



Article

Technological Innovation, the Kyoto Protocol, and Open Innovation

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Abstract: This study investigates the role of technological innovation in increasing the effectiveness of the Kyoto Protocol in terms of greenhouse gas (GHG) mitigation. Panel data showing the number of patents for climate change mitigation technology as a measure of innovation are obtained from 54 countries for the period 1990–2015 to verify whether technological innovation is effective in reducing GHG emissions and whether it has a significant synergetic relationship with the Kyoto Protocol. The historical trends in the number of patents for climate change mitigation technology reveal a relationship between the Kyoto Protocol and technological innovation and show differences between specific types of mitigation technology. Based on these innovation data, this study conducts two-stage least squares analysis that considers the time-lag effect. The empirical results confirm that mitigation innovations for buildings and the production or processing of goods have a strong positive association with GHG emission reduction. The findings also support the long-term synergetic effect between innovation and participation in the Kyoto Protocol in terms of GHG mitigation. This study contributes to international climate change governance by providing empirical evidence for technological innovation's role in strengthening the effectiveness of international regimes and implications for promoting open innovation.

Keywords: climate change mitigation technology; effectiveness of international regime; GHG mitigation; innovation; synergetic effect



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1. Introduction

Since the United Nations (UN) released Our Common Future in 1987 to propose a new direction for the relationship between the environment and development, sustainable development has become a core international political agenda for international environmental governance. In particular, climate change has emerged as a major global challenge to sustainability, and the establishment of international regimes has been the first step in the global response to this issue.

The Kyoto Protocol, which was adopted in 1997 and entered into force in 2005, is one of the most influential institutional frameworks for the mitigation of climate change [1]. Based on the principle of “common but differentiated responsibility and respective capabilities”, the Kyoto Protocol proposes an annex-based structure and differentiated responses for countries depending on their emissions contribution, history, and economic situation [2,3]. During the first two commitment periods (2008–2012 and 2012–2020), industrial countries had the primary responsibility for mitigating pollution based on internationally binding emission reduction targets.

In 2015, 196 parties adopted the Paris Agreement, a new legally binding international treaty on climate change, at the Conference of the Parties 21. This agreement proposed a universal greenhouse gas (GHG) reduction goal to limit global warming and offered a new direction for global climate action that “brings all nations into a common cause to undertake ambitious efforts to combat climate change” [1]. Therefore, developing countries were also held responsible for combating climate change to ensure a sustainable low-carbon future. Many of the parties to the Paris Agreement have since faced challenges in implementing

strategies to comply with this new regime. In particular, developing countries, which are greatly affected by the negative externalities of international environmental issues, including climate change, have expressed concern about the negative economic effects of ratifying international environmental regimes such as the Paris Agreement [3,4].

Preventing negative economic impacts is crucial to ensuring the participation of individual countries and thus maintaining the integrity of international environmental regimes [3,5]. Previous studies have found that the cost of implementing international environmental policies designed to reduce emissions places an economic burden on individual countries [6–8], and this is often a key determining factor in whether a country participates in an international agreement [9]. In combination with the free-rider issue, the disincentive of potential economic damage reduces the overall effectiveness of international regimes [10], and this needs to be carefully considered, particularly for developing countries.

In order to improve environmental sustainability while reducing the economic burden facing individual countries, technical innovation related to the environment, commonly referred to as green technological innovation or green innovation, is a promising option [11]. Indeed, the Porter hypothesis argues that both environmental and economic benefits can be achieved simultaneously through innovation that eliminates inefficiencies and reduces environmental impacts. Stringent but flexible environmental policies can stimulate green innovation and thus help to minimize the emission of pollutants and optimize their treatment efficiency while reducing the economic burden for individual countries [11,12].

Meta-analyses have found that environmental regulations boost innovation and increase country-level competitiveness and that green technology is important for reducing the costs of environmental protection and achieving further environmental innovation and green growth [13,14]. Moreover, policy evaluation research has assessed the impact of environmental policies and regulations on technological innovation. Kerr and Newell [15] reported that flexible market-based regulation leads to effective technology adoption. Other studies have also provided empirical evidence that environmental performance and green innovation are positively associated with environmental regulation [16,17].

