green transformation (Tian e*t al*., 2022). Fan *et al.* (2021) further find that the reinforcement of green credit regulation increases the difficulty of applying for loans in non-compliant firms and indeed brings about better environmental performance. A growing body of studies is paying attention to green innovation (Bhutta *et al*., 2022) and testing the impact of a green credit policy on corporate green innovation. This type of credit policy is able to promote more green innovation output (Hu *et al*., 2021; Wang & Li, 2022), improve innovation quality (Wang *et al*., 2022), and foster radical green innovation (Zhang *et al*., 2022b). Some studies also note that green credit policy yields a negative influence on firm performance in heavily polluting industries (Yao *et al*., 2021), which may generate an uncertain effect on the macroeconomy. In fact, how green finance affects national renewable energy innovation has received scant attention in academia.

This leads us to investigate the influence of green finance on renewable energy innovation at the economies level. Is renewable energy innovation affected by national green finance? If it is, then does this influence remain the same among different renewable energy types and different countries? Moreover, due to the insufficient cost competitiveness of renewable energy in the market, policy stability is key to renewable energy technology innovation, which may shape the relationship between green finance and renewable energy innovation. In other words, if green finance affects renewable energy innovation, does it change with the level of government stability?

After answering these questions, this research expands upon current studies in three ways. First, it investigates the influence of green finance on economies renewable energy innovation by using complete green bond data from the Climate Bonds Initiative, which provides new insight into the real consequences of green finance. Second, when we identify the influence of green finance on national renewable energy innovation, we further test whether it varies for different kinds of energy types and economic development levels. Third, given the fact that policies are key to renewable energy technology development, we check whether government stability changes the relationship between green finance and renewable energy innovation.

The anticipated results are offered. Using cross-economies data from 64 economies from 2014–2019 and the panel fixed effects model, this research explores the influence of green finance on innovation in renewable energy technologies. The results indicate that green finance is conducive to promoting renewable energy innovation. This positive effect of green finance is prominent in non-OECD economies as well as middle-income and low-income economies. We also find that government stability enhances the positive influence of green finance on renewable energy innovation. Moreover, green finance mainly promotes innovation progress for wind energy and yields limited influence for other renewable energies.

The rest of this paper runs as follows. Section 2 expresses research progress on green finance and technology innovation. Section 3 provides the empirical model, variables, and data sources. Section 4 displays baseline regression results, heterogeneous analysis, and robustness tests. Section 5 concludes and gives practical implications.

Literature review

It is well-known in the innovation literature that financial constraint is a major restriction to the operation of an innovation project (Lee *et al.*, 2020). With the nature of high uncertainty and time-consuming, innovation activities require a lot of financial support, implying that external financing plays a substantial role in innovation activities (Hu *et al.*, 2021). Compared with innovation in a normal field, renewable energy innovation projects face more obstacles during the process of obtaining finance, due to double externalities. Double externalities refer to renewable energy innovation not simply producing knowledge spillovers, like traditional innovation, but also generating environmental spillovers, which lead to higher levels of information asymmetry. In this case, financial institutions, such as banks and capital venture firms (Lee *et al.*, 2022), are much less willing to finance ecology-friendly renewable energy innovation. Consequently, due to the high cost, high uncertainty, and long time periods for innovation projects, firms are discouraged from promoting renewable energy innovation (Yu *et al.*, 2021). Such development faces an obstacle on how to efficiently finance innovation projects. As noted by Bhutta *et al.* (2022), financing plays a key role in supporting green development.

To solve the problem of financing constraints in environment-friendly projects, including renewable energy innovation, green finance now is regarded as an effective tool and has grown at rapid speed around the world (Managi *et al*., 2022). Green finance refers to "the financing of investments that provide environmental benefits in the broader context of sustainable development". Green finance can increase money flow to environment-friendly projects and attach restrictions on polluting projects to reshape financial resource allocation, thereby relieving any financing constraint on less polluting firms. At the same time, green finance can improve financial as well as environment information communication among firms, financial institutions, and investors, hence gathering together more finance from financial markets and investors (Yu *et al*., 2021). One type of green finance instruments, the green bond, is growing fast and helping to support sustainable development and relax financial restraints.

Some studies have identified the impact of green finance on the environment and a firm's financial restraints (Xu & Li, 2020). Meo and Abd Karim (2021) investigate the impact of green finance on carbon emissions and find that green finance contributes to lower national CO2 emissions. Yu *et al.* (2021) state that green finance policies can efficiently ease a firm's financial restraints. Fan *et al.* (2021) show that green credit reform increases the financing constraint of non-compliant enterprises, including a higher interest rate, a lower loan amount, and greater difficulty of access to loans. Fan *et al.* (2021) further find that the reinforcement of green credit regulation indeed improves a firm's environment performance, whereas this effect is induced by a firm's strategy. Large firms tend to lower emission intensity, and small firms directly reduce production. Sinha *et al.* (2021) show that green bond financing has a gradual inhibiting transformational influence on environmental and social responsibilities.

