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Can CDM projects trigger host countries' innovation in renewable energy? Evidence of firm-level dataset from China

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ABSTRACT

The goal of the Clean Development Mechanism (CDM) is both emission reduction and sustainable development, in this process, whether the host country's own technological innovation can be promoted should be an important part of the post assessment of CDM projects. This paper examines whether the CDM projects accumulated at the province level are positively correlated with Chinese firms' innovation in technological fields associated with renewable energy and energy efficiency. We assemble a unique firm-level dataset with both firms' patent innovation in renewable energy and CDM projects accounted for. We obtain some novel findings. CDM projects have contributed to the firm-level innovation in renewable energy and energy efficiency. The heterogeneity is detected. This positive enhancement effect is pronounced in invention patents, but is muted in utility patents. The induced innovation effect varies across industrial energy intensity. The more energy intensive the industry, the larger impacts the firms could absorb from the CDM projects. When inspecting CDM by specific energy type, the type-specific induced innovation effect is only documented for biofuel-related CDM projects, indicating that firm-level innovation in biofuels appears to benefit from the related CDM projects within the same province. Lastly, we do find some regional spillover effects in which the CDM projects accumulated at the province level have positive impacts on renewable energy innovation of the non-CDM firms.

1. Introduction

Technology plays a key role in promoting sustainable development and striving for a low-carbon future. According to the Fifth IPCC report, global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate. The system transitions consistent with adapting to and limiting global warming to 1.5°C include the widespread adoption of new and possibly disruptive technologies and practices and enhanced climate-driven innovation (IPCC, 2018). Technology advances in renewable energy, energy-efficient technologies or carbon dioxide removals (CDR) are undoubtedly at the forefront of the global agenda in combating climate change impact.

It is acknowledged that technological change is a complex process which normally proceeds through three stages: invention, innovation and diffusion. At each stage, incentives in the form of prices or regulations will affect the development and adoption of new technologies (Popp, 2011). The United Nations Framework Convention on Climate Change (UNFCCC), being the first global treaty addressing climate change, has strived for decades to call for greater cooperation among all nations to technology development and transfer. There have been three types of catalyst employed by the UNFCCC to facilitate climate technology transfer: (i) institutions, namely the Expert Group of Technology Transfer; (ii) information-sharing, through the Access and Benefit-sharing Clearing-house; and (iii) financial vehicles, including the Global Environment Facility and the CDM (Pueyo et al., 2012; Zhang et al., 2019). Paragraph 5 of Article 4 "Commitments" of the UNFCCC clearly states that developed country Parties shall take a number of practical steps to promote and facilitate the transfer of environmentally sound technologies to developing country Parties, and support the development and enhancement of endogenous capacities and technologies of developing country Parties in order to facilitate the technologies transfer.

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Through CDM projects, EU Emission Trading Scheme (ETS) can provide incentives and motivations for R&D and investment in mitigation technologies, which will directly drive the development of clean energy industry and indirectly promote the innovation of other industries in the host country(Sun et al., 2019). Based on the EU ETS, the CDM, a market-oriented policy, is by far the most important international financial mechanism for facilitating technology transfer to developing countries. As of 31 December 2018, the CDM has spurred registration of 7,806 projects in the pipeline, which are expected to be credited with more than 7.7 billion tons of CO_2 emissions reductions to the end of 2020 (UNFCCC, 2018a).

Although the CDM does not have a mandate, it can facilitate technology transfer by financing carbon emissions reduction projects using technologies not available in the host country. By stimulating the demand for technologies, the CDM provides incentives like demand-pull policies (Nemet, 2009). A growing body of literature has sought to study technology transfer within the CDM by examining project documentation (Dechezleprêtre et al., 2009, 2008; Gandenberger et al., 2016; Haites et al., 2006; Murphy et al., 2015; Seres et al., 2009). Although the sample size varies in these studies, they usually documented a high proportion of the CDM projects that claim to involve technology transfer. It is worth noting that caution is required to interpret the claims on technology transfer within the CDM documentation as it is not possible ex-ante to know whether projects will actually deliver technology transfer, or what their impact will be on technological capabilities in recipient firms(Watson et al., 2015). In spite of this, the CDM as an information platform may also have indirect impacts on firms, even they are not directly involved in any CDM project. As pointed in UNFCCC (2018b), the CDM's methodologies, standards and infrastructure are accessible to all, and have amplified climate action in ways that remain unquantified.

Another indicator of innovation and technology transfer is patent. Patent data focus on outputs of the innovation process(Griliches, 1990) and can be disaggregated into specific technological areas (Dechezleprêtre et al., 2011). In recent years, there has been an increasing number of empirical studies using patent data to analyze innovation and international technology transfer, particularly in the environmental fields (Calel and Dechezleprêtre, 2016; Dechezleprêtre et al., 2013, 2011; Johnstone et al., 2010; Popp, 2003; Soltmann et al., 2014). Most of these studies have a focus on the role of a national or regional policy in promoting technological change, e.g., the Clean Air Act, the EU ETS or a comprehensive measure of policy stringency. Relatively few studies have paid attention to technology transfer. There is scant attention on CDM by using patent data. One exception is Haščič and Johnstone (2011), which used patent application data in the field of wind power generation from over 100 countries during the period 1998–2008 and found that the direct contemporaneous effect of the CDM has had a positive impact on the extent of the transfer.

As far as China is concerned, the role of CDM in promoting renewable energy is very obvious. On July 1, 2004, the Chinese government promulgated the "Interim Measures for the Operation and Management of Clean Development Mechanism Projects", which promoted the rapid development of CDM projects. According to the BP Statistical Review of World Energy, in 2004 China renewable energy output was 3.88 KWh, accounting for 1.2% of the world' total. In 2018, the output was 634.22 KWh, with a proportion of 25.57%, which has increased by 165 times in 14 years. Therefore, the massive introduction of CDM projects has greatly promoted the development of China's renewable energy industry.

China is by far the major host country in the CDM, accommodating approximately 48 percent of the total projects to date (UNFCCC, 2018a). According to the China CDM Database, China has approved 5074 projects as of 13 August 2016, and 3807 of them have been registered by the CDM Executive Board. Not surprisingly, a lion's share of investment under the CDM went to the projects located in China. It has been noted that the CDM has played a strategically important role upon China's technology development (Watson et al., 2015). The guidelines for CDM projects clearly stated that "CDM project activities should promote the transfer of environmentally sound technology to China". As pointed out in Haščič and Johnstone (2011), involvement in the CDM is likely to have an influence on absorptive capacity, at least for those countries that see it as an opportunity to gain access to advanced technologies.