Studies on climate change policies have found that they have a partially positive effect on innovation. Scholars demonstrated that only those climate change policies related to technologies that directly reduce carbon pollution stimulate innovation in environmentally friendly technologies, while this effect is more limited than incentives for technology use [18,19]. Horbach [20] found that innovations supported by environmental subsidies were particularly important in reducing carbon dioxide, more so than for other types of environmental pollution. It is important to note that, based on a review of theoretical and quantitative research, some studies have pointed out that market-based instruments for promoting innovation have been weaker than expected and that more stringent policies are required to develop eco-innovation [21,22]. Based on the findings of previous studies, the present study investigates the following hypothesis:

Hypothesis 1 (H1). *Green technological innovation is effective in mitigating GHG emissions.*

Despite the active discussion surrounding green technological innovation, studies at the international level are rare, with few attempts to expand the relationship between policy and innovation to international agreements. Some studies have investigated the possibility that international regimes stimulate technological innovation and that the improvement in green technology mitigates pollution while limiting economic damage [23–28]. These studies have attempted to demonstrate the impact of international policies on technological development and research and development (R & D) or to develop approaches to enhance international cooperation. Many of these studies have suggested that a long-term perspective is necessary to evaluate the potential synergy between international regimes and innovation. Even though the Porter hypothesis has provided the inspiration to analyze the role of technological innovation in the effectiveness of international environmental regimes, there remains room for further discussion. If this approach is valid for interna-

tional regimes, international agreements or protocols should trigger innovations within participating countries to achieve a reduction in pollution and to promote economic growth. However, there is a lack of empirical evidence for the relationship between environmental policy and innovation at the international level.

The Kyoto Protocol is an appropriate international regime for evaluating the impact of technological innovation on the success or otherwise of international regimes because the parties to this protocol can use various flexible market-based mechanisms to achieve emission reduction and eliminate inefficiencies [3,5]. The Clean Development Mechanism (CDM) prescribed in Article 12 of the Kyoto Protocol is a representative institutional framework for the market-based approach. The CDM allows Annex B Parties to fulfill their commitment to cutting emissions by launching emission-reduction projects in developing countries that can transfer technologies and know-how. The CDM is expected to lead to the transfer or diffusion of technology, investment, and regional development within developing countries [29]. As of March 2021, the number of registered projects was 7851, leading to the reduction or avoidance of 2 billion tons of carbon dioxide [1,30]. Moreover, since the CDM acts as a bridge between Annex B countries and developing countries with low technical capacity, the adoption and diffusion of technologies through the CDM can stimulate open innovation, which is an innovation theory formulated by Henry Chesbrough that proposes companies can develop technology by using both internal and external resources across various sectors, countries, and worldwide [31–33].

However, an empirical approach to assess the impact of technological innovation and its diffusion for parties to the Kyoto Protocol is required. Most research on the Kyoto Protocol has simply evaluated the effectiveness of the protocol in terms of promoting GHG reductions [3,5,34,35]. Based on this past research, the following hypothesis is proposed:

Hypothesis 2 (H2). *Green technological innovation has a synergetic relationship with the Kyoto Protocol in mitigating GHG emissions.*

Given this context, the aim of this study is to investigate the role of green technological innovation in the effectiveness of international environmental policies, focusing on the Kyoto Protocol. Unlike previous studies, this study focuses on an international regime and investigates climate change mitigation technologies as a representative of a country's innovative capacity to reduce emissions. Determining whether technological innovations effectively decrease GHG emissions and generate a significant synergy effect with the aims of the Kyoto Protocol would provide a stronger understanding of the role of green innovation in governing the impact of international policies on environmental sustainability and may suggest promising strategies for global sustainable development. In providing empirical evidence for the impact of technological innovation on GHG mitigation efforts, this study can suggest a way forward for climate change governance in terms of setting effective GHG mitigation targets. Moreover, the verification of a synergetic effect between international policies and domestic technological improvement would offer valuable insight into climate strategies to stimulate open innovation under the new Paris Agreement framework.

2. Materials and Methods

2.1. Research Method

This study assumes that a country with a higher degree of technological innovation would exhibit stronger emission mitigation. Before investigating the role of technological innovation on the effectiveness of the Kyoto Protocol, this study assesses the historical trends for selected patents related to climate change mitigation technologies from 1990 to 2015 using the calculated technological innovation for each country.

To measure the degree of green technological innovation and its relationship with the Kyoto Protocol, this study uses patents to monitor the trends in green innovation over time [36]. Previous studies have considered patents to be a concrete indicator of innovation

performance and have used them to assess the degree of green innovation [36–38]. Using patent data, this study calculates technological innovation using an equation adopted from Grupp [39], Fankhauser et al. [38], and Waltz and Eichhammer [40]:

$$\text{Technological innovation}_{it} = p_{it}^E / p_{it} \tag{1}$$

where p_{it}^E is the number of patents for climate change mitigation technologies in country i in year t , and p_{it} is the total number of patents in country i in year t . Because this study focuses on the Kyoto Protocol, technological innovation is assessed based on patents for GHG reduction technology in accordance with the aims of the protocol.