As the driver of sustainable growth, green innovation has received considerable attention. One strand of the literature focuses on the relationship between green finance and green innovation. Most research studies find that green finance is conducive to more green technology innovation of an enterprise. Hu *et al*. (2021) examine the influence of green credit policy on green innovation and present that China's green credit policy yields more green innovation output in high-polluting enterprises by relaxing financial constraints. Wang and Li (2022) explore how the issuance of green credit policy affects green technology innovation, finding that such an issuance indeed stimulates more green innovation through an improvement in investment effectiveness, and firms with more legitimacy deficiency in environmental compliance experience larger increases in innovation output. Wang and Li (2022) further prove that an increase in green innovation output is driven by higher productivity in application technology innovation.

Green finance is also likely to produce a heterogeneous effect on green innovation output. Wang *et al.* (2022) check the impacts of green credit guidelines in China on green innovation quality. They show that such guidelines enhance the quality of green innovation, especially for firms owned by local and central governments and located in less financially developed regions. Wang *et al.* (2022) find that China's green credit policy significantly stimulates incremental green technology innovation, while it produces a hindering effect on radical green technology innovation. However, Yu *et al.* (2021) show that green finance seems to have little benefit for reducing the financing restraints of private-owned enterprises, thereby restricting green innovation. It is noteworthy that empirical studies do not always support the positive role of green finance in a firm's development. For instance, Yao *et al*. (2021) investigate the effect of green credit policy on firm performance in China and find that such a policy has a negative effect on firm performance in heavily polluting industries, because of increased financing constraints and lower investment levels.

Another important point about green finance and renewable energy innovation is policy stability. The literature claims that innovation in renewable technologies is sensitive to public policy stability (Wen *et al*., 2021). Due to a cost competitive disadvantage, renewable energy innovation is largely relevant to public funding support. A lack of credit commitment from governments on public spending may undermine a firm's willingness to participate in renewable energy innovation activities. Public support stability helps to reduce the investment risk and encourage firms to undertake innovation projects in renewable energy fields. Consequently, policy stability is able to strengthen a firm's confidence on innovation success and enhance the influence of green finance on renewable energy innovation.

To sum up, although many studies have examined the impact of green finance on a firm's green technology innovation, few studies have attempted to explore the innovation consequence of green finance at the global level. We also observe that renewable energy technological innovation has received scant attention in the literature, even as renewable energy innovation is capable of accelerating energy transition and improving environmental pollution directly. Moreover, given that policy stability can influence renewable energy innovation, the role of such stability has still not been adequately addressed. Therefore, this paper explores the impact of green finance on economies renewable energy innovation and how policy stability reshapes it.

Research methods

The model

In order to explore the relationship between green finance and renewable energy innovation, we utilize the linear panel model, which takes individual-invariant and time-invariant factors into account. The advantages of the panel fixed effects model include more reliable estimators and statistical tests (Wang *et al*., 2021). The empirical model is set as:

$$RE_{it} = \alpha GF_{it} + \beta \boldsymbol{X_{it}} + \gamma_i + \gamma_t + \mu_{it} \tag{1}$$

where RE_{it} refers to renewable energy innovation, GF_{it} represents green finance, $\boldsymbol{X_{it}}$ is a set of control variables, γ_i captures unobserved time-invariant factors for each economies that affects renewable energy innovation, γ_t captures unobserved economies-invariant factors for each year that affects renewable energy innovation, i refers to economies, t refers to year, and ε_{it} is the error term. α is the coefficient of green finance, and β represents the parameter vector of control variables.

To ensure the validity of the main findings, we use the dynamic panel model and the panel Tobit model in the robustness test. The dynamic panel model is set as:

$$RE_{it} = \varphi RE_{it-1} + \alpha GF_{it} + \beta \boldsymbol{X_{it}} + \gamma_i + \gamma_t + \mu_{it} \tag{2}$$

where RE_{it-1} refers to renewable energy innovation economies i of in year t-1. φ refers to the coefficient of lagged renewable energy innovation. The dynamic panel model considers the persistence of the dependent variable and has the capacity to deal with endogeneity problems. We employ a two-step Generalized Method of Moments (GMM) method to estimate the dynamic panel model. Because the data of RE is limited in a 0 to 1 range, the use of the panel fixed effects model, could not result in consistent estimators, which requires the Tobit model to solve truncated data problem. The panel Tobit model is set as:

$$RE^*_{it} = \alpha GF_{it} + \beta \boldsymbol{X_{it}} + \gamma_i + \gamma_t + \mu_{it}$$
$$RE_{it} = \begin{cases} 0, otherwise \\ RE^*_{it}, when\ RE^*_{it} > 0 \end{cases} \quad (3)$$

where RE_{it} refers to renewable energy innovation, RE^*_{it} is the potential renewable energy innovation.

