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THE IMPACT OF MONETARY POLICY ON GREEN INNOVATION: GLOBAL EVIDENCE

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Abstract. This research investigates and robustly verifies the impact of expansionary monetary policy actions on green innovation, conducted on a panel covering 133 countries from 1960 to 2018. Overall, we find that such actions have a significantly positive effect on green innovation performance, no matter in the static or dynamic model. A lower degree of central bank independence and poorer property rights protection in developing countries may hinder monetary policies' effect to be transmitted to green innovation activities smoothly. Moreover, stringent environmental regulation contributes to magnifying the expansionary monetary policy's positive effect on green innovation, but such a positive moderating effect should be supported by good national governance quality (including better control over corruption, higher efficiency of governments and a complete law system). Accordingly, several policy suggestions are provided.

Keywords: green innovation, monetary policy, environmental regulation.

JEL Classification: Q55, Q56, P28, E52.

Introduction

Faced with the urgent need for transitioning to a low-carbon society brought about by the restrictions of limited resources and increasingly public environmental requirements (Lv et al., 2021; Zheng et al., 2021), how to achieve green growth has become a crucial concern in academia lately (Hickel & Kallis, 2020). Various measures in recent years have been carried out to shift to the development path of green growth (Chen, 2008; Wen et al., 2021b, 2021c), among which promoting green innovations is playing a key role (Aghion et al., 2009). On the one hand, green innovation helps sustain the economic benefits generated from conventional innovations, while on the other hand, it encourages economic entities to internalize their environment-emission externality (Dai et al., 2021). Green innovation activities thus play

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a significant role in having a better trade-off between economic growth and environment protection (Lv et al., 2021).

Existing literature relevant to the driving force of green innovation can be broadly divided into two branches. The first concerns how to facilitate the development of green innovation from the perspective of firms' internal governance, such as research and development (R&D) collaboration (Marchi, 2012; Liu et al., 2020; Hu et al., 2022; Wang et al., 2022; Zhao et al., 2022; Yang et al., 2022), executive hiring, and corporate operations (Gadenne et al., 2009), while the other pays more attention to the policies (or factors) related to some macro-level environment and institutional factors, likes environmental regulation (Horbach, 2008), trade openness (Fu et al., 2020; Feng et al., 2021; Li & Shao, 2021; Wang et al., 2021; Yang et al., 2022), property rights (Kyle & Qian, 2014), financial market development (Fang et al., 2017), etc. However, there is a huge gap between current investment and what would be needed for a transition to an environmental-friendly economic system (United Nations Framework Convention on Climate Change [UNFCCC], 2010; McCollum et al., 2013), and the extant works may contribute relatively little for a policy-decision maker to draw inspiration to confront financing difficulty in green innovation activities that economic entities are stuck in. Campiglio (2016) points out that a depressed macroeconomic environment and an unattractive risk-return profile are the main obstacles preventing sufficient financial support to be raised for green innovation activities. By conventional wisdom, these two critical factors could have a strong association with the monetary policies. We thus aim to explore monetary policy's potential to alleviate the dilemma of poor green innovation performance and answer a question: Does an expansionary monetary policy promote green innovation?

As an important macroeconomic management tool to influence the workings of an economy (Zhao et al., 2020), most economists agree that monetary policy actions can exert a significant impact on real output at least in the short run, and such a real output effect may sustain for more than two years (Romer & Romer, 1989; Bernanke & Blinder, 1992; Christiano et al., 1996). From the conventional view of the influencing mechanism presented in many textbooks, central banks utilize their gearing with respect to the short-term interest rate in order to impose their control on the cost of capital that then affects spending and investment, leading to changes in aggregate demand and real output. Bernanke and Gertler (1995) lay a more solid foundation for the textbook mechanism by giving a detailed interpretation of the credit market's friction based on the theories of balance sheet channel and bank lending channel. These two channels have been robustly confirmed to be valid even during a financial crisis period (Dahlhaus, 2017). Drechsler et al. (2018) provides a new unified framework that is concerned more about the market power of commercial banks, of which the aim to analyze a monetary policy's outcome cannot be explained by the two friction-related channels just mentioned. In general cases, by initially affecting financial institutions' operations, such as adjusting the overnight rate, QE, and so on, the central bank's impact can be further transmitted through the liquidity premium and risk premium for non-financial entities engaged in production of the real economy, which then change their cost of funding, investment, and consumption decisions and hence have some 'real effect' on economic activities.

From the perspective of Bernanke and Gertler's extended friction-related theory (1997), an expansionary monetary policy may directly strengthen green innovation-related firms' balance sheets straightforwardly in two ways. First, to the extent that green innovation-

related firms have outstanding floating rate (or short-term) liabilities, lowering interest rates decrease interest expenses directly, thus saving net cash flows and strengthening their financial position. Since those green innovation-related firms may heavily count on short-term liabilities to finance their working capital, such an improvement in their financial position can be fairly significant. Second, increasing asset values are also typically associated with lower interest rates, which may raise the evaluation of the green innovation-related firms' collateral. Moreover, an expansionary monetary policy may save net cash flows and raise the evaluation of collateral indirectly through the spillover effect with respect to the linkages among supply chains and sales networks. These direct and indirect strengthening effects on balance sheets contribute to reducing the risk premium and term premium of green innovation-related firms' programs.