Based on the classifications used in the Organization for Economic Cooperation and Development (OECD) patent database, specific patent fields are included in the model to identify the specific climate change mitigation technologies that exhibit the strongest influence on GHG emissions via the Kyoto Protocol [36]. Using the collected data, this study traces the historical trends in the patents for selected climate change mitigation technologies from 1990 to 2015.

Before investigating the synergetic relationship between technological innovation and international environmental policies, it is necessary to confirm the impact of the Kyoto Protocol and innovation on environmental performance. For this purpose, GHG emissions are used as a proxy for environmental performance because the aim of the Kyoto Protocol is to reduce these emissions. Based on the quantitative regime effect model introduced by Michell [41] to evaluate the effectiveness of international environmental agreements, this study utilizes the following equation:

$$\text{GHG}_{it} = \alpha_0 + \alpha_1 \text{RAT}_{it} + \alpha_2 \text{INNOV}_{it} + \alpha_3 \text{GDPP}_{it} + \alpha_4 \text{EUSE}_{it} + \alpha_5 \text{ELECPROD}_{it} + \alpha_6 \text{RENEW}_{it} + \varepsilon_{it} \tag{2}$$

The regime effect dummy variable RAT_{it} reflects the impact of participating in the Kyoto Protocol. It takes a value of 1 if country i ratified the protocol in year t , otherwise it is 0. If a country withdraws from the protocol, it switches from 1 to 0 the year after its withdrawal. INNOV_{it} reflects the technological innovation in country i in year t as calculated using Equation (1) based on patents for climate change mitigation technology.

The present study includes economic and energy-related variables as control variables. Because the degree of economic development is closely related to GHG emissions, the gross domestic product (GDP) per capita of country i in year t is added to the model as GDPP_{it} [3,42,43]. Variables related to the energy sector are also added because energy usage and structure significantly affect GHG emissions [44–46]. To reflect the differences in energy structure and usage, this study includes data on energy consumption, electricity production from fossil fuels, and renewable energy consumption for country i in year t (EUSE_{it} , ELECPROD_{it} , and RENEW_{it} , respectively).

To produce a more precise estimation of the economic impact on the GHG emissions, this study applies a two-stage least squares (2SLS) approach based on the significant results produced by the Durbin–Wu–Hausman test for endogeneity. Because the factors included in the previous model (Equation (2))—the ratification of the Kyoto Protocol, innovation, and energy usage—strongly influence economic performance, it is necessary to employ the two-stage model using the 2SLS estimator with simultaneous equations and instrumental variables. Thus, the first stage involves estimating the economic impact using the dependent variable GDPP_{it} to generate the fitted GDPP value:

$$\text{GDPP}_{it} = \beta_0 + \beta_1 \text{RAT}_{it} + \beta_2 \text{INNOV}_{it} + \beta_3 \text{CAPITAL}_{it} + \beta_4 \text{LABOR}_{it} + \beta_5 \text{HUMAN}_{it} + \beta_6 \text{EUSE}_{it} + \beta_7 \text{ELECPROD}_{it} + \beta_8 \text{RENEW}_{it} + \varepsilon_{it} \tag{3}$$

This model contains RAT_{it} and INNOV_{it} in order to consider the impact of ratification and innovation, as in Equation (2). The model also includes capital, labor, and human capital variables from the Cobb–Douglas GDP function to control for factors related to economic performance. The fitted value ($\widehat{\text{GDPP}}_{it}$) from Equation (3) is then applied to the

environmental impact model (Equation (2)) as a factor that affects the GHG emissions via instrumental variable regression. The final model can be expressed as follows:

$$\text{GHG}_{it} = \gamma_0 + \gamma_1 \text{RAT}_{it} + \gamma_2 \widehat{\text{GDPP}}_{it} + \gamma_3 \text{INNOV}_{it} + \gamma_4 \text{EUSE}_{it} + \gamma_5 \text{ELECPROD}_{it} + \gamma_6 \text{RENEW}_{it} + \varepsilon_{it}. \quad (4)$$