The CDM project facilitates the technology transfer of, but it does not necessarily trigger technological innovation in the host country, especially endogenous technological innovation at the enterprise level. The literature indicates that to achieve these developing countries require assistance with developing human capacity (knowledge, techniques and management skills), developing appropriate institutions and networks, and with acquiring and adapting specific hardware. Technology transfer, in particular from developed countries to developing countries, must therefore operate on a broad front covering these software and hardware challenges, and ideally within a framework of helping to find new sustainable paths for economies as a whole (Dechezleprêtre et al., 2008; Liao and Shi, 2018; Murphy et al., 2015; Popp, 2011). To measure the success of CDM projects, we must not only look at the emission reductions, but also the impact of CDM projects on the sustainable development of host countries, especially the endogenous low-carbon technology innovation capabilities. It is thus of great interest to empirically examine whether the CDM leverages innovation in the low-carbon technologies in China.

This paper seeks to examine the impacts of the CDM initiated in China on firm-level innovation in the technological fields of renewable energy and energy efficiency. With this objective in mind, we assemble a unique firm-level patent dataset during the period of 1990–2015. We further incorporate the provincial CDM projects by energy type and explore whether the CDM projects are positively correlated with firms' related patent innovation. This article adds to the existing literature in two ways. Firstly, we contribute to the relatively few studies of technology development in the CDM with patent data. To the best of our knowledge, this is the first study that employs firm-level patent data in China to examine the induced innovation effects of the CDM projects hosted in China during the 2005–2015 period. Secondly, the study contributes to the literature on the CDM in that it has an absorptive capacity focus. Earlier studies employing aggregate time-series data have shown that CO_2 emissions in China are negatively related to research intensity, technology transfer and the absorptive capacity of the economy to assimilate foreign technology (Ang, 2009). By identifying firms engaged in the CDM and aggregating firm-level patent data to the provincial level, we are able to empirically examine whether the CDM can ex-post leverage low-carbon technology innovation in China. The spillover effect to non-CDM firms documented in this study provides further evidence of absorptive capacity of Chinese firms in renewable energy and energy efficiency.

The remaining of the paper is structured as follows. Next section introduces data sources and construction of key variables of interests. Section 3 presents the empirical model and the results, while the last section concludes the paper.

2. Theoretical framework

CDM is an emission reduction mechanism that relies on the EU ETS, which provides a good platform for North-South cooperation in controlling greenhouse gas emissions, enabling the global reduction of total abatement costs while achieving the same emission reduction targets. On the one hand, for developed countries, the cost of compliance is reduced and the flexibility of compliance is improved; on the other hand, for developing countries, capital and technology can be obtained from developed countries with the advantage of low marginal abatement costs. Therefore, CDM is a Win-Win option. From the perspective of promoting the sustainable development, the CDM mechanism is more important for developing countries, because if CDM can be used well, it will become a new channel to attract foreign direct investment with high technology and reasonable structure. Spillover from innovation is the underlying cause of increasing returns to scale and thus sustaining economic growth, which is also one of the main reasons for the formation of industrial agglomeration. Through the spillover effect, host Country can continuously improve their innovation capabilities in the field of climate change and promote their sustainable development. As a special type of FDI, there are four possible spillover channels for CDM projects: imitation-demonstration, competitive effects, the linkage effect, and technician mobility (Kokko, 1994).

2.1. Imitation and demonstration

It is said that due to the existence of a technology gap between the home country and the host country, enterprises of the host country may improve its technology and productivity by learning and imitating. With the development of network information technology, the spillover effect of innovation has been accelerated (Agarwal and Gort, 2001). With the continuous deepening of cooperation, innovation not only manifests itself as a spatial spillover effect, but also as a value chain spillover effect. From the perspective of innovation spillovers, technology trade and technical cooperation are two typical technology diffusion paths. As far as the CDM project is concerned, the host country's enterprises can learn advanced technical knowledge and experience in the collaborative construction of CDM projects, and imitate the manufacture of advanced equipment. In this process, through the "learning by doing" effect, the host country's enterprises constantly improve the ability to innovate.

2.2. Competition effect

This effect occurs mostly between the various manufacturers in the intra-industry. In the process of competing for limited market resources, the competition between the home country's enterprises and the host country's enterprises has increased market competition, stimulating the host country's enterprises to use existing resources more effectively, and promote local technical efficiency. On the other hand, in industries that have strong industrial barriers, the social welfare level has been improved because the entry of CDM projects has eliminated monopoly to a certain extent. Wang and Blomström (1992) construct a basic model of the game between the home country enterprise and the host country enterprise, which proved that the technology gap between the two companies was reduced due to spillovers, and the technology gap between the two was narrowed. The influx of CDM projects has intensified competition between home-state companies and host-state companies, then host companies have to increase R&D investment in order to gain market competition(Liu et al., 2019; Shi et al., 2016). It can be seen that CDM projects can force the host country companies to carry out technological research and development through competitive effects, thereby enhancing their innovation capabilities.

2.3. Linkage effect

The linkage effect is seen as an inter-industry way, including CDM project's interaction with local companies or customers, back-ups with upstream companies such as suppliers, and forward linkages with downstream companies such as vendors. Aitken and Harrison (1999) argue that spillovers from forward linkages are important in most industries. The promotion of advanced technology and equipment to be introduced in the host country is also considered to be one of the performances of forward linkage. Therefore, CDM projects can promote technological innovation capabilities of energy, environmental and equipment manufacturing companies through forward and backward linkages.

2.4. Technician mobility

In the field of climate change, IPCC defines technology transfer as including technical knowledge, experience, and equipment mobility for mitigation and adaptation to climate change among different stakeholders. It comprises the process of learning to understand, utilize and replicate the technology, including the capacity to choose it and adapt it to local conditions and integrate it with indigenous technologies. Thus, the mobility of technician after mastering technical knowledge and experience has become an important channel for CDM projects to exert spillover effects. The experience of developed countries confirms that the competitive advantage of foreign capital cannot be completely materialized in equipment and technology from its human resources (Ye et al., 2019). Therefore, the effective operation of CDM projects is often combined with the development of local human resources. Such as local technical and management personnel and experts dispatched from the consultants or credit buyer; training of local personnel; local technical personnel involved in the improvement of technology, products and processes, and even research and development activities. Therefore, CDM projects can promote the technological innovation capabilities of host countries through the technician mobility.

3. Data

This section begins with a discussion of several data sources we have assembled together. We then introduce the construction of key variables of interests.