Based on Drechsler's market power-based framework (2018), an expansionary monetary policy weakens commercial banks' market power in the credit market, thus facilitating them to absorb more deposits and improving liquidity in the financial sector. Because risky programs' funding needs to be matched to some liquid buffers, the improvement in liquidity lowers the cost of holding liquid buffers that support green innovation activities, which then reduce the risk premium and borrowing cost of green innovation-related firms. Bernanke and Gertler (1995) remind us that a change in the nominal interest rate is not macroeconomic neutral if borrowers are relatively constrained in the economic system or if they do have more investment and spending opportunities than lenders do. The decrease in the interest rate generated by an expansionary monetary policy that creates a redistribution from lenders to borrowers can have an overall positive effect on aggregate demand, which is conducive to raising expectations with respect to the macroeconomic environment.

The above discussion shows that expansionary monetary actions offer contributions to ameliorate the risk premium and a depressed macroeconomic environment, which are the two main factors preventing green innovation activities from sufficient financial support. We thus derive the core hypothesis of our research: expansionary monetary actions promote green innovation performance.

As the world's main growth engine, Asian countries play an increasingly important role in the global economy. Their sustainable-development-pattern transition may significantly affect the global balance between climate change and economic development and therefore has raised extensive concern. Hence, we are further interested in whether the possibility exists for an expansionary monetary policy's impact on facilitating green innovation in Asian developing economies. If it does not, then which factors hinder the impact conduction of the expansionary policy? First, central bank independence (CBI) benefits price stability (Garriga & Rodriguez, 2020), generates additional real purchasing power, and lowers the real cost of finance, playing an important role in monetary policy transmission. Second, stock market development has an enhancing effect on corporate governance and information symmetry (Wang, 2021; Chang et al., 2021), and this effect also influences a number of non-listed economic entities through the requirement of information disclosure with respect to listed companies, thus narrowing the information gap in the economic system and stimulating lending activities. Lastly, another essential element for smooth transmission may be property rights protection. Compared to information asymmetry, a more severe factor hindering credit expansion or even economic growth in some undeveloped countries is the incom-

pleteness of contracts. Property rights protection is fairly essential to the supply of sufficient collateral as it contributes to increased credit access (Aretz et al., 2020) by dealing with the issue of incomplete contracts and therefore plays a crucial role in monetary policy transmission. Compared to Occident countries, the relatively weak performance of CBI, stock market development, and property rights protection in Asian developing economies may do harm to the positive-effect transmission running from an expansionary monetary policy to green innovation activities.

Going a step further, we are also interested in under what circumstances of national governance can an expansionary monetary policy have a facilitating effect on green innovation more effectively. Lv et al. (2021) find that environmental regulations play a significant role in moderating the impact on green innovation that an improvement in finance availability has. Hence, firms or other economic participants under more stringent environmental regulations may have a motivation to reduce their obeyance cost, which increases the potential demand for green innovation in the economic system and helps guide more additional real purchasing power generated from expansionary monetary actions to flow into green innovation-related activities. However, the enactment of a stringent environmental regulation is not adequate enough to force economic participants to internalize their externality of emissions, and hence the regulatory quality of the government, which means the ability of the government to implement sound policies, is essential to stringent environmental regulation execution. More specifically, better corruption control contributes to guaranteeing the additional real purchasing power services for green innovation activities that reduce the abiding cost of environmental regulation, rather than for the bribery and rent seeking that aim to avoid the investment and expenditures toward obeying the rules. A government with higher efficiency, which may bring convenience to transactions with respect to the green sector, can also benefit the implementation of environmental regulations by making green-related trading easy. A more complete law system that has a good quality of regulation enforcement can also cultivate the habit of taking environmental factors into consideration and rendering that the environmental-regulation violator be timely punished, thus asserting the authority of the green-related rules. We thus infer that a stringent level of environmental regulation, the regulatory quality of the government, control of corruption, government efficiency, and completeness of the law system may have a positive moderating effect on the relationship between expansionary monetary policy and green innovation.

Thus far, we have theoretically deduced the positive impact that an expansionary monetary policy has on green innovation, the obstacles that may hinder the conduction of this favorable impact in developing economies, and the national governance factors that may have a significant positive moderating effect on monetary policy – green innovation relationship. For verifying our deduction, we perform a suite of empirical work to provide robust evidence. The empirical work and contribution of this study are briefly summarized as follows.