To provide a more specific interpretation of the role of technology innovation in the impact of the Kyoto Protocol on GHG emissions, the last step adds the synergetic effect variable $(\text{RAT} \times \text{INNOV})_{it}$, which represents the interaction between ratification and innovation based on the total number of patents for climate change mitigation technologies. This study adopts a finite distributed lag (FDL) model to consider the time-lag effect of this synergetic effect. The coefficients of the policy variables in the FDL model estimate their short- and long-term impacts. Given this, the synergetic effect model is represented by Equation (5):

$$\begin{aligned} \text{GHG}_{it} = & \delta_0 + \delta_1 \text{RAT}_{it} + \delta_2 \text{INNOV}_{it} + \delta_3 (\text{RAT} \times \text{INNOV})_{it} + \delta_4 (\text{RAT} \times \text{INNOV})_{i(t-1)} \\ & + \delta_5 (\text{RAT} \times \text{INNOV})_{i(t-2)} + \delta_6 (\text{RAT} \times \text{INNOV})_{i(t-3)} + \delta_7 \widehat{\text{GDPP}}_{it} + \delta_8 \text{EUSE}_{it} \\ & + \delta_9 \text{ELECPROD}_{it} + \delta_{10} \text{RENEW}_{it} + \varepsilon_{it}. \end{aligned} \quad (5)$$

This study adopts a fixed-effect model based on the results of a Wu–Hausman test and controls the time-varying covariates and unobserved time-invariant individual heterogeneity of the panel data. Based on the Wu–Hausman test, which is used to select between a fixed-effects and random-effects model, this study adopts a fixed-effects model due to the rejection of the null hypothesis. All variables take a log-linear form, and the statistical analyses are conducted using STATA/SE 14.

2.2. Data

To test the role of green innovation and the impact of the Kyoto Protocol, this study employs a country-based panel dataset for 54 countries from 1990 to 2015. The dataset is established by integrating the information from different reliable sources. Since the patent data cover a limited range of countries, only 54 countries are included in the database: Argentina, Australia, Austria, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Malaysia, Malta, Mexico, the Netherlands, New Zealand, Norway, Peru, the Philippines, Poland, Portugal, Russia, Saudi Arabia, Singapore, Slovak Republic, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, the United Kingdom, and the United States.

To verify the participation status of the Kyoto Protocol, this study adopts a dummy variable based on the Status of Ratification of the United Nations Treaty Collection (UNTC) [47] and United Nations Environment Programme (UNEP) [1]. The UNTC provides detailed information about the registration and publication of treaties in accordance with Articles of the Charter of the United Nations and the UNEP focuses on the history and activities of the UNFCCC, including the ratification status for the Kyoto Protocol. This study collects the ratification status from these sources, which is considered a formal decision of participation. This program effect dummy is 1 if a county ratifies the protocol in a certain year, and 0 otherwise.

The degree of technological innovation is measured using the number of patents taken from the OECD patent database available at the OECD. Stat interface [36], which includes statistics on patents by technology type and International Patent Classification for both OECD and non-OECD countries collected from various sources: patent applications to the European Patent Office (EPO); patents granted by the EPO; patent applications to the US Patent and Trademark Office (USPTO); patents granted by the USPTO; patents filed under the Patent Co-operation Treaty; and patents that belong to triadic patent families (OECD definition), which is a group of patents filed together at the EPO, at the Japanese Patent

Office (JPO), and at the USPTO [48]. This study uses triadic patent families to overcome the statistical limitations of office-based patent data because this approach can avoid home bias and the influence of the geographical location of a certain patent office. The triadic patent families are defined as “a set of patents taken at the EPO, the JPO and the USPTO that protect the same invention” [48].

Because this study focuses on the Kyoto Protocol and the synergy between it and technological innovation, only patents related to climate change mitigation technologies are considered. The selected patents cover five specific fields: those related to (i) buildings, (ii) energy generation, transmission, or distribution, (iii) the capture, storage, sequestration, or disposal of GHGs, (iv) transportation, and (v) the production or processing of goods [36]. This study calculates the proportion of the total number of patents for each country that are classified as each of the five technology types.

Other variables are obtained from the World Development Indicators (WDIs) provided by the World Bank Databank [49]. The dependent variables are total greenhouse gas emissions (kt of CO₂ equivalent) and GDP per capita (constant 2010 USD) to reflect economic and environmental performance, respectively. The capital, labor, and human capital variables employed are gross fixed capital formation (constant 2010 USD), total labor force participation rate (% of total population ages 15–64), and education expenditure (current USD), respectively. The control variables related to the energy sector that affect GHG emissions are energy use (kg of oil equivalent) per \$1000 GDP (constant 2017 PPP), electricity production from oil, gas, and coal sources (% of total), and renewable energy consumption (% of total final energy consumption).

The data in current (nominal) price for each year are affected by price inflation, thus, this study uses a constant series, which shows the data for each year in the value of a particular base year, to evaluate true economic growth by adjusting for the effects of price inflation. [49]. Moreover, in order to allow the use of the latest data from reliable sources, this study employs GDP per capita and gross fixed capital formation in constant 2010 USD, education expenditure in current USD, and energy use in constant 2017 purchasing power parity (PPP). Table 1 provides a summary of the descriptive statistics for these variables.