3.1. Data sources

The data pertain to the Chinese publicly-listed firms in stock markets of Shanghai and Shenzhen during the period of 1990–2015, covering all firms in the manufacturing and public utility sectors. We further merge and match listed firms and their subsidiaries with those that have filed patent applications and their applications have been successfully granted based upon the archive of the State Intellectual Property Office (SIPO) of China. To further link patents to technologies associated with renewable energy and energy efficiency, we follow the Green Inventory List of the World Intellectual Property Office (WIPO) according to the UNFCCC. The WIPO provides a list of International Classification Code (IPC) of patents that are associated with technologies in the field of energy efficiency and renewable energy. For each patent applied by listed firms, we could define its associated technology in the category of energy efficiency or renewable energy by specific energy type (i.e., biofuels, wind, solar, and hydro).

UNFCCC provides the detailed information about the CDM projects in China, including a total of 3,763 CDM projects initiated in China during the period of 2005 to 2015. For each project, we could retrieve information regarding launching year, province, project type, and many others. Specifically, project type is related to technologies in the fields of energy efficiency or renewable energy.

Moreover, we further retrieve firm-level control variables and provincial-level control variables from China Stock Market and Accounting Research (CSMAR) and National Bureau of Statistics (NBS) of China, respectively. The CSMAR provides the firm-level fundamentals in a similar role as Compustat database access from Wharton Research Data Services. The corporate financial information includes startup year, asset, capital, revenue, operating cost, R&D, and many other fundamentals, which are served as firm-level covariates in empirical models. The NBS of China supplies the provincial-level energy intensity, income, and R&D intensity, all of which are correlated with firms' incentive to conduct innovation in the technological fields of renewable energy and energy efficiency.

3.2. Variables construction

3.2.1. Firm-level patent

Key dependent variable of interests is the firm-level patents associated with renewable energy and energy efficiency. Following the conventional wisdom, we use patent applications to measure innovation. These patent applications have been successfully granted by the SIPO of China. Define RE_Patent_{it} as the logarithm number of patents applications in the fields of renewable energy and energy efficiency.[1]

One potential caveat of China Patent Data is a lack of citations, leading to an inaccurate measure of innovation quality. The SIPO of China, however, defines two types of patents: invention patent and utility patents. By definition of the SIPO, the former is related to technical innovations that are practical, inventive and new, while the latter is associated with technical solutions to the shape or structure of an object. Moreover, recent literature studying the Chinese patents suggests that invention patents are subject to longer examination period and have lower approval rate than utility patents (Hu and Jefferson, 2009; Hu et al., 2017; Wei et al., 2017). Thus, invention patents represent radical and more important innovation relative to utility patents. Along with this line, to distinguish the effects of the CDM projects on innovation by quality type, we further calculate invention patents and utility patents in the technological fields of renewable energy and energy efficiency, denoted by $RE\_InvtPatent_{it}$ and $RE\_UtyPatent_{it}$, respectively.

To measure innovation by type of renewable energy, we also count the number of patents applications associated with each renewable energy. Specifically, for each firm *i* at year *t*, let EE_Patent_{it} be the logarithm number of patents applications in energy efficiency technologies, and let $Biofuel\_Patent_{it}$, $Wind\_Patent_{it}$, $Solar\_Patent_{it}$, and $Hydro\_Patent_{it}$ be the logarithm number of patents application in biofuels, wind, solar, and hydro, respectively.

3.2.2. CDM projects

Of our central interest is the number of CDM projects at province-year level. There are 3,763 CDM projects initiated in China during the 2005–2015 period, covering a wide range of provinces in China. Among these projects, over 90% of them are associated with biofuels (i.e., biomass energy), wind, hydro, solar, and energy efficiency. The CDM projects in the category of energy efficiency (EE) include those with CDM types belonging to EE household, EE industry, EE own generation, and EE supply side.

For each year *t* and province *p*, we calculate the number of CDM projects related to renewable energy and energy efficiency, denoted by CDM_total_{pt}. We then compute the number of CDM projects by type. Define $CDM\_biofuels_{pt}$, CDM_hydro_{pt}, CDM_solar_{pt}, CDM_wind_{pt}, and CDM_ee_{pt}, as the number of CDM projects in technological fields of biofuels, hydro, solar, wind energy, and energy efficiency, respectively. All variables are expressed in the logarithm fashion similar to patent innovation.

3.2.3. Other control variables

Firm-level fundamentals that may play an important role in determining innovation are included to serve as control variables, including age, asset, leverage, revenue, capital intensity, and cash ratio. First, when representing the age and assets of a firm, we take for both the natural logarithm term. Age and asset are two basic characteristics, which can indicate a firm's size and capacity of innovation. Firms with an older age and bigger size are easier to innovate. Second, we use leverage to proxy firm's financing risk and revenue capacity. Third, to indicate firms' capital intensity, we use the natural logarithm of capital to labor ratio, which is defined as the ratio of the book value of plants and machinery to the number of employees. Furthermore, cash ratio is added in our model to indicate firms' financial constraints.

Lastly, but not the least, we also add provincial-level covariates that may confound with firms' decision of conducting innovation. Provincial GDP per capita, denoted by GDP_p, is included to capture economic development level. Firms located in more developed regions are more likely to have resources devoted to innovation. Moreover, we control for R&D intensity measured by R&D labor per employment (i.e., $RDLab\_p$) and R&D per capita (i.e., RD_p) at province level. These two proxies are positively correlated with firms' innovation decisions. Along with this line, energy intensity, measured by electricity consumption per capita (i.e., EC_p), is included to control for incentives for changing innovation direction toward renewable energy or energy efficiency. Finally, we also include year fixed effect and firm fixed effect to control for time trend and unobservable firm productivity, respectively. A full set of province linear year trend and industry linear year trend is also added to control for unobservable industry or province-level targets of CO_2 emissions reductions through improving energy efficiency or developing renewable energy.

3.3. Descriptive statistics

Fig. 1 depicts the number of CDM projects initiated in China across years and the number of firm-level patents in technologies associated with renewable energy and energy efficiency. Starting from 2005, the number of CDM projects has been experiencing an upward trend. In 2012, there are over 1,500 projects registered, three times more than the number of projects established in 2011. The trend of firm-level patent innovation in renewable energy and energy efficiency mirrors the similar upward trend with the CDM projects. This pattern sheds light on the potential positive correlation between CDM projects and firms' innovation in renewable energy.