First, we employ a panel of 133 countries covering the period 1960–2018 and adopt the panel fixed effect model to analyze an expansionary monetary policy's effect on green innovation, through which we derive a basic result that such a policy has a significantly positive impact on green innovation performance. A series of robustness testing, including replacing the proxy of monetary policy and green innovation, adding additional potential omitted con-

trol variables, and employing alternative model specifications, are then conducted to verify our basic result. Moreover, in order to alleviate the potential concern of endogeneity and investigate the dynamic behavior of an expansionary monetary policy's effect on green innovation, we adopt a dynamic panel model specification and then estimate it using the GMM technique – an endogenously insensitive estimation method. We find that the basic result is endogeneity-concern robust, and that an expansionary monetary policy has a dynamically positive effect on green innovation, which runs in line with the static model. Second, by performing a set of sub-group estimation, we substantiate our theoretical inference that the weak performance of CBI and property rights protection in Asian developing economies hinders the conduction of expansionary monetary policies' positive impact on green innovation. Third and finally, by adding some relevant institutional proxies and their interaction term with the monetary policy's measurement in a re-estimated model respectively, we empirically confirm our theoretical inference of the moderating effect of national governance factors, that is, stringent environmental regulations supported by the high regulatory quality of the government (high government efficiency and good control of corruption) and a complete law system, can positively moderate and magnify the promoting effect on green innovation.

To our best knowledge, there is very little empirical literature that has focused on the potential of a central bank in facilitating sustainable development while this study may provide the first investigation in this field. Moreover, seldom research before has directly placed attention to the funding dilemma of green innovation activities, and our analysis of the monetary policy – green innovation relationship contributes to drawing policy inspiration that may help alleviate the financing predicament. Lastly, we offer additional evidence for the "real effect" in a relatively long period of monetary policy action and provide a reminder that aside from being independent during the decision-making procedure, the management of a central bank may have the reason to consider the factors that benefit sustainable growth in the long term.

The rest of this paper is presented as follows. Section 1 introduces the data and empirical specification. Section 2 provides empirical results, including basic results and robustness tests. The last Section concludes this study and proposes several policy inspirations.

1. Data and empirical specification

1.1. Data

Panel data enlarge the volume of a sample, therefore alleviating collinearity, enhancing the external validity of econometric model estimation, and enabling us to control the unobservable individual effect and capture the dynamic behavior in terms of economic relationship. Hence, we employ a (unbalanced) panel of 133 countries covering the period 1960–2018, to investigate monetary policy actions' impact on green innovation[1]. Table 1 presents the definitions of the variables adopted in this research.

[1] We thank Xi-Li Lin, our research assistant from School of Economics and Finance, Xi'an Jiaotong University, for her work on data collation and part of our empirical strategy design.

Table 1. Variable descriptions and sources

Variable	Description	Source
GI	Total number of environmental-related-technology patent applications	OECD Statistics
Broad Money	Sum of narrow money and other assets that can be easily converted into cash to buy goods and services	WDI
Reserve Money	Total amount of currency in circulation, bankers' and others deposits with the central bank	WDI
GDP	GDP per capita (constant 2010 US$)	WDI
Industry	Proportion of manufacturing industry to GDP	WDI
POP	Country-level population size	WDI
GCF	Gross capital formation (% of GDP)	WDI
Openness	Total export-import volume divided by GDP	WDI
Gov	General government final consumption expenditure (% of GDP)	WDI

Note: WDI is the abbreviation for World Development Indicators.

(1) Dependent variables

Griliches (1990) proposes that the number of patent applications is an effective proxy to measure the innovation performance of a country. Furthermore, the information of patents is recorded systematically in most countries of the world and thus provides a good measurement for country-level innovation activities (Wen et al., 2021a; Wen et al., 2022a, 2022b; Yin et al., 2022). Therefore, following Cai et al. (2020) and Hu et al. (2021), we adopt *GI*, the total number of environmental-related technology patent applications in each country (documented in OECD statistics), as the proxy of green innovation. The two main components of green innovation, *GI_EM* (environmental management patents) and *GI_CCM* (climate-change-mitigation patents), are employed for robustness tests.

(2) Independent variables

In the past 25 years, several influential research studies have placed emphasis on the interest rate when evaluating monetary policies. Nevertheless, Belongia and Ireland (2015) point out the QE policy raised by some countries' central banks appears to deviate from this standard practice. They suggest that movements in the (properly measured) monetary aggregate is essential for identifying monetary policy shocks. Hence, inspired by Zhao et al. (2020) and Boschen and Mills (1995), we adopt *Broad money* and *Reserve money* as the core proxies of monetary policy actions in this study and employ *Lending rate* (for the private sector) and *Treasury bill rate* as alternative measurements for a robustness test. All the mentioned monetary policy measurements are obtained from World Development Indicator Database.

(3) Control variables

We follow the extant green innovation literature and control for a number of country-level features in our investigation of monetary policies' impact on green innovation activities[2]. Our

[2] Detailed definitions of variables are listed in Table 1.

first control variable is per capita GDP (*GDP*) to take into account the probability that better economic development usually raises more resources to support green innovation (Lv et al., 2021). Industrial structure (*Industry*), a measurement for capturing the industrial structure of a country, is important to be controlled for its potential positive effect when examining green innovation performance (Lv et al., 2021). Following Wen and Zheng (2020) and Zheng et al. (2020), we include population size (*POP*) to account for the potential that a larger population is associated with a greater mass of labor, thus helping to stimulate innovation-related activities. We also add *Openness* to control the influence of green innovation-relevant factors brought by foreign trade (Lv et al., 2021) and further incorporate *GCF* (gross fixed capital formation) and *Gov* (fiscal expenditures) to control for their substitution effects on the driving economic development of green innovation (Brunnermeier & Cohen, 2003; Lv et al., 2021).