Table 1. Definition of the selected variables and descriptive statistics.

	Variables	Obs.	Mean	SD	Min	Max
RAT	Ratification of the Kyoto Protocol (dummy)	1404	0.506	0.500	0	1
GHG	Total greenhouse gas emissions (kt of CO ₂ equivalent) per population	1208	602,998.2	1,398,985	573.963	1.25 × 10 ⁷
GDPP	GDP per capita; GDP divided by the midyear population (constant 2010 USD)	1383	25,583.2	21,010.79	575.502	111,968.4
INNOV_TOTALENV	Selected climate change mitigation-related technologies (number)	1360	59.507	223.871	0	2721.085
INNOV_BLDG	Mitigation technologies related to buildings	1324	0.668	2.626	0	47.059
INNOV_ENERGY	Mitigation technologies related to energy generation, transmission, or distribution	1326	2.349	5.262	0	90.212
INNOV_CAP	Capture, storage, sequestration, or disposal of greenhouse gases	1318	0.164	1.204	0	33.333
INNOV_TRANS	Mitigation technologies related to transportation	1328	1.342	4.438	0	100
INNOV_PROD	Mitigation technologies in the production or processing of goods	1327	2.351	5.954	0	75.002
(RAT × INNOV)	Synergy effect	961	1.089	1.174	−2.344	4.893
CAPITAL	Gross fixed capital formation (constant 2010 USD)	1333	1.92 × 10 ¹¹	4.27 × 10 ¹¹	1.52 × 10 ⁸	3.48 × 10 ¹²
LABOR	Labor force participation of the population ages 15–64 (% of total)	1404	69.292	7.12	48.49	88.37
HUMAN	Education expenditure (current USD)	1364	3.27 × 10 ¹⁰	8.31 × 10 ¹⁰	1.83 × 10 ⁷	8.22 × 10 ¹¹
EUSE	Energy use (constant 2017 PPP)	1343	127.275	65.996	39.62	538.66
ELECPROD	Electricity production from oil, gas and coal sources (% of total)	1378	57.264	29.921	0.012	100
RENEW	Renewable energy consumption (% of total)	1404	16.994	15.715	0	77.345

Note: All the variables except the ratification and synergetic effect dummies are log-transformed for the analysis.

3. Results

3.1. Technological Innovation and the Kyoto Protocol

To measure the degree of innovation, patent data by technology type are used for the analysis. This study explores the historical trends for the patents for climate change mitigation technologies from 1990 to 2015.

Figure 1 presents the historical trend for all patents related to climate change mitigation technologies between binding-target countries and countries with no emission reduction obligations during the study period. During the first commitment period from 2008 to 2012, the average number of patents increases significantly. The total average patent count is 76.226 in 1990 and 260.138 in 2011. Interestingly, both binding and non-binding countries show a similar tendency to increase. Technological diffusion via Kyoto Protocol mechanisms, such as the CDM, contribute to this trend [29,30]. There is a dramatic rate of increase during the first commitment period of the Kyoto Protocol, with the highest annual increase rate occurring from 2008 to 2009 (18.998%). Though the present study only includes the first three years of the second commitment period (2013 to 2020) due to limitations in the patent data, the number of patents clearly falls during this period. The number of patents is 220.347 in 2013 and 190.661 in 2015. There is no clear difference between binding and non-binding target countries.