We further decompose the trend of CDM projects by type as illustrated in Fig. 2. In the beginning period of 2005–2010, more than half of CDM projects are related with hydro energy. Starting from 2011, the number of CDM projects associated with wind energy has exceeded the number of projects related to hydro energy, becoming the largest type among all renewable energy. Energy efficiency was also one of favorable CDM projects receiving technology support from sponsoring countries. Solar energy becomes the third-largest type of CDM projects in year 2012, and followed by biofuels (i.e., biomass energy). Starting from 2013, CDM projects are gradually phased down due to the end of the first commitment period of the Kyoto Protocol.

Table 1 provides summary statistics for key variables of interests. The data used in this paper include 17,471 firm-year observations associated with 1,858 unique listed firms, covering all manufacturing and public utility sectors in China.

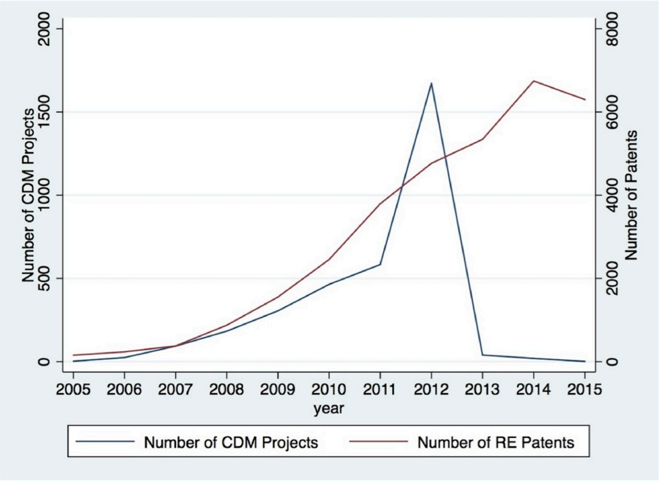

Fig. 1. Number of CDM Projects in China and Number of Firms' Patents associated with Renewable Energy.

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[1] We use log(1+x) to measure the logarithm number of patents. Similar transformation applies for all innovation variables appeared in this paper.

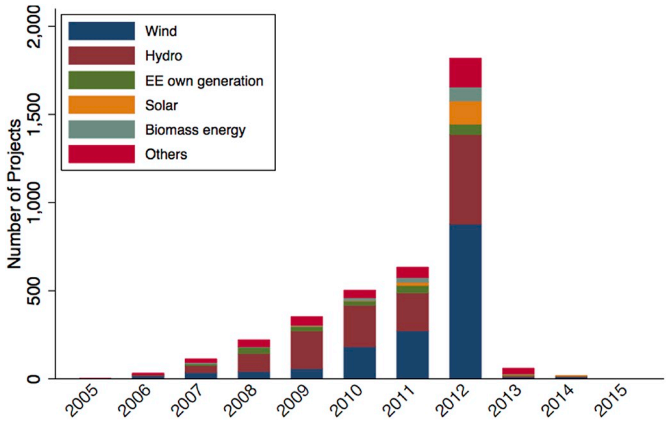

Fig. 2. Number of CDM projects in China by type.

Table 1
Summary statistics.

variable	N	mean	sd	min	max
RE_Patent	17,471	1.35	13.32	0.00	927.00
RE_InvtPatent	17,471	0.62	6.17	0.00	452.00
RE_UtyPatent	17,471	0.73	7.78	0.00	475.00
EE_Patent	17,471	0.68	4.92	0.00	247.00
Biofuel_Patent	17,471	0.07	1.32	0.00	86.00
Wind_Patent	17,471	0.07	1.57	0.00	134.00
Solar_Patent	17,471	0.13	1.45	0.00	66.00
Hydro_Patent	17,471	0.02	0.61	0.00	72.00
CDM_total	17,471	0.41	0.92	0.00	6.79
CDM_biofuels	17,471	0.02	0.05	0.00	0.35
CDM_hydro	17,471	0.11	0.32	0.00	2.83
CDM_solar	17,471	0.02	0.06	0.00	0.48
CDM_wind	17,471	0.22	0.76	0.00	5.93
CDM_ee	17,471	0.03	0.04	0.00	0.21
Asset	17,471	12.00	1.35	7.71	21.33
Intangible Ratio	17,471	0.05	0.05	−0.03	0.78
Cash	17,471	0.00	0.15	0.00	19.92
Capital Intensity	17,471	−1.05	0.94	−7.08	6.59
Revenue	17,471	18.25	1.47	8.11	26.42
Leverage	17,471	0.43	0.19	0.01	3.08
Age	17,471	12.10	5.55	0.00	56.00
EC_p	17,471	2.88	1.14	0.54	8.09
GDP_p	17,471	7.39	3.96	0.63	17.38
RDLabor_p	17,471	0.30	0.27	0.01	1.15
RD_p	17,471	1.80	1.22	0.15	6.01

Notes: *EC_p*: provincial energy consumption per capita, *GDP_p*: provincial GDP per capita, *RDLabor_p*: provincial R&D labor per employment, and *RD_p*: provincial R&D expenditure per capita.

4. Empirics

In this section, we first introduce the empirical model that examines the relationship between provincial-level CDM projects and firms' innovation on renewable energy and energy efficiency. Baseline empirical results are then provided along with a discussion on heterogeneity results by different CDM types.

4.1. Empirical method

We seek to estimate the relationship between provincial CDM projects and firm innovation in renewable energy, controlling for firm-level fundamentals and provincial covariates, both of which would play a substantial role in shaping firms innovation direction toward renewable energy. For firm i in industry j located in province p at year t, the empirical model is proposed as follows,

$$REInnov_{ijpt} = \alpha_0 + \beta_0 CDM\_total_{pt} + X_{it} + W_{pt} + \delta_i + \lambda_t + \theta_{pt} + \eta_{jt} + \varepsilon_{ijpt} \tag{1}$$

where $REInnov_{ijpt}$ denotes firm-level innovation in renewable energy, measured by *RE_Patent*, *RE_InvtPatent*, and *RE_UtyPatent*. The core explanatory variable of interest is CDM_total_{pt}, capturing the provincial-level CDM projects in China. X_{it} represents firm-level fundamentals, including asset, intangible asset ratio, cash, capital intensity, revenue, leverage, and age. W_{pt} is a set of province-level control variables with energy intensity, income per capita, and R&D intensity accounted for. Moreover, the industry linear year trend and province linear year trend, absorbed by η_{jt} and θ_{pt}, respectively, could further help filter out unobserved factors, such as industry or province-level targets of reducing CO_2 emissions or improving energy efficiency. The firm fixed effect δ_i is also included to control for firm-level unobservable heterogeneity, while λ_t captures the year fixed effect. Finally, ε_{ijpt} is an unobserved error term. The corresponding parameter of primary interest, captured by β_0, represents the induced innovation effect of CDM projects on firms' innovation in technological fields of renewable energy and energy efficiency.