Dependent variable

Innovation research often takes patents as a good measurement for innovation performance, because patents reflect something in the form of advanced and novel progress in technology activity. A patent denotes the intermediate output of innovation activities and is capable of showing the ultimate value of technological innovation (Wang *et al*., 2021). Apart from this, many databases provide available patent application data and offer good quality of data, thus enabling us to explore the determinants of innovation performance. We measure renewable energy innovation by utilizing the total number of renewable energy patents (*RE*), obtaining the data from the OECD Environmental Statistics.

Explanatory variable

Green bonds are often employed to proxy green finance progress (Yang *et al*., 2021; Wang *et al*., 2021). As stated by Meo and Abd Karim (2021), green bonds are capable of providing long-term finance for projects that are environmental-friendly or reduce pollution. Renewable energy projects like solar energy and wind energy receive a lot of support from green bonds. Therefore, we obtain green bond data from Climate Bonds Initiative to proxy for a economies's green finance. Climate Bonds Initiative records self-labelled debt instruments from a global scale to construct a complete green bonds database. Three prerequisites for the inclusion of green bonds include debt instrument, self-labelled, and public disclosure. Specifically, we collect data on the amounts of green bonds issued (*AoGB*) and number of deals (*NoD*) to measure green finance. Figure 1 offers the trend of global green bonds around the period 2014–2020. Both the amount of green bonds and the number of deals exhibit rapid growth rates in recent years, corroborating to the fast rise of green bonds on a global scale.

Control variables

Although green finance is a crucial factor, renewable energy innovation may be affected by other economic variables. We account for these following variables in the model. A higher level of economic development reflects more available resources allocated to renewable energy innovation activities and leads to more market demand for renewable energy products (Zheng *et al*., 2021). We use real gross domestic products per capita (*GDP*) to proxy a economies's economic development level (Yang *et al*., 2021; Long *et al*., 2021). Urbanization denotes the agglomeration of talents and skilled labor, creating a knowledge spillover effect on renewable energy innovation. Urbanization rate (*Urban*) is employed to measure the influence of urbanization. Education is an important determinant of innovation activities through human capital accumulation. Following Fu *et al.* (2023), we measure it with the share of education expenditure on government fiscal expenditure. Trade activities can promote renewable energy innovation by offering high-quality intermediate input and flow of advanced knowledge (Wang *et al*., 2021). As such, we capture the effect of trade openness with the ratio of trade in GDP. Financial development is essential to the innovation process (Yu *et al*., 2021). We use the ratio of domestic credit to the private sector by banks in GDP to measure the financial development level. Market price adjustment will alter a firm's decision on innovation projects (Evers *et al*., 2020). We control the inflation rate (*CPI*) in the model to relieve the effect of price adjustment. The details of variables are presented in Table 1.

Data

Our data are gathered from several sources. The data of renewable energy patents in generation-related fields are from the OECD Environmental Statistics (https://www.oecd-ilibrary.org/environment/data/oecd-environm ent-statistics_env-data-en). The Green Bonds Database of Climate Bonds Initiative provides information about green bonds around the world (https://www.climatebonds.net/market/data/). Other data are from World Development Indicators (https://datatopics.worldbank.org/world-develo pment-indicators/). The final sample includes unbalanced panel data of 64 economies during the period during the period 2014–2019. The economies list is provided in Table 2. Table 3 offers descriptive statistics of the variables used in this research. We observe that the mean value of *RE* reaches 0.07, indicating that countries have 70 renewable energy technology patents on average. The minimum value and maximum value of *RE* are respectively 0 and 1.133, which suggests a significant distinction in renewable energy innovation performance in the sample countries. The mean of *AoGB* is 0.621, implying that sample countries issued US $ 621 million in bonds on average for environmental-friendly projects. The standard deviation of *Urban*, *Education*, and *Trade* are large, suggesting that urbanization, education expenditure, and trade openness differ among the sample countries.

Results and discussion

Benchmark results

We first check for whether green finance exerts an influence on renewable energy innovation. Table 4 offers the regression results about the influence of green finance and national renewable energy innovation. Amount of green bonds issued (*AoGB*) is used as the measure of green finance in columns 1 and 3, whereas that of columns 2 and 4 is the number of deals (*NoD*). The model accounts for economies fixed effects in columns 1 and 2 and includes time fixed effects in columns 3 and 4. We observe in column 1 that the coefficient of *AoGB* is 0.036 and exhibits statistical significance, suggesting that issuing a greater amount of green bonds can enhance renewable energy innovation performance. This results remain consistent in column 3 with the inclusion of time fixed effects.