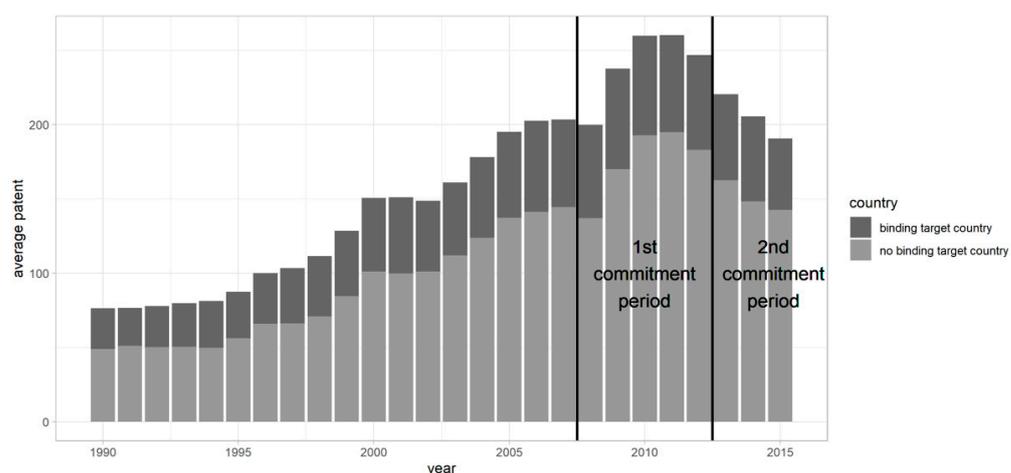


Figure 1. Historical trend in the number of patents for selected climate change mitigation technologies. Note 1: The binding-target countries in the first commitment period are: Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Ireland, Iceland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, the Netherlands, Portugal, Japan, Poland, Romania, Slovakia, Slovenia, Spain, Hungary, Sweden, Switzerland, Norway, New Zealand, the United Kingdom, the United States, Greece, Russia, and Ukraine. Note 2: The binding target countries in the second commitment period are: Australia, Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Kazakhstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Monaco, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, and the United Kingdom.

Figure 2 presents the historical trend in the number of patents related to climate change mitigation by technology type. All the patent types increase from 1990 to 2010 with some minor fluctuations, after which they decrease. The average number of patents related to energy and transportation exploded during the first commitment period before decreasing considerably after 2010, thus exhibiting a similar pattern to that shown for all patents combined in Figure 1. The number of patents for energy is 46.891 in 2010 and for transportation is 29.861 in 2011. However, the change in the number of patents for technologies related to buildings, the disposal of GHGs, and production is not significant

during the commitment periods. It is also worth noting that the production or processing of goods was the only category that did not decrease in the second period.

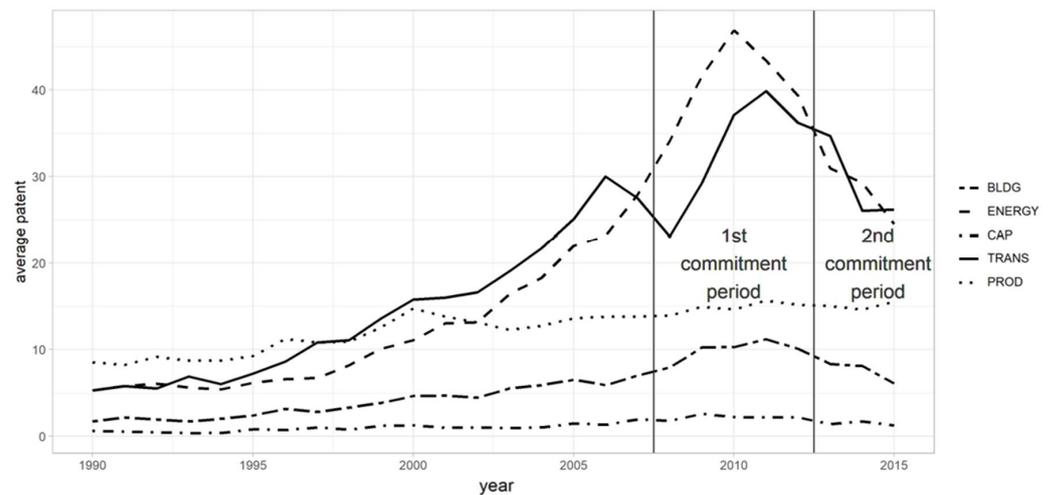


Figure 2. Historical trend of specific fields of selected patents. Note: Climate change mitigation technologies related to buildings (BLDG), energy generation, transmission, or distribution (ENERGY), capture, storage, sequestration, or disposal of GHGs (CAP), transportation (TRANS), and the production or processing of goods (PROD).

The trends shown in Figures 1 and 2 suggest that the implementation of the Kyoto Protocol has had an impact on technological innovation for climate change mitigation, with Figure 2 highlighting significant differences between selected patent types. Specifically, the protocol stimulated countries to encourage investment and R & D activities in mitigation technologies, and its flexible mechanisms promoted climate change governance effectively by transferring climate technologies among various actors from the perspective of open innovation. In this regard, this descriptive analysis demonstrates that green technological innovation helped increase the Kyoto Protocol's effectiveness, which has implications for the synergetic effect between innovation and international regimes for better climate change governance.

3.2. Impact of Innovation on Environmental Performance

Using green technological innovation data represented by the number of patents, this study investigates the impact of technological innovation and the Kyoto Protocol on emission reduction, and the synergetic relationship between innovation and the protocol. Table 2 summarizes the results of the impact of the Kyoto Protocol and innovation in a general impact model, and their synergetic impact on GHG emission mitigation in a synergetic impact model. The first and second columns show the results of the general impact model without the interaction variable, and the final two columns present the synergetic impact model with and without the consideration of time lag.