Moreover, for each type of renewable energy (i.e., biofuel, wind, solar, hydro) and EE, we are interested in exploring the induced innovation effect by identifying a direct link between type-specific provincial CDM projects on firms' corresponding innovation. Along with this line, whether the industrial energy intensity would enhance this induced innovation effect. The empirical model with the interaction term between the industrial energy intensity ($EnergyIntens_j$) and type-specific CDM projects at province level (CDM_type_{pt}) is proposed as follows,

$$\begin{aligned} Innov\_type_{ijpt} = \alpha_0 + \beta_1 CDM\_type_{pt} + \beta_2 CDM\_type_{pt} \times EnergyIntens_j \\ + X_{it} + W_{pt} + \delta_i + \lambda_t + \theta_{pt} + \eta_{jt} + \varepsilon_{ijpt} \end{aligned} \tag{2}$$

where $Innov\_type_{ijpt}$ denotes type-specific patent innovation, i.e., *EE_patent*, *Biofuel_Patent*, *Wind_Patent*, *Solar_Patent*, and *Hydro_Patent*. The CDM projects by type is measured by CDM_type_{pt}, while $EnergyIntens_j$ represents the industrial-level energy intensity measured by coal-equivalent energy consumption per value added in year 2000. The parameter of interest, denoted by β_2, represents the moderating effects of industry energy intensity on the enhancement effect from CDM project to firms' innovation in renewable energy. The more energy intensive the industry, the stronger the enhancement effects would be.

4.2. Baseline results

Table 2 presents the results on the effects of provincial CDM projects on firms' innovation on renewable energy and energy efficiency. In all columns, we control for both firm-level fundamentals and province-level covariates that would shape the innovation direction. Columns vary with the choice of fixed effects that are used to absorb confounding unobservable at province or industry level, both of which could capture provincial targets of reducing energy intensity or industrial pressures of CO_2 emission reductions through energy conservation. Standard errors presented in the parenthesis are clustered at industry level.

Of our central interest is to examine the innovation-induced impact of CDM projects on firms' innovation. As shown in column (1) of Table 2, there is a positive and statistically significant coefficient about CDM_total_{pt}, indicating that CDM projects accumulated at province level have a positive impact on the firm-level innovation in renewable energy.[2] By including additional the industry-linear year trend effect, the estimated coefficient becomes smaller but remains the statistical significant at the 10% level. When it comes to the model with both the

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[2] As a robustness check, we use CDMInvst_total to denote the total investments of CDM projects at the province-year level. A series of robustness checks are conducted by employing this alternative measure. We obtain consistent results that about the induced-innovation effects of the provincial CDM projects on the firm-level renewable energy innovation. Moreover, the larger the total investments of CDM projects, the stronger the spillover effect of CDM would be.

Table 2
CDM effects on firms' innovation in renewable energy.

VARIABLES	RE_Patent		
	(1)	(2)	(3)
CDM_total	0.046***	0.039*	0.028*
	(0.016)	(0.021)	(0.015)
Asset	0.033*	0.026	0.023
	(0.019)	(0.018)	(0.016)
Intangible Ratio	−0.137	−0.032	−0.033
	(0.157)	(0.106)	(0.102)
Cash	−0.003	−0.007	−0.006
	(0.011)	(0.009)	(0.009)
Capital Intensity	0.013	0.021*	0.022*
	(0.011)	(0.010)	(0.011)
Revenue	0.024*	0.035***	0.034***
	(0.013)	(0.011)	(0.010)
Leverage	0.157***	0.144***	0.147***
	(0.056)	(0.050)	(0.052)
Age	0.024**	0.051***	0.088***
	(0.011)	(0.006)	(0.013)
EC_p	−0.084***	−0.061**	0.015
	(0.030)	(0.023)	(0.022)
GDP_p	0.029	0.020	−0.014
	(0.019)	(0.017)	(0.011)
RDLab_p	−0.246	−0.475**	−0.453*
	(0.264)	(0.199)	(0.265)
RD_p	0.145**	0.123**	−0.003
	(0.060)	(0.046)	(0.039)
Constant	−1.014**	−0.955***	−0.746***
	(0.414)	(0.290)	(0.269)
Observations	17,471	17,471	17,471
R-squared	0.159	0.250	0.254
Province Year Trend	N	N	Y
Industry Year Trend	N	Y	Y
Firm FE	Y	Y	Y
Year FE	Y	Y	Y

Notes: dependent variables: *RE_Patent* denotes the logarithm number of patents in renewable energy. *EC_p*: provincial energy consumption per capita, *GDP_p*: provincial GDP per capita, *RDLab_p*: provincial R&D labor per employment, and *RD_p*: provincial R&D expenditure per capita. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

industry linear year trend and province linear year trend considered, as shown in column (3), the estimated impact of CDM projects on firm renewable energy innovation is still positive and statistically significant at the 10% level. Such downsizing innovation-induced impacts of CDM projects are due to the explanatory powers by both industry and province linear year trends. One percentage increase in CDM projects could lead to 2.8 percentage increase in firm-level patent innovation associated with renewable energy and energy efficiency.

Next, we explore the role of firm-level covariates in determining patent innovation toward renewable energy and energy efficiency. In all columns, we find positive coefficients for firm size measured by asset and revenue. The estimated coefficient is statistically significant at the 1% level for revenue, but not statistically significant at any conventional levels for asset, as shown in column (3). These findings suggest that the larger the firm size in terms of revenue, the more resources the firm could denote to innovation in renewable energy. In addition, there is positive and statistically significant coefficient for capital intensity, indicating the positive correlation between capital intensity and patent innovation at firm level. When it comes to proxy for firms' financial constraints, we use cash and leverage to measure financial resources that were required to conduct long-term and high-risk innovation. The estimated coefficient for cash is consistently negative but not statistically significant at any conventional levels, while the coefficient for leverage is positive and statistically significant at the 1% level across all columns. These findings shed light on the potential impact of financial resources in terms of leverage on firms' innovation direction. Lastly, we document a consistently positive coefficient for firm age, capturing that the older the firm, the more patent innovation in renewable energy the firm would have.

Lastly, but not the least, provincial factors including income per capita, energy intensity, and R&D intensity are not statistically significant at any conventional levels, as shown in column (3) of Table 2. Part of the reasons lies in that publicly listed firm could not absorb provincial resources and denote them into innovation toward renewable energy and energy efficiency.