We next turn to check whether the number of deals affects renewable energy innovation. In columns 2 and 4 the coefficients of *NoD* are respectively 0.015 and 0.021 and pass the significance test at least at the 5% level, implying that issuing more green bonds could stimulate more innovation output in renewable energy technologies. Our results support the argument that if an economy issues more green bonds and has a greater level of green finance, then it will experience higher performance in renewable energy innovation. Our finding corroborates recent studies that examine the role of green finance in corporate green technology innovation from the micro-level perspective (Hu *et al*., 2021; Tian *et al*., 2022; Wang & Li, 2022; Alharbi *et al*., 2023). Yu *et al.* (2021) show that green credit policy can improve a corporate's access to financial resources and relieve financial constraints, thereby fostering green technology innovation. Our study complements this strand of research on green finance and renewable energy innovation at the economies level from a macro-level perspective.

For the control variables, we find that the variable *GDP* is positive and significant at the 1% level in columns 3 and 4 with the inclusion of economies and time-fixed effects, showing that greater economic development is accompanied by a higher level of renewable energy innovation. This finding is in line with Ahmed (2020), who states that economic development positively relates to green technology innovation. We also see that the variable *Urban* is significantly positive in all specifications of Table 2, meaning that the urbanization process helps to improve renewable energy innovation performance. As noted by Wang *et al.* (2021), urbanization can promote technological innovation progress by aggregating human capital into cities and accelerating knowledge spillover in advanced technology (Lin & Zhu, 2021).

Table 5 presents the variance inflating factor (VIF). The literature argues that the VIF cannot exceed 5 and its tolerance cannot be smaller than 0.2. In Table 3, we see that the VIF is smaller than 5 and the tolerance is larger than 0.2 for all explanatory variables, which implies that the model results are not threatened by the multicollinearity problem.

Different renewable energy types

We next investigate whether national green finance influences technology innovation for wind energy, solar energy, etc. Different renewable energies differ in their degree of mature technologies and production cost. Wind energy and solar energy show the advantages of being cost-competitive and having mature technology, while ocean technologies are one form of emerging technologies with less advantage of being cost-competitive. Facing a compliance cost from strict environmental regulation, firms with access to green finance are likely to choose renewable energy innovation in mature technologies. The reason is that choosing emerging technologies in renewable energy fields faces a smaller probability of innovation success and market profit along with high technology uncertainty. It is therefore necessary to identify the heterogeneous influence of green finance on renewable energy technology innovation.

Table 6 displays the estimation results of the heterogeneous effect of green finance in five technologies: wind energy (*Wind*), solar energy (*Solar*), marine energy (*Marine*), hydropower energy (*Hydro*), and geothermal energy (*Geothermal*). It appears that the variable *AoGB* is significantly positive at least at the 5% level, implying that green finance yields more patents in wind energy technologies. The variable *AoGB* is positive and shows significance at the 10% level, presenting a relatively weak positive relationship between green finance and solar energy innovation. For the other three renewable energies, the coefficient of *AoGB* loses its statistical significance, which means that green finance cannot generate a promoting effect on technology innovation in marine energy, hydropower energy, and geothermal energy. When turning to Number, we also find similar results — that is, the number of green finance deals promotes innovation for wind energy, while its produces little effect for other renewable energy technologies. Our results are consistent with Zhang *et al*. (2022b), who find that green credit policies only enhance incremental green innovation. With more access to green finance, firms will devote resources to innovation fields with mature technology (like wind energy), while reducing inputs to emerging technologies with high R&D costs (Shao *et al*., 2020). Moreover, some studies find that green finance produces heterogeneous effect on renewable energy development.

Wang and Taghizadeh-Hesary (2023) investigate the impact of green finance on renewable energy in OECD countries. Their results show that green finance has a significant positive effect on wind energy, while no effect on solar energy. The explanation is that green bond issuing is mainly in the field of wind energy, while there is no need to issue green bond for solar energy (Adekoya *et al*., 2021), because private firms and startups have devoted lots of financial resources into solar energy development.

The role of government stability

The literature has shown that government efficiency is a pivotal factor regarding green innovation performance, especially for clean technology innovation (Herman & Xiang, 2019). Government efficiency can improve the effectiveness of energy policies and bring about benefits to innovation activities. On the contrary, low government efficiency, such as government instability, cannot maintain declared environment programs and cannot provide a steady environment for renewable energy innovation activities. Government instability is hence regarded as a bottleneck to impede technology innovation process. Given the fact that renewable energy innovation is determined by government policies (Hille *et al*., 2020), government stability shapes the relationship between green finance and renewable energy innovation.

We next check the role of government stability in the nexus of green finance and renewable energy innovation. We use the government stability index (*GS*) to capture the degree of an economy's government stability. This index is constructed by three subcomponents, including government unity, legislative strength, and popular support, and obtains original data from the International Country Risk Guide (*ICRG*) database. The range of the government stability index is from 0 to 12, and a higher value shows greater stability. We add GS and interact it with green finance in the model.