1.2. Baseline specification

We adopt the panel fixed-effect model as our baseline specification to investigate monetary policy actions' impact on green innovation. The country-specific and time-specific fixed effects in this specification contribute to controlling the estimation bias brought by some unobservable or immeasurable country-level characteristics and policy shocks other than monetary policy actions. In order to alleviate the inefficiency result of the estimation generated by extreme values and heteroscedasticity, most variables (except those in units of percentage) take a non-negative transformation and transform into a natural logarithm. The baseline specification of the panel fixed-effect model in this research is then set as follows:

$$GI_{it} = \alpha M_{it} + \beta' X_{it} + \mu_i + \mu_t + \varepsilon_{it}, \quad (1)$$

where *GI* represents the number of green patents applied; *M* denotes core explanatory variables – *Broad money* and *Reserve money*, measuring the monetary policy actions; *X* is a vector of control variables, including *GDP*, *Industry*, *Population*, *Openness*, *GCF*, and *Gov*, whose definitions are introduced in the previous subsection; μ_i and μ_t represent country-specific and time-specific fixed effects, respectively; ε_{it} is the error term; and the subscripts *i* and *t* refer to country and year, respectively.

2. Results

From the descriptive statistics in Table 2, among the variables used in our basic analysis we find that the mean of *GI* is close to 1.219, while the standard deviation of *GI* is 1.984, implying that there exist huge differences in the green innovation performance among different countries in the world. The mean value of *Broad money* is 24.743, and its standard deviation is 4.791, indicating that there is a disparity of monetary policy action among countries in our sample; for *Reserve money*, the minimum, maximum, mean, and median values are respectively – (–10.434), 35.094, 23.258, and 23.737. To save space, we do not describe statistical information of other control variables here.

Table 2. Summary statistics

Variable	N	Mean	SD	Min	Median	Max
GI	5124	1.219	1.984	0.000	0.000	9.791
Broad Money	5124	24.743	4.791	–8.279	25.146	37.015
Reserve Money	4663	23.258	5.047	–10.434	23.737	35.094
GDP	5124	0.829	1.391	0.020	0.294	9.196
Industry	5124	2.734	1.161	0.324	2.559	8.780
POP	5124	15.926	1.773	11.010	15.921	21.055
GCF	5124	0.023	0.009	–0.013	0.022	0.089
Openness	5124	7.464	4.986	0.020	6.423	44.262
Gov	5124	14.916	6.118	0.911	14.052	62.133

2.1. Basic results

Table 3 displays regressions of green innovation on the proxy of monetary policy actions and control variables by employing the fixed-effect approach (with robust t statistic). The core explanatory variable of columns (1)–(3) is *Broad money* and that of columns (4)–(6) is *Reserve money*, and the dependent variable is *GI* in all six columns. *Broad money* or *Reserve money* enters positively and significantly at the 1% level in the model listed in columns (1)–(6). In columns (1) and (3), we only control for the fixed effects of country and time, which turn out to have a statistically and economically significant impact on green innovation as expected. Columns (2) and (4) include *GDP*, *Industry*, and *POP* to take the potential influences of economic development, industrial structure, and population size on green innovation into consideration. Columns (3) and (6) incorporate *GCF*, *Openness*, and *Gov* to capture the impacts of fixed capital formulation, trade openness, and fiscal expenditures. The control-variable results show that economic development and trade openness do have a positive and significant association with the performance of green innovation, while industrial structure may not really matter. Overall, the results of Table 3 reveal that expansionary monetary policy actions have a significantly positive impact on green innovation performance, thus supporting our core hypothesis theoretically derived in the introduction.

2.2. Robustness test

For the concern over whether the basic results vary across specific proxies or potential omitted variables, several robustness tests are conducted as follows.

Columns (1)–(4) in Table 4 display regressions of green innovation performance on Broad money and Reserve money, replacing *GI* with alternative green innovation indicators. While our baseline estimates focus on the role of expansionary monetary actions at increasing the number of environmental-related technology patent applications (*GI*), we here turn to their impacts on the number of environmental management patents (*GI_EM*) and climate change mitigation patents (*GI_CCM*), which are the two main components of green innovation. We find that Broad money and Reserve money remain positive and significant

Table 3. Baseline regression

	(1) GI	(2) GI	(3) GI	(4) GI	(5) GI	(6) GI
Broad Money	0.040***	0.065***	0.065***			
	(7.64)	(10.96)	(10.62)			
Reserve Money				0.025***	0.050***	0.046***
				(5.00)	(8.90)	(8.02)
GDP		0.442***	0.589***		0.446***	0.581***
		(8.06)	(12.15)		(8.50)	(12.00)
Industry		–0.037*	–0.015		–0.046**	–0.016
		(–1.80)	(–0.62)		(–2.17)	(–0.65)
POP		–0.170	–0.702***		0.021	–0.480***
		(–1.58)	(–5.62)		(0.18)	(–3.55)
GCF			–0.479			0.685
			(–0.28)			(0.38)
Openness			0.032***			0.025***
			(5.05)			(4.02)
Gov			0.012***			0.020***
			(4.27)			(6.51)
Country	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	7461	5894	5124	6861	5417	4663
Adj-R^2	0.844	0.861	0.876	0.850	0.863	0.877