4.3. Heterogeneity by firms' internal and external factors

To provide further managerial and policy implications regarding the effects of CDM projects on the firm-level innovation in renewable energy, we further account for firms' internal and external factors that may play substantial roles in the knowledge spillover effects. Specifically, we consider firms' revenue, asset, and leverage as firms' internal factors and interact it with the provincial CDM projects based upon the baseline model specification.[3] The interaction term captures the role of firms' internal factors in the innovation effects of CDM projects. Table 3 reports the corresponding results while regressing renewable innovation by patent type with provincial CDM projects and firm's internal factors.

In columns (1)–(3), we report the results for renewable innovation measured by invention patents, while in the remaining columns, we show the results for renewable innovation proxied by utility patents. In all columns, the estimated coefficients for CDM_total are consistently negative and statistically significant in most cases. When it comes to the interaction term between CDM_total with firms' internal factors, we document the consistently positive coefficients. These coefficients are statistically significant at the 1% level, suggesting the positive role of firms' internal factors in the CDM's spillover effects. When firms' internal factors are proxied by firms' asset (revenue), the point estimated coefficient for the interaction term is around 0.05 (0.03). This magnitude indicates that a 1 percent increase in firms' assets could lead to a 5 percentage point increase in renewable energy innovation. The point estimate for the interaction term between CDM projects and firm's leverage is around 0.157, suggesting that a one percent increase in firms' leverage is associated with 15.7 percentage point increase in renewable energy patent applications.

Along this line, we consider provincial energy consumption per capita, R&D labor per capita and R&D expenditure per capita as the firm's external factors. For each of them, we interact with provincial CDM project numbers based upon the baseline specification. Table 4 provides the corresponding results. In columns (1)–(3), the dependent variable is renewable innovation by invention patents, while in the remaining columns it is utility patents. In all columns, there are consistently positive estimates for the interaction terms between provincial CDM projects and firms' external factors. These estimates are statistically significant at the 10% level for invention patents but are not significant at the conventional level for utility ones. These findings suggest that firms' external factors measured by provincial energy consumption per capita or R&D intensity have positive impacts on the knowledge spillover effects of CDM projects.

4.4. Heterogeneity by patent type

Innovation quality does matter. We distinguish innovation quality by patent type, i.e., invention patents and utility patents. Table 5 presents the corresponding results regarding the impacts of CDM projects on firms' innovation in renewable energy by paten type. All columns include both firm-level and province-level covariates appeared in the

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[3] We also consider firms' other covariates as internal factors interacting with provincial CDM project numbers, such as age, cash, intangible ratio, etc. None of them are economically and statistically significant at the conventional level.

Table 3
CDM effects and Firm's internal factors.

VARIABLES	RE_InvtPatent_t			RE_UtyPatent_t		
	(1)	(2)	(3)	(4)	(5)	(6)
CDM_total × Asset	0.048***			0.055***		
	(0.008)			(0.008)		
CDM_total × Revenue		0.033***			0.037***	
		(0.004)			(0.006)	
CDM_total × Leverage			0.157***			0.144***
			(0.045)			(0.052)
CDM_total	−0.589***	−0.592***	−0.035**	−0.677***	−0.674***	−0.033
	(0.098)	(0.074)	(0.017)	(0.100)	(0.106)	(0.022)
Asset	0.002	0.014*	0.011	0.003	0.017*	0.013
	(0.008)	(0.008)	(0.009)	(0.008)	(0.008)	(0.009)
Intangible Ratio	−0.026	−0.014	−0.005	−0.046	−0.033	−0.022
	(0.071)	(0.073)	(0.070)	(0.084)	(0.079)	(0.081)
Cash	0.011	0.010	0.011	0.006	0.005	0.006
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Capital Intensity	0.017*	0.017*	0.018	0.016**	0.016**	0.017**
	(0.010)	(0.010)	(0.011)	(0.007)	(0.008)	(0.008)
Revenue	0.023***	0.010	0.025***	0.023**	0.008	0.025***
	(0.008)	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)
Leverage	0.102**	0.114**	0.061	0.117***	0.132***	0.085*
	(0.044)	(0.045)	(0.042)	(0.042)	(0.043)	(0.043)
EC_p	0.011	0.012	0.010	0.018	0.019	0.016
	(0.024)	(0.025)	(0.025)	(0.020)	(0.020)	(0.021)
GDP_p	−0.007	−0.006	−0.011	−0.015	−0.014	−0.019*
	(0.013)	(0.012)	(0.013)	(0.010)	(0.010)	(0.011)
RDLab_p	−0.211	−0.287	−0.326	−0.149	−0.236	−0.283
	(0.176)	(0.182)	(0.195)	(0.213)	(0.217)	(0.235)
RD_p	−0.007	−0.012	−0.010	0.009	0.003	0.005
	(0.024)	(0.024)	(0.025)	(0.034)	(0.034)	(0.035)
Observations	17,471	17,471	17,471	17,471	17,471	17,471
R-squared	0.220	0.214	0.205	0.229	0.222	0.212
Firm FE	Y	Y	Y	Y	Y	Y
Province Year Trend	Y	Y	Y	Y	Y	Y
Industry Year Trend	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

Notes: *RE_InvtPatent* and *RE_UtyPatent* denote the logarithm number of invention patents and utility patents related to renewable energy, respectively. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

baseline model. A full set of fixed effects at year, firm, province liner trend and industry linear trend is also controlled. The analysis distinguishes impacts on firms of different energy intensity with the inclusion of interaction terms between CDM projects and energy intensity at the industry-level.

Columns (1) and (2) in Table 5 presents induced innovation effects of CDM projects on invention patents and utility patents in renewable energy of the same year, respectively. The estimated coefficients for the interaction terms between CDM projects and industrial energy intensity are positive and statistically positive at the 10% level for invention patents and at the 1% level for utility patents. For firms located in provinces hosting CDM projects, induced innovation effects of CDM vary across industry. The more energy intensive the industry, the larger the induced innovation effects would be.

The remaining columns of Table 5 show the results on the lagged induced innovation effects of CDM projects. Since CDM is a demand-pull policy, there may be a time lag between the development of CDM projects and the observed impacts on new technology innovation in related technological fields. There is also a time lag between the time of invention and patent applications depending on the patent filing process. As in the first two specifications, positive and statistically significant coefficients for the interaction terms are documented both for invention patents and utility patents. However, the effect of CDM projects on invention patents is statistically significant at the 10% level. By comparing the estimated coefficients reported in odd columns and even columns in Table 5, the induced innovation effect of CDM projects is more pronounced in incremental innovation captured by utility patents than radical innovation represented by invention patents.