Table 7 presents the results with regard to government stability. We see that the interaction term of government stability and green finance is positive and passes the significance test at the conventional level, implying that government stability can enhance the effect of green finance on renewable energy innovation. Our results corroborate the finding of Qin *et al*. (2021) that policy stability is of great importance for renewable energy innovation. Due to higher cost and market uncertainty, renewable energy innovation is highly contingent on policy support (Lim *et al*., 2021), which relates to government stability. A stable government can implement effective policies and lower uncertainty faced by renewable energy innovators (Zhang *et al*., 2022b), thereby promoting innovation performance in renewable energy technologies.

Subsample analysis

As noted by Zheng *et al.* (2023), exploring the basic results in several subsamples can enhance the understanding for heterogeneity of economic development in various countries. Economic development is positively associated with financial market development level and available finance resources. Compared to emerging economies, developed countries generally have proper functioning finance systems and possess higher levels of financial resources (Wang *et al*., 2021). This implies that no matter whether green finance is provided or not, renewable energy innovators face less constraints in the innovation process in developed countries. This transmission channel infers that the promotion effect from green finance to technology innovation performance in renewable energy fields is weaker in developed countries.

To examine whether economic development changes the impact of green finance on renewable energy innovation, we implement a baseline regression on several subsamples. More precisely, we divide the full sample into OECD economies and non-OECD economies, because the former generally have higher levels of economic development. To ensure robustness, we also consider high-income economies and non-high-income economies. Middle-income and low-income economies, Non-OECD countries are defined as emerging economies, while high-income economies and OECD members belong to developed countries.

The corresponding results of these four subsamples appear in Table 8. From Panel A of Table 8, we see that the coefficients of the green finance variable show insignificance for OECD economies, but express statistical significance in non-OECD economies irrespective of whether the measure of green finance is *AoGB* or *NoD*, which supports the argument that green finance yields a promotion effect in non-OECD economies, while this effect disappears for OECD economies. We observe similar results in Panel B of Table 8, where green finance exhibits positive coefficients and significance only in non-high-income economies. Consequently, we conclude that the influence of green finance on renewable energy innovation depends on economic development levels, and green finance mainly plays the role of supplementing the local financial system.

Our results are consistent with Lee *et al.* (2023) and Xu *et al*. (2023), who find that green finance development significantly contributes to renewable energy development or green innovation. The positive role of green finance is found in emerging economies, like China (Tang & Zhou, 2023; Zheng *et al*., 2023). For developed economies, some studies find green finance generates limited influence on specific renewable energy development. For instance, Wang and Taghizadeh-Hesary (2023) explore the role of green bonds in renewable energy development for the OECD countries. They find that green bonds exert no significant impact on solar energy in OECD countries. This results remind us that green finance policy formation should consider the heterogeneity of economic development level.

Robustness check

For the robustness of our baseline findings, this study conducts several tests as follows. First, it accounts for the dynamics of renewable energy innovation in the model. Potential uncertainty exists in the process of renewable energy innovation, and R&D activities need considerable materials and researchers, implying that successful patent applications require much time. At the same time, innovation is a process of knowledge accumulation, and past performance plays a role in current performance (Wang *et al*., 2021). This reminds us that we need to capture the dynamics of renewable energy innovation in the model, and so we consider the dynamics of renewable energy innovation by using the dynamic panel model with the generalized method of moments (GMM) estimation. Panel A of Table 9 presents the results of the dynamic panel model. The p value of AR(1) test is less than 0.1, p value of AR(2) test and Sargan test is higher than 0.1, showing that the used instrument variable is valid and there is over-identification problem in the dynamic panel model. We see that green finance variables are still positive and significant at the 1% level, which implies that green finance yields a positive effect on renewable energy innovation.

Second, we consider the data censoring problem. The assumption of the panel linear model is that the distribution of the dependent variable is normal. Nevertheless, the dependent variable used is patent applications and is left-censored at zero. This implies that using the panel fixed effects model may induce bias in the results. We hence employ the panel Tobit model, which can deal with the problem of data censoring. Panel B of Table 9 presents the results of the panel Tobit model. The Likelihood Ratio (LR) test is passed with significance in all specifications, suggesting that the results of the panel Tobit model are reliable. It appears that green finance variables remain significantly positive at the 1% level, revealing that green finance promotes renewable energy innovation development.

Third, we deal with cross-sectional dependence in the model. As pointed out by Ordoñez-Callamand *et al*. (2017), cross-sectional dependence widely exists in cross-economies investigations — that is, several economic indicators may be relevant to a small number of common factors. For R&D and innovation indicators, Ali *et al*. (2021) find cross-sectional dependence appears in the series. We hence use the panel fixed effects model with Driscoll-Kraay standard errors (Driscoll & Kraay, 1998) to solve cross-sectional dependence. Panel B of Table 9 presents the results of dealing with cross-sectional dependence. We still see that the variables of *AoGB* and *NoD* remain significantly positive, thus providing a reference for our baseline findings.