Notes: Regressions are estimated using OLS. Robust t statistics are in parentheses for the coefficients' statistical inference. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

Table 4. Alternative innovation proxies and explanatory variables

	(1) GI_EM	(2) GI _CCM	(3) GI_EM	(4) GI _CCM	(5) GI	(6) GI
Broad Money	0.065***	0.053***				
	(11.51)	(9.19)				
Reserve Money			0.048***	0.037***		
			(9.08)	(6.71)		
Lending rate					–0.001**	
					(–2.37)	
Treasury bill rate						–0.004**
						(-2.12)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	5124	5124	4663	4663	3008	1575

Notes: Same as Table 3.

when all control variables are added. In columns (5) and (6), the proxy of green innovation (*GI*) remains unchanged, but we replace the core explanatory variables from the quantity measurement of monetary policy actions (*Broad money* and *Reserve money*) with the price measurement (*Lending rate* and *Treasury bill rate*). *Broad money*'s (*Lending rate*'s) and *Reserve money*'s (*Treasury bill rate*'s) significantly positive (negative) coefficients appear in Table 4, indicating a conclusion that the basic result is not sensitive to monetary policy or green innovation measurements.

According to Al Mamun et al. (2018), Sun et al. (2019), Wang et al. (2021, 2022), foreign direct investment, educational attainment, stock market development, and economic institutional quality are also likely to affect the green innovation performance of an economy. Overlooking their influence may raise the concern that our basic conclusion derived above is sensitive to a specific set of control variables. To deal with this issue of the potential omitted variables, we move on to control *FDI* (the ratio of foreign direct investment to gross domestic product), *Education* (the gross secondary school enrollment rate), *MCP* (the proportion of market capitalization of a listed company to gross domestic product), and *INS* (institutional quality measured by economic freedom index) in a re-estimated model. Table 5 presents the result, in which the coefficients of *Broad money* in columns (1)–(3) and that of *Reserve money* in columns (4)–(6) are positive at the 5% level, indicating that the basic results of Table 3 are robust after accounting for the possibly omitted variables.

Table 5. Additional control variables

	(1) GI	(2) GI	(3) GI	(4) GI	(5) GI	(6) GI
Broad Money	0.071*	0.496***	0.230**			
	(1.92)	(6.75)	(2.25)			
Reserve Money				0.065**	0.394***	0.187***
				(2.06)	(6.39)	(2.61)
Additional CVs						
FDI	−1.318***	−0.438	−0.046	−1.277***	−0.416	−0.043
	(−4.68)	(−1.34)	(−0.15)	(−4.53)	(−1.19)	(−0.14)
Education	2.548***	−0.174	0.861	2.606***	−0.001	0.947
	(5.28)	(−0.28)	(1.34)	(5.42)	(−0.00)	(1.39)
MCP		−0.548	−0.735*		−0.541	−0.748*
		(−1.44)	(−1.91)		(−1.27)	(−1.76)
INS			−0.302			−0.387
			(−0.48)			(−0.62)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	1610	700	582	1515	679	572

Notes: Same as Table 3.

2.3. Alternative model specification

(1) Concern for the inconsistent variance

Provided that the change in monetary policy actions is exogenous after controlling the covariates added and (country and year) fixed effects, the estimator derived in 3.1 and 3.2 should be consistent with the true causality influence on green innovation that the expansionary monetary policy actions have. However, the robust t used to test the significance of such a causality effect may still be invalid, because of overlooking cross-sectional dependence. To obtain a consistent estimation of the variance-covariance matrix for the estimated coefficients' vector in the baseline regression so that the evaluation of statistical significance in terms of an expansionary monetary policy's promoting effect on green innovation can be more precise, we first re-estimate the baseline regression using FGLS (feasible generalized least square) estimators that take a normalizing transformation on the variables used to fit the model before OLS estimation. This can meet the assumption of classical linear regression and alleviate the potential impact aroused by cross-sectional dependence. While FGLS is a relative efficient method to deal with the issue of cross-sectional dependence, we also adopt a more robust approach, the PCSE (panel-corrected standard error) estimator, allowing for groupwise heteroscedasticity and cross-sectional correlation to verify the basic result again. Moreover, since the FGLS or PCSE estimators do not account for non-contemporaneous dependence of different data cross-sections, we then employ the DK (Driscoll & Kraay, 1998) estimator that adopts a non-parametric method to obtain a consistent variance to further confirm the validity of our basic result.

Table 6 displays the regression results of green innovation performance on Broad money and Reserve money using these alternative model specifications. Concretely, FGLS is listed in columns (1)–(2), PCSE in columns (3)–(4), and DK in columns (5)-(6). We note that Broad money or Reserve money remains significantly positive at the 1% level in all the columns, verifying again the earlier findings in Table 3 that an expansionary monetary policy on average spurs more green innovation output.