The general impact model is run twice for all and specific GHG mitigation technologies. The total version of the general model considers all patents for climate change mitigation technologies, while the specific patent version of the model tests individual patent types based on the classification system employed by the OECD patent database. The R^2 of each model is 0.698 and 0.477, representing a moderate model fit.

Table 2. Results of the impact of the Kyoto Protocol and green technological innovation on GHG emission mitigation.

Model	General Impact		Synergetic Impact	
	Total	Specific	No Time Lag	Time Lag
RAT	−0.048 *** (0.013)	−0.039 ** (0.017)	−0.026 (0.021)	−0.007 (0.022)
INNOV_TOTALENV	0.001 (0.005)	-	0.006 (0.007)	0.004 (0.009)
INNOV_BLDG	-	−0.020 *** (0.008)	-	-
INNOV_ENERGY	-	0.021 (0.013)	-	-
INNOV_CAP	-	0.004 (0.007)	-	-
INNOV_TRANS	-	0.022 ** (0.009)	-	-
INNOV_PROD	-	−0.028 * (0.016)	-	-
(RAT × INNOV)	-	-	−0.013 (0.009)	−0.006 (0.012)
L1.	-	-	-	0.001 (0.008)
L2.	-	-	-	−0.007 (0.007)
L3.	-	-	-	−0.015 ** (0.006)
GDP	0.574 *** (0.066)	0.114 (0.152)	0.582 *** (0.066)	0.694 *** (0.083)
EUSE	0.558 *** (0.071)	0.443 *** (0.136)	0.565 *** (0.071)	0.657 *** (0.079)
ELECPROD	0.048 *** (0.016)	−0.005 (0.025)	0.047 *** (0.016)	−0.017 (0.015)
RENEW	−0.096 *** (0.0173)	−0.068 *** (0.021)	−0.095 *** (0.017)	−0.084 *** (0.015)
Constants	−12.854 *** (0.955)	−7.497 *** (2.145)	−12.967 *** (0.958)	−14.391 *** (1.176)
R ²	0.698	0.477	0.698	0.575
Number of samples	790	236	790	544

Note 1: ***, **, and * denote significance levels of 1%, 5%, and 10%, respectively. Note 2: INNOV_TOTALENV represents all selected climate change mitigation-related technologies. The specific mitigation technologies are those related to buildings (INNOV_BLDG), energy generation, transmission, or distribution (INNOV_ENERGY), the capture, storage, sequestration, or disposal of GHGs (INNOV_CAP), transportation (INNOV_TRANS), and the production or processing of goods.

Participation in the Kyoto Protocol (RAT) has a statistically significant effect on the environmental performance in all models. Coefficients with a negative sign indicate that ratification of the Kyoto Protocol has an important effect on GHG emission mitigation. Specifically, ratification of the Kyoto Protocol leads to a 0.048% and 0.039% higher emission reduction than non-participants in the total and specific models, respectively. This is in line with previous studies that have reported that the Kyoto Protocol has a positive influence on emission reduction [23–28]. Thus, the results for the 54 countries investigated in the present study provide supporting evidence for the benefits of participation in international regimes.

The innovation variable INNOV_TOTALENV, which represents all patents related to climate change mitigation technologies is not significant in the total general impact model, while the general model for specific patent types clearly indicates the differential impact of different technologies. To compare the impact of different specific mitigation technologies, this study attempts to visualize the coefficient of the five mitigation technologies based on the regression results. Figure 3 presents an error bar plot with a 95% confidence interval (CI) for the impact of specific mitigation technologies based on the regression results.