Conclusions

Developing green finance has become a hot approach to promote renewable energy technology progress and low-carbon transition, yet whether green finance can speed up renewable energy innovation remains an unclear question. This research uses cross-economies data from 64 countries to check the effect of green finance on innovation in renewable energy technologies. We find that green finance has a positive effect on renewable energy innovation. This effect is prominent in non-OECD economies as well as middle-income and low-income economies, suggesting that green finance mainly promotes renewable energy innovation in emerging economies. Government stability further enhances the influence of green finance on renewable energy innovation. Moreover, the results indicate that green finance mainly promotes innovation progress for wind energy and produces little effect for other renewable energies.

Our findings provide several policy implications for policy makers around the world as noted below. First, emerging economies should carry out various actions to promote green finance development for the goal of renewable energy innovation progress. Our results identify the positive influence of green finance on renewable energy innovation that is only significant in emerging economies with low renewable energy innovation and high environment degradation. Specifically, wind energy innovation receives a greater positive influence from green finance. Therefore, more policies on green bonds and green credit should be initiated to improve renewable energy innovation in emerging economies, especially for wind energy technology.

Second, developed countries can strengthen international finance support for emerging countries to accelerate renewable energy innovation. Our results show that green finance yields little effect on renewable energy innovation in developed countries. It is straightforward that developed countries have a greater level of financial development and a properly functioning financial system, which provides considerable resources to innovation activities in renewable energy fields. This leads to limited space for green finance. As a result, developed countries can implement international cooperation policies to promote green finance in emerging countries, including direct finance support, experiences sharing of green credit policies, and researcher training.

Third, government stability should be enhanced to create a steady environment for renewable energy innovation activities. As shown in this paper, technology progress in renewable energy fields requires a steady policy environment. Government stability is the essential determinant of policy stability that significantly affects an innovator's decision about technology innovation. Only stable policies are more conducive to renewable energy innovation. It is hence especially important that governments should set up predictable and reliable policy paths to promote green finance and renewable energy innovation development.

Although our research advances the relationship between green finance and renewable energy innovation, there are still some limitations. First, this paper just focuses on the global evidence by using economies-level data, and lacks micro firms' investigations. It is suggested that future researches can use micro firm data to examine the impact of green finance on renewable energy technology innovation. Second, even this research confirms the positive influence of green finance on renewable energy innovation, the potential mechanisms are unclear. It is valuable to explore the underlying mechanism through which green finance promotes renewable energy innovation in the future research. Third, green finance is a multi-dimensional financial activities aiming at sustainable development. Besides green bonds, green insurance, green venture capital, and carbon finance are effective tools to support environment-friendly projects. It is recommended that researchers in the future can discuss and compare the role of different green finance tools in accelerating renewable energy development and energy transition.

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Annex

Table 1. Variable definitions

Variable	Name	Definitions	Unit
RE	Renewable energy innovation	the total number of renewable energy patents	Thousand
AoGB	Green finance amount	the amounts of green bonds issued	Billion dollar
NoD	Green finance number	Number of deals for green bonds	Deals
GDP	Economic development	Real gross domestic products per capita	US dollar 2015 constant
Urban	Urbanization	Urbanization rate	percent
Education	Education	the share of education expenditure on government fiscal expenditure	percent
Trade	International trade	the ratio of trade in GDP	percent
FD	Financial development	the ratio of domestic credit to private sector by banks in GDP	percent
CPI	Price adjustment	Consumer price index percent change	percent

Table 2. Economies list

Armenia	Estonia	Kenya	Poland
Australia	Finland	Sri Lanka	Portugal
Austria	France	Lithuania	Paraguay
Belgium	United Kingdom	Luxembourg	Qatar
Belarus	Greece	Macao SAR, China	Romania
Brazil	Hong Kong SAR, China	Morocco	Russian Federation
Switzerland	Hungary	Moldova	Senegal
Chile	Indonesia	Mexico	Serbia
China	India	Malaysia	Slovak Republic
Colombia	Ireland	Netherlands	Slovenia
Cyprus	Iran	Norway	Sweden
Czech Republic	Iceland	New Zealand	Thailand
Germany	Israel	Pakistan	Ukraine
Denmark	Italy	Panama	Uruguay
Algeria	Jordan	Peru	Vietnam
Spain	Kazakhstan	Philippines	South Africa