4.5. *Heterogeneity in CDM type*

The CDM projects differ by energy type. We investigate the lagged induced innovation effects of type-specific CDM projects on firms' innovation in the corresponding renewable energy type. Table 6 presents the results. Each column represents a specific type of renewable energy (i.e., biofuels, wind energy, and solar energy) and energy efficiency technology (i.e., EE). We only document statistically significant coefficients for the biofuels-specific CDM projects in column (2). Depending on the energy intensity, biofuel projects have mixed effects on related patent applications.

Firms in energy-intensive sectors show a positive impact of biofuel projects on innovation in corresponding technological fields. In the remaining columns, however, the estimated coefficients for the interaction terms are not economically and statistically significant at any conventional levels. Thus, the provincial CDM projects have moderate induced innovation effects on firms' innovation in biofuel but have muted impacts on firms' innovation in other types of renewable energy. These findings suggest that, unlike biofuels, firms' innovation in solar and wind energy is less likely attributed to the knowledge spillover effects of provincial CDM projects in related energy types.

4.6. *Spillover effects to Non-CDM firms*

CDM is a demand-pull policy (provide subsidies to technology users) to drive technology innovation in renewable energy and energy efficiency, creating a market for these technologies(Nemet, 2009). CDM projects could have direct and indirect impacts on firm-level innovation

Table 4
CDM effects and firms' external factors.

VARIABLES	RE_InvtPatent$_t$			RE_UtyPatent$_t$		
	(1)	(2)	(3)	(4)	(5)	(6)
CDM_total × EC_p	0.030*			0.015		
	(0.016)			(0.013)		
CDM_total × RDLab_p		0.052*			0.051	
		(0.027)			(0.043)	
CDM_total × RD_p			0.012*			0.011
			(0.006)			(0.010)
CDM_total	−0.073	−0.032	−0.041	−0.027	−0.034	−0.041
	(0.053)	(0.024)	(0.028)	(0.044)	(0.039)	(0.047)
Asset	0.009	0.009	0.009	0.011	0.011	0.011
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)
Intangible Ratio	−0.002	−0.002	−0.002	−0.020	−0.020	−0.019
	(0.072)	(0.073)	(0.073)	(0.081)	(0.081)	(0.081)
Cash	0.012	0.012	0.012	0.006	0.006	0.007
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)
Capital Intensity	0.017	0.017	0.017	0.016*	0.016*	0.016*
	(0.011)	(0.011)	(0.011)	(0.008)	(0.008)	(0.008)
Revenue	0.025***	0.025***	0.025***	0.025***	0.025***	0.025***
	(0.008)	(0.008)	(0.008)	(0.009)	(0.009)	(0.009)
Leverage	0.122**	0.123**	0.123**	0.140***	0.141***	0.141***
	(0.045)	(0.045)	(0.045)	(0.043)	(0.043)	(0.043)
EC_p	0.003	0.015	0.015	0.013	0.021	0.022
	(0.024)	(0.025)	(0.025)	(0.021)	(0.020)	(0.020)
GDP_p	−0.011	−0.006	−0.006	−0.019*	−0.014	−0.015
	(0.014)	(0.013)	(0.012)	(0.011)	(0.011)	(0.011)
RDLab_p	−0.339	−0.369*	−0.354*	−0.296	−0.325	−0.310
	(0.203)	(0.210)	(0.206)	(0.241)	(0.255)	(0.248)
RD_p	−0.019	−0.020	−0.023	−0.004	−0.005	−0.008
	(0.026)	(0.025)	(0.025)	(0.035)	(0.035)	(0.035)
Observations	17,471	17,471	17,471	17,471	17,471	17,471
R-squared	0.202	0.202	0.202	0.209	0.209	0.209
Firm FE	Y	Y	Y	Y	Y	Y
Province Year Trend	Y	Y	Y	Y	Y	Y
Industry Year Trend	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

Notes: *RE_InvtPatent* and *RE_UtyPatent* denote the logarithm number of invention patents and utility patents related to renewable energy, respectively. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

Table 5
Effects of CDM on Firms' Innovation in Renewable Energy by Patent Type (Invention vs. Utility).

VARIABLES	RE_InvtPatent$_t$	RE_UtyPatent$_t$	RE_InvtPatent$_{t+1}$	RE_UtyPatent $_{t+1}$
	(1)	(2)	(3)	(4)
CDM_total	0.013	0.001	−0.021*	−0.021
	(0.013)	(0.013)	(0.012)	(0.013)
CDM_total × EnergyIntens	0.436**	0.718*	0.452**	0.803**
	(0.214)	(0.359)	(0.191)	(0.336)
Observations	17,471	17,471	15,939	15,939
R-squared	0.203	0.211	0.189	0.202
Firm-level Control	Y	Y	Y	Y
Province-level Control	Y	Y	Y	Y
Province Year Trend	Y	Y	Y	Y
Industry Year Trend	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

Notes: Dependent Variables: *RE_InvtPatent* and *RE_UtyPatent* denote the logarithm number of invention patents and utility patents related to renewable energy, respectively. *CDM_total* denotes the number of CDM projects at the province level, and *EnergyIntens* represents the industrial-level energy consumption intensity. All firm-level covariates and province-level control variables appeared in Table 1 are included but not reported due to limited space. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

in renewable energy. For those firms participating in CDM projects, CDM induces them to innovate. For firms never involved in any CDM projects, CDM may have spillover effect on their innovation. Since CDM's methodologies, standards and infrastructure are accessible to all firms including those who are not involved in any CDM project. As a consequence, CDM projects accumulated at the province level could play a role as an information platform, thereby leading an indirect impact on the renewable energy innovation of non-CDM firms. To isolate the spillover effects of CDM projects, we identify publicly listed firms that have registered CDM projects and then focus on a subsample of non-CDM firms (i.e., listed firms that have never participated in any CDM projects). By regressing the provincial CDM projects on renewable energy innovation of non-CDM firms, we could tease out the spillover effects of CDM projects on renewable energy innovation while

Table 6

Effects of CDM on one-year forward renewable energy innovation by renewable energy field.