Table 6. Alternative estimators

	(1) GLS GI	(2) GLS GI	(3) PCSE GI	(4) PCSE GI	(5) DK GI	(6) DK GI
Broad Money	0.047***		0.061***		0.065***	
	(6.05)		(6.76)		(5.91)	
Reserve Money		0.029***		0.054***		0.046***
		(4.55)		(6.13)		(4.50)
CVs	Yes	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	1504	1504	1504	1504	5124	4663

Notes: Robust t statistics taking cross-sectional dependence into consideration are in parentheses for the coefficients' statistical inference. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

(2) Concern for the inconsistent estimator and dynamic behavior investigation

The robustness of the basic result, which is derived from the baseline regression and verified by the above tests, relies heavily on the exogeneity of monetary policy actions when controlling the other covariates. The panel fixed-effect estimation employed in 3.1 and the extended model displayed in 3.2 with additional control variables may partly address endogenous bias due to omitted variables, while the potential existence of measurement error (Broad money or Reserve money may not fully capture the movement of monetary policy that leaves part of it in the error term) and reverse causality (green innovation performance may affect some economic variables, like employment, that are strongly associated with the target set by some central banks) may still confuse the validity of our basic result. Taking into account both the difficulty of finding a desired instrumental variable for monetary policy actions in 133 countries and the ambition to investigate the dynamic behavior of the relationship between monetary policy and green innovation, we estimate a dynamic panel model with a lagged term of GI by using two kinds of generalized method of moments (difference GMM and system GMM) technique respectively, which serve for a more consistent estimation asymptotically. These two GMM estimators use a set of lagged variables (the collapsed-style instrumental variables) as exogenous components to identify the explanatory vector, among which difference GMM (DIF-GMM) utilizes the specification of the difference equation to control unobservable country-level features (Arellano & Bond, 1991), while system GMM (SYS-GMM) includes information with respect to the level equation so as to address the concern of a weak instrument by DIF-GMM (Arellano & Bover, 1995; Blundell & Bond, 1998).

Columns (1)–(4) of Table 7 present the estimation results. The p-values of the Hansen J statistic and AR (2) statistic for all the four models are well above 0.1, indicating that at the 10% level we do not reject the reasonableness of GMM specification. The estimated impacts of expansionary monetary policy actions (Reserve money's and Broad money's coefficients) on green innovation performance (GI) derived from all four models are significantly positive at the 5% level, which is consistent to our basic results shown in 3.1. The coefficients of the lagged term of GI listed in the four columns are significantly positive at the 5% level as well, among which the SYS-GMM's coefficients are fairly close to 0.2, indicating that the impact on green innovation performance that the expansionary monetary policy has is not merely a static stimulating effect, but rather a dynamic impetus that does not converge to zero for more than two years, which is consistent to the previous finding that the impact of monetary policy actions on real output-related variables lasts for two years or more (Romer & Romer, 1989). This significant dynamic effect also may provide evidence for the "financial accelerator" supported by Bernanke et al. (1996) and Benedictow and Hammersland (2020) – that is, expansionary monetary policy actions improve the financial position of green innovation-related firms and other relevant participants, and such an improvement effect can be propagated and magnified through the linkages of balance sheets among various economic entities, which then significantly reduce the risk premium (or external finance premium), thus having an persistently positive impact on green innovation over time by lowering the cost of funding in the next few years sustainably.

Table 7. Dynamic model and endogeneity alleviation

	(1)	(2)	(3)	(4)
	DIF-GMM		SYS-GMM	
	GI	GI	GI	GI
L. GI	0.123**	0.124*	0.185**	0.195**
	(2.02)	(1.77)	(2.56)	(2.37)
Broad Money	0.269**		0.242**	
	(2.49)		(2.42)	
Reserve Money		0.152**		0.205**
		(2.42)		(2.12)
CVs	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
AR(2)	0.118	0.220	0.470	0.935
Hansen	0.282	0.765	0.921	0.585
N	4938	4486	5106	4646

Notes: Same as Table 3.

2.4. Heterogeneity analysis

Due to its prominent role in the global economic recovery, the advancement in Asian developing economies has drawn increasing attention in recent decades. Their course in shifting the growth path from an energy-extensive mode to an environmental-friendly pattern may considerably impact the evolution of global climate change. Naturally, on the basis of the previous general-case analysis that confirms the positive causal relationship between monetary policy and green innovation, we are further interested in the potential of an expansionary monetary to enhance green innovation performance in Asian developing economies.

We first conduct a subsample test that re-estimates the baseline regression in the subsample of Asia developing countries, Asian countries, and Occident countries, respectively[3]. The results presented in Panel A of Table 8 show that an expansionary monetary policy promotes green innovation performance in both the cases of Asian countries (columns (2) and (5)) and Occident countries (columns (3) and (6)), while the positive impact's economic significance is relatively weak in the Asian subsample. Moreover, noticing the insignificant result of Asian developing countries' subsample listed in columns (1) and (3), we can infer that such a difference is mainly due to the block of monetary policy transmission in the developing economies of Aisa[4].

[3] The subsample of Asian countries contains samples from both developing and developed economies in Asia.

[4] An augmented Hausman test (based on seemingly unrelated regression, SUR) indicates that a loose monetary policy's positive effect on Occident countries is significantly higher than that in Asian developing countries at the 1% level.