Table 3. Descriptive statistics

Variable	N	Mean	S.D.	Minimum	Median	Maximum
RE	448	0.070	0.190	0.000	0.005	1.133
AoGB	1526	0.621	3.606	0.000	0.000	52.900
Number	1526	4.598	56.529	0.000	0.000	1225.000
GDP	1401	8.757	1.436	5.601	8.692	12.119
Urban	1498	60.615	23.980	11.776	61.681	100.000
Education	910	0.145	0.049	0.008	0.140	0.350
Trade	1254	92.978	58.245	9.955	81.452	425.976
FD	1186	52.609	40.181	1.711	45.103	280.339
CPI	1213	0.046	0.166	-0.037	0.021	3.800

Table 4. The effect of green finance on renewable energy innovation

	(1) *RE*	(2) *RE*	(3) *RE*	(4) *RE*
Amount	0.036***		0.038***	
	(4.81)		(5.73)	
NoD		0.015**		0.021***
		(2.54)		(3.91)
GDP	0.001	0.024	0.298***	0.328***
	(0.02)	(0.35)	(4.30)	(4.55)
Urban	0.020***	0.023***	0.043***	0.046***
	(3.34)	(3.73)	(7.22)	(7.36)
Education	-0.096	0.006	0.132	0.242
	(-0.31)	(0.02)	(0.49)	(0.86)
Trade	-0.001	-0.001	-0.001	-0.001
	(-1.28)	(-1.25)	(-1.45)	(-1.44)
FD	0.001**	0.001**	0.001***	0.001***
	(2.27)	(2.18)	(3.12)	(3.04)
CPI	0.028	0.050	-0.039	-0.026
	(0.33)	(0.56)	(-0.51)	(-0.32)
constant	-1.381**	-1.880***	-5.926***	-6.421***
	(-2.43)	(-3.12)	(-7.74)	(-8.15)
Country	Y	Y	Y	Y
Year	N	N	Y	Y
N	262	262	262	262
Within R^2	0.307	0.249	0.474	0.428

Notes: This table presents the regression results of green finance on renewable energy innovation. *t* statistics are in parentheses. The model accounts for country-specific effects and time-specific effects. Y refers to country (or time) fixed effects that are considered, while N does not. *, **, and *** refer to significance at the 10%, 5%, and 1% levels, respectively.

Table 5. Multicollinearity test of variables

	(1) *VIF*	(2) *Tolerance*	(3) *VIF*	(4) *Tolerance*
AoGB	1.25	0.797		
NoD			1.33	0.750
GDP	3.22	0.310	3.23	0.309
Urban	2.25	0.445	2.24	0.445
Education	1.21	0.823	1.20	0.836
Trade	1.32	0.756	1.39	0.716
FD	1.73	0.578	1.76	0.568
CPI	1.30	0.768	1.30	0.769

Notes: This table reports the results of the multicollinearity test. VIF represents the variance inflating factor (VIF). Tolerance is defined as the reciprocal of VIF.

Table 6. Green finance and renewable energy innovation: distinct energy

	(1) *Wind*	(2) *Solar*	(3) *Marine*	(4) *Hydro*	(5) *Geo*
Panel A Green finance: amount issued					
AoGB	0.007***	0.003*	-0.001	-0.001	0.001
	(3.17)	(1.92)	(-1.20)	(-1.32)	(0.78)
Controls	Y	Y	Y	Y	Y
Country	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y
N	185	146	97	120	51
Within R^2	0.121	0.134	0.268	0.184	0.070
Panel B Green finance: number of deals					
NoD	0.005***	0.001	-0.000	-0.001	0.000
	(2.95)	(0.63)	(-0.02)	(-0.86)	(0.11)
Controls	Y	Y	Y	Y	Y
Country	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y
N	185	146	97	120	51
Within R^2	0.113	0.103	0.250	0.173	0.045

Notes: This table presents the regression results of green finance and renewable energy innovation in five energy fields. *t* statistics are in parentheses. The model accounts for country-specific effects and time-specific effects. We hide these control variables due to limited space, but they are available upon request. Y refers to country (or time) fixed effects that are considered, while N does not. *, **, and *** refer to significance at the 10%, 5%, and 1% levels, respectively. Panel A presents the results of green finance amount, while Panel B indicates the results of the number of green bond deals.

Table 7. Green finance and renewable energy innovation: considering government stability

Variable	**(1)** ***RE***	**(2)** ***RE***
*AoGB*GS*	0.055***	
	(13.73)	
*NoD * GS*		0.031***
		(8.17)
AoGB	-0.345***	
	(-12.14)	
NoD		-0.198***
		(-7.27)
GS	-0.010***	-0.013***
	(-3.45)	(-3.38)
Controls	Y	Y
Country	Y	Y
Year	Y	Y
N	254	254
Within R^2	0.746	0.585

Notes: This table presents the regression results of how government stability shapes the nexus between green finance and renewable energy innovation. *t* statistics are in parentheses. The model accounts for country-specific effects and time-specific effects. We hide these control variables due to limited space, but they are available upon request. Y refers to country (or time) fixed effects that are considered, while N does not. *, **, and *** refer to significance at the 10%, 5%, and 1% levels, respectively.