VARIABLES	EE_Patent $_{t+1}$ (1)	Biofuel_Patent $_{t+1}$ (2)	Wind_Patent $_{t+1}$ (3)	Solar_Patent $_{t+1}$ (4)
CDM_ee	−0.392			
	(0.328)			
CDM_ee × EnergyIntens	1.097			
	(2.512)			
CDM_biofuel		−0.334*		
		(0.174)		
CDM_biofuel × EnergyIntens		6.268***		
		(1.601)		
CDM_wind			−0.009	
			(0.009)	
CDM_wind × EnergyIntens			0.073	
			(0.085)	
CDM_solar				0.104
				(0.102)
CDM_solar × EnergyIntens				0.106
				(1.318)
Observations	15,939	15,939	15,939	15,939
R-squared	0.213	0.068	0.043	0.053
Firm-level Control	Y	Y	Y	Y
Province-level Control	Y	Y	Y	Y
Province Year Trend	Y	Y	Y	Y
Industry Year Trend	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

Notes: dependent variables: *EE_Patent*, *Biofuel_Patent*, *Wind_Patent*, *Solar_Patent*, and *Hydro_Patent* denote the one-year forward logarithm count of patents in energy efficiency, biofuel, wind, solar, and hydro technological fields, respectively. *CDM_ee*, *CDM_biofuel*, *CDM_wind*, *CDM_solar*, and *CDM_hydro* indicate the number of provincial-level CDM projects related to energy efficiency, biofuels, wind, solar, and hydro. *EnergyIntens* is the industrial-level energy intensity. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

controlling for their firm-level covariates and a set of fixed effects at the firm, year, industry linear trend and province linear trend. Table 7 reports the results on the lagged spillover effects of CDM projects on renewable energy innovation of non-CDM firms.

Columns (1) to (3) in Table 7 presents the spillover effects of CDM projects on patents and two subcategories, invention patents and utility patents, respectively. No coefficient is significant in any column. Corresponding one by one to the first three columns, the remaining columns of Table 7 show the results on the enhanced spillover effects of CDM projects through the industrial energy intensity. Positive coefficients for the interaction terms are observed, while it is not statistically significant for utility patents. These findings indicate that the spillover effects of CDM projects are pronounced in more valuable innovation captured by invention patents relative to utility ones for firms in energy-intensive sectors.

5. Conclusions and policy implications

This paper examines whether CDM projects accumulated at the province level have induced innovation effects on firms in technological fields associated with renewable energy and energy efficiency. With this objective in mind, we assemble a unique firm-level dataset with firm-level patent innovation in renewable energy and CDM projects accounted for. We obtain some novel findings. First, CDM projects have the induced innovation effects on firm-level innovation in renewable energy and energy efficiency. This positive enhancement effect is pronounced in invention patents, but is muted in utility patents. Secondly, induced innovation effect varies across industrial energy intensity. The more energy intensive the industry, the larger impacts the firms could absorb from the CDM projects. Thirdly, the type-specific induced innovation effect is only documented for biofuel-specific CDM projects, indicating that firm-level innovation in biofuels appears to benefit from the related CDM projects within the same province. Fourthly, we document the spillover effects of CDM projects to non-CDM firms. There are two possible channels of the spillovers. On one hand, the CDM as a demand-pull policy creates a market for technologies which may also motivate non-CDM firms to direct innovation toward related fields. On the other hand, the CDM's methodologies, standards and infrastructure are accessible to all, which plays a role as an information platform.

The results presented in this paper have profound policy implications. Under the Kyoto Protocol, the CDM played an important role in allowing developed countries that have committed to emission reduction targets to sponsor greenhouse gas emissions reduction projects in the developing countries in exchange for emission reduction credits. One of the important roles for the CDM projects is to potentially facilitate the North-South transfer for climate-friendly technologies. While the CDM is now drawing to the end with the completion of the second Kyoto commitment period in 2020, international negotiations are considering future use of CDM CERs in other instruments, such as to meet Carbon Offsetting and Reduction Scheme for International

Table 7

The effects of provincial CDM programs on one-year forward renewable energy innovation of Non-CDM firms.

VARIABLES	RE_Patent$_{t+1}$ (1)	RE_InvtPatent $_{t+1}$ (2)	RE_UtyPatent $_{t+1}$ (3)	RE_Patent $_{t+1}$ (4)	RE_InvtPatent $_{t+1}$ (5)	RE_UtyPatent $_{t+1}$ (6)
CDM_total	−0.009	−0.014	−0.011	−0.022	−0.021**	−0.017
	(0.015)	(0.012)	(0.011)	(0.014)	(0.010)	(0.012)
CDM_total × EnergyIntens				0.530***	0.291***	0.259
				(0.144)	(0.094)	(0.253)
Observations	14,352	14,352	14,352	14,352	14,352	14,352
R-squared	0.246	0.196	0.203	0.247	0.196	0.203
Firm-level Control	Y	Y	Y	Y	Y	Y
Province-level Control	Y	Y	Y	Y	Y	Y
Province Year Trend	Y	Y	Y	Y	Y	Y
Industry Year Trend	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

Notes: dependent variables are one-year forward patent innovation, measured by logarithm count of patents in technological fields related to renewable energy and energy efficiency. *CDM_total* denotes the number of CDM projects at the province level, and *EnergyIntens* represents the industrial-level energy consumption intensity. All firm-level covariates and province-level control variables appeared in Table 1 are included but not reported due to limited space. Standard errors in parenthesis are clustered at industry level. *** significant at 1% level, ** significant at 5% level, * significant at 10% level.

Aviation requirements and towards meeting NDCs under the Paris Agreement. Paris Agreement Article 6 recognizes the importance of voluntary international cooperation in the implementation of NDCs, including the use of internationally transferred mitigation outcomes towards NDCs and to establish a mechanism to incentivize and facilitate participation in the mitigation of greenhouse gas emissions by public and private entities to contribute to the reductions of emissions in the host Party, and to deliver an overall mitigation in global emissions. It has been recognized that the CDM's standards, procedures, and institutional arrangements can provide important lessons for improving the design of future international carbon crediting mechanisms (UNFCCC, 2018c). Our results highlight the benefits of CDM in terms of technology improvements in China, providing direct evidence for future climate policy negotiations on supporting international carbon crediting mechanisms. Despite legal uncertainty of the CDM, our results suggest that CDM host countries can implement alternative international partnership to facilitate cooperation in mitigation. Moreover, they could use domestic policies that can forge the collaboration between domestic entities and foreign entities to further facilitate technological advancement in climate change mitigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Jingbo Cui: Conceptualization, Formal analysis, Writing - original draft. **Xi Liu:** Methodology, Data curation, Formal analysis. **Yongping Sun:** Conceptualization, Validation, Writing - original draft, Data curation. **Haishan Yu:** Conceptualization, Writing - review & editing.

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