Table 8. Heterogeneity analysis of monetary policy transmission

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A:						
Basis for Grouping	Asian developing countries	Asian countries	Occident countries	Asian developing countries	Asian countries	Occident countries
Broad Money	0.006	0.076***	0.116***			
	(0.35)	(3.59)	(4.00)			
Reserve Money				0.011	0.050*	0.088***
				(0.65)	(2.50)	(3.77)
N	1108	1495	1192	1005	1391	1178

	(1)	(2)	(3)	(4)
Panel B:				
Basis for Grouping	Central bank independence Low	Central bank independence High	Central bank independence Low	Central bank independence High
Broad Money	0.018	0.054***		
	(1.37)	(4.92)		
Reserve Money			0.011	0.038***
			(0.87)	(3.92)
N	1850	1648	1827	1355
Panel C:				
Basis for Grouping	Stock market development Low	Stock market development High	Stock market development Low	Stock market development High
Broad Money	0.018	0.379***		
	(0.54)	(4.64)		
Reserve Money			–0.018	0.178*
			(–0.63)	(2.35)
N	988	466	929	464
Panel D:				
Basis for Grouping	Property rights protection Low	Property rights protection High	Property rights protection Low	Property rights protection High
Broad Money	–0.041	0.319***		
	(–1.35)	(5.88)		
Reserve Money			–0.010	0.259***
			(–0.50)	(5.36)
N	1571	1035	1423	1018
CVs	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes

Notes: Same as Table 3.

In the Introduction section, we have theoretically deduced that the relatively poor performances of CBI, stock market development, and property rights protection may hinder the transmission of the positive effect running from an expansionary monetary policy action to green innovation in Asian developing economies. To verify their impediment effect on

monetary policies' conduction, we split the sample into high and low groups by the levels of the three key factors respectively and re-estimate the baseline regression model[5]. The results of these subsample tests appear in Panels B, C, and D of Table 8, revealing in those economies with higher degrees of CBI, a properly developed stock market, and better property rights protection that expansionary monetary policy actions have a more significantly positive impact on green innovation activities, which means CBI, stock market development, and property rights play vital roles in the transmission of monetary policies.

We then perform univariate t tests with respect to the differences of the three key factors' mean values between developing countries in Asia and Occident countries respectively and find that compared to Occident countries, Asian developing countries are associated with significantly weaker performance in CBI and property rights protection (at the 1% level), but shows no significant difference in stock market development. Hence, combining the results of subsample-heterogeneity analysis and univariate t tests, we partially confirm our theoretical deduction: the weak performances of CBI and property rights protection, rather than an undeveloped stock market, hamper the transmission of the positive effect running from an expansionary monetary policy action to green innovation in Asian developing economies.

2.5. Moderating effect analysis

The above heterogeneity analysis surrounding developing economies in Aisa has concurrently verified the crucial factors of transmitting a monetary policy action's impact to green innovation activities. Going a step further, we are interested in the moderating role of national governance of the monetary policy-green innovation nexus. In other words, we explore the potential of several kinds of national governance quality in magnifying expansionary monetary policies' benefit on green innovation.

According to Lv et al. (2021), stringent environmental regulations may positively moderate the impact on green innovation that the increase of finance availability has, as such regulations may motivate firms to cut down on their rule-obeying cost, which spurs the potential demand for green innovation and directs more additional real purchasing power brought by expansionary monetary actions towards green innovation activities. We thus employ *EPS* (environment protection stringency score published by OECD Statistics) and its interaction term with the proxy of monetary policy actions (*Broad money* or *Reserve money*) to investigate the moderating effect of stringent environmental regulations on the positive relationship between expansionary monetary policy and green innovation. *EPS*'s interaction terms of both *Broad money* (column (1) of Panel A in Table 9) and *Reserve money* (column (1) of Panel B in Table 9) are reported to be positively significant at the 1% level, confirming the speculation that environmental regulations play the role as a positive moderator, which amplifies an expansionary monetary policy action's positive impact on green innovation activities.

[5] Following the practices in previous literature, central bank transparency and independence index (Dincer & Eichengreen, 2013; Long et al., 2022), market capitalization of listed domestic companies (Zeqiraj et al., 2020), and the score of property rights protection in the Index of Economic Freedom are adopted as the measurements for the three key factors – central bank independence (covering the time span 1970–2012), stock market, and property rights protection.

Table 9. Moderating effect analysis of environmental regulation

Panel A:					
	(1) GI	(2) GI	(3) GI	(4) GI	(5) GI
Broad Money	0.369***	0.142***	0.090***	0.136***	0.118***
	(9.36)	(4.39)	(2.74)	(4.63)	(3.56)
*Broad Money*EPS*	0.040***				
	(3.76)				
*Broad Money*RQ*		0.080***			
		(6.43)			
*Broad Money*CC*			0.037***		
			(2.73)		
Broad Money GE*				0.111***	
				(8.32)	
Broad Money RL*					0.064***
					(4.43)
N	469	2558	2562	2558	2563
Panel B:					
	(1) GI	(2) GI	(3) GI	(4) GI	(5) GI
Reserve Money	0.351***	0.076***	0.041*	0.070***	0.062**
	(9.23)	(3.14)	(1.74)	(3.05)	(2.49)
*Reserve Money*EPS*	0.027***				
	(2.87)				
*Reserve Money*RQ*		0.065***			
		(5.69)			
*Reserve Money*CC*			0.030**		
			(2.47)		
*Reserve Money*GE*				0.080***	
				(6.60)	
*Reserve Money*RL*					0.052***
					(4.02)
N	469	2381	2382	2381	2383
CVs	Yes	Yes	Yes	Yes	Yes
Country	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes

Notes: Same as Table 3.