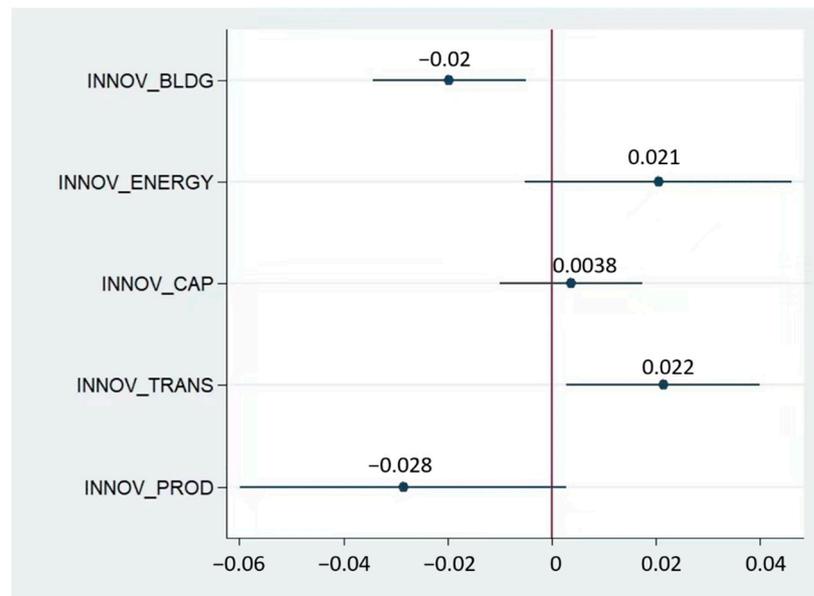


Figure 3. Error bar plot with 95% CI for specific mitigation technologies. Note: Climate change mitigation technologies related to buildings (BLDG), energy generation, transmission, or distribution (ENERGY), the capture, storage, sequestration, or disposal of GHGs (CAP), transportation (TRANS), and the production or processing of goods (PROD).

In the specific patent version of the general impact model, only three GHG mitigation technologies related to buildings, transportation, and the production or processing of goods are statistically significant. Innovation in mitigation technologies related to buildings and to the production or processing of goods have a significant effect on the reduction of GHG emissions. Previous studies have indicated that there is a difference in the impact of different technologies, with technologies that directly reduce carbon emissions effectively encouraging innovation [18,19]. Based on the results of the present study, improving mitigation technologies related to buildings (INNOV_BLDG) and production (INNOV_PROD) are likely to be effective in achieving emission reductions. An increase in the mitigation technology patents related to buildings of 1% leads to a 0.02% decrease in GHG emissions, and an increase in patents related to production of 1% leads to a 0.028% reduction in emissions.

Interestingly, mitigation technologies related to transportation have a negative impact on the reduction of GHG emissions. The results indicate that, if patents for transportation technology increase by 1%, GHG emissions will increase by 0.022%. One potential explanation for this counter-intuitive finding is the delay between the introduction of a technological innovation and its effects. Countries with CO₂-intensive transportation systems are likely to have a greater need for innovations in the transportation sector due to increased emissions [50], however, in the technological innovation diffusion process, the time lag between the creation, adoption, distribution, and practical effects of technology should be considered [51–54]. In this respect, even if these countries target the mitigation of emissions in the transportation sector via patent development, they may need more time to generate lower emissions using these advanced technologies. Further long-term

research is thus needed on the relationship between the innovation of specific technologies and their environmental performance.

The other technological innovation variables do not have a statistically significant effect on GHG reductions. These results offer important empirical evidence for the first hypothesis. Even though the overall degree of technological innovation related to climate change mitigation does not have a significant effect on GHG mitigation, certain technology types can effectively reduce emissions, thus supporting the findings of previous studies [38,55–57]. These results also have implications for future climate change regimes; in particular, programs or policies designed to promote technology transfer to improve environmental performance should consider the specific technology type based on the socio-economic context of the target countries.

In terms of the economic variables, fitted GDPP (\widehat{GDPP}) has a significant effect on increasing GHG emissions in the overall general model. This is in line with previous studies that have shown that economic development leads to a higher production of pollutants [3,42,43]. In particular, carbon emissions tend to increase in line with economic development because they are closely related to industrial development, which strongly depends on fossil fuel use. Therefore, to achieve sustainable development, employing strategies to overcome the tradeoff between GHG emissions and economic growth is required.

In terms of the control variables, the energy use of each country is statistically significant in all models, indicating that higher energy use leads to an increase in GHG emissions. Electricity production from oil, gas, and coal also has a significant impact on rising emissions. In contrast, renewable energy consumption is highly effective in mitigating GHG emissions, with a significance at the 1% level. Therefore, both international and domestic policies related to energy consumption, especially energy usage, are needed to facilitate sustainable development.

The third and fourth columns in Table 2 present the results for the synergetic effect model investigating the relationship between the Kyoto Protocol and innovation with and without a time lag. This model utilizes an FDL approach to test the long-term synergetic effect. To investigate the time-lag effect, this study applies a 1-year, 2-year, and 3-year time lag. The R^2 of the synergetic effect models without and with a time lag is 0.698 and 0.575, respectively, thus they are relatively reliable.

The ratification of the Kyoto Protocol and technological innovation for GHG emission reductions have no significant effect in the model without a time lag. In addition, although the synergetic effect of ratification and innovation ($RAT \times INNOV$) has a negative sign, it is not significant. In the time-lag model, no short-term elasticity, i.e., impact propensity, is observed, but the long-term elasticity is