Table 8. Subsample analysis

Panel A OECD vs. NOECD economies				
Variable	**OECD**	**OECD**	**NOECD**	**NOECD**
AoGB	0.000		0.102***	
	(0.01)		(7.48)	
NoD		-0.001		0.035***
		(-0.30)		(3.25)
Controls	Y	Y	Y	Y
Country	Y	Y	Y	Y
Year	Y	Y	Y	Y
N	128	128	134	134
Within R^2	0.037	0.038	0.653	0.491
Panel B HIGH vs. NHIGH economies				
Variable	HIGH	HIGH	NHIGH	NHIGH
AoGB	0.000		0.099***	
	(0.06)		(6.70)	
NoD		-0.001		0.036***
		(-0.39)		(3.11)
Controls	Y	Y	Y	Y
Country	Y	Y	Y	Y

Table 8. Continued

Panel B HIGH vs. NHIGH economies				
Year	Y	Y	Y	Y
N	149	149	112	112
Within R^2	0.024	0.026	0.660	0.513

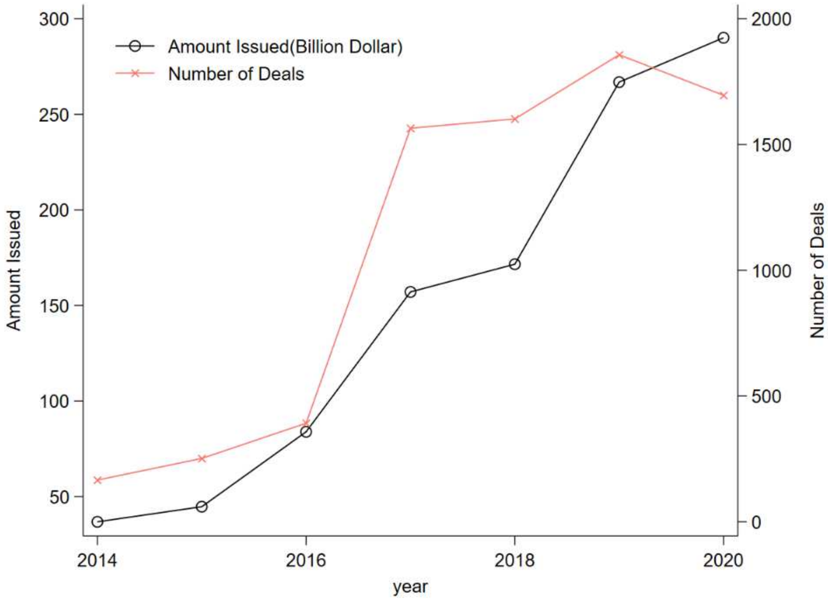
Notes: This table presents the regression results of green finance and renewable energy innovation in several subsamples. *t* statistics are in parentheses. Panel A is relevant for the comparison of OECD economies and non-OECD (NOECD) economies, while Panel B aims to express the difference between high-income (HIGH) economies and non-high-income (NHIGH) economies. We hide these control variables due to limited space, but they are available upon request. Y refers to country (or time) fixed effects that are considered, while N does not. *, **, and *** refer to significance at the 10%, 5%, and 1% levels, respectively.

Table 9. Robustness check

Panel A Dynamic panel model		
L. *RE*	0.897***	0.912***
	(63.09)	(41.92)
AoGB	0.012***	
	(4.73)	
NoD		0.008***
		(4.66)
AR(1)	0.099	0.087
AR(2)	0.183	0.148
Sargan	0.241	0.202
N	196	196
Panel B Tobit model		
AoGB	0.060***	
	(9.53)	
NoD		0.035***
		(7.32)
N	283	283
LR test	270.56***	304.38***
Panel C Cross-sectional dependence		
AoGB	0.038**	
	(3.36)	
NoD		0.021**
		(3.86)
N	283	283
R^2	0.482	0.437

Notes: This table is relevant to robustness tests. *t* statistics are in parentheses. Panel A is the dynamic panel model, where AR denotes the Arrelano-Bond second-order autocorrelation test, and Sargan refers to the Sargan over-identification test. Panel B is the panel tobit model, where the LR test is the Likelihood Ratio test. Panel C aims to deal with cross-sectional dependence with the method of Driscoll and Kraay (1998) who propose the Driscoll-Kraay standard errors. We hide these control variables due to limited space, but they are available upon request. Y refers to country (or time) fixed effects that are considered, while N does not. *, **, and *** refer to significance at the 10%, 5%, and 1% levels, respectively.

Figure 1. The growth of green bonds during the period 2014–2020



Source: the Climate Bond Initiative.