Most of the governments of the economies in our sample with stringent environmental regulations may have the corresponding implementation capacity. However, the promulgation of environmental regulation, especially in developing economies, may not be adequate to force firms and other economic participants to consider the social cost of emissions self-consciously. Its successful implementation needs to be supported by the good governance

quality of a government. To verify the importance of national governance for environmental regulations' positive moderating role on the monetary policy-green innovation linkage, we conduct additional interaction term analyses (similar with those of *EPS*) for four kinds of national governance quality: the government's regulatory quality (*RQ*), control of corruption (*CC*), government efficiency (*GE*), and rule of law (*RL*) successively[6]. Columns (2)–(5) of Panel A present the results where monetary policy actions are proxied by *Broad money*. All the four governance indicators' cross terms (that interact with *Broad money*) are significantly positive at the 5% level. Columns (2)–(5) of Panel B where monetary policy actions are proxied by *Reserve money* also report the same (qualitative) results. The four national governance indicators' positively moderating effect indicates that, when promulgating some stringent environmental regulations that aim to magnify expansionary monetary policy actions' positive impact on green innovation, there should be better control over corruption that prevents additional finance resources generated by a loose monetary policy from bribery, and governments' greater efficiency can lessen the transaction cost relevant to the green sector, which contributes to the execution of the enacted green rules. A complete law system that punishes violating behaviors in time is also important for the effectiveness of stringent environmental regulation.

Conclusions

In this research, we first employ a robust investigation and find that an expansionary monetary policy action enhances green innovation. Moreover, through a sub-group heterogeneity analysis surrounding Aisa, the main growth engine of the world, we figure out the crucial factors that may hinder transmitting expansionary monetary policies' positive effect to green innovation activities. Furthermore, by conducting an interaction term analysis, we further investigate the role of environmental regulations in magnifying the positive impact that an expansionary monetary policy has on green innovation, and probe the importance of various kinds of national governance quality for this magnifying effect.

Our research may provide the first empirical investigation concerning the linkage between monetary policies and green economic activities, implying the importance of central bank actions for shifting the growth pattern to an environmental-friendly one, and hence could lure further studies for a central bank's potential toward supporting sustainable development. Moreover, previous empirical works have seldom directly been concerned with how to alleviate the funding difficulties in green innovation activities, and this research confirms that an expansionary monetary policy contributes to doing so. Furthermore, our work, especially the dynamic behavior investigation of the monetary policy-green innovation nexus, offers additional evidence for the non-neutrality of monetary policy actions, providing a reminder that the change in currency supply should not just be regarded as a veil of the real economy since it does affect economic activities for a long time.

From the empirical analysis results of our research, we propose several policy suggestions for economies seeking green growth. First, expansionary monetary policy actions can lower the risk premium and raise expectations in the macroeconomic environment, encouraging credit to flow into green-innovation-related firms and stimulating green innovation

[6] *RQ*, *CC*, *GE*, and *RL* are the country-level governance indicators extracted in World Bank Open Data.

performance, for which the accumulative effect can be amplified and propagated over time. Second, some factors affecting monetary policy transmission, especially central bank independence (which benefits stable inflation expectations) and property rights protection (which guarantees sufficient collateral during credit expansion) on which developing countries have weaker performance, play important roles for monetary policies' impact on green innovation activities. Thus, we note that improvement in central bank independence and property rights protection will benefit the transmission of an expansionary monetary policy's promoting effect on green innovation activities. Third, stringent environmental regulation contributes to guiding additional real purchasing power brought by an expansionary monetary policy into green innovation activities, but the validity of the regulation requires matched enforcement capacity that seems to be relatively insufficient in developing countries, rather than merely the enaction of some law. Most countries with more stringent environmental regulations do have implementation ability, but for the authorities of developing countries, the introduction of stringent environmental regulation does not automatically generate its executive enforcement. Moderating analysis in our research implies that a favorable implementation of environmental regulation that magnifies an expansionary monetary policy's effect on green innovation may be supported by a complete law system and high regulatory quality (control of corruption and government efficiency). Compared to Occident countries, developing countries have weaker performance in these regulation-supporting conditions, implying that improvement in the control of corruption, government efficiency, and law system will help magnify an expansionary monetary policy's impact on green innovation performance in developing countries. Lastly, even though the authority of a developing country may already have the enforcement capacity for stringent environmental regulation, it should take the opportunity cost into consideration in terms of guiding more resource flow into green-innovation-related firms rather than other economic sectors when selecting the level of regulation and enforcement. A cost-benefit or even general equilibrium analysis may be necessary to formulate a shifting agenda onto the path of green growth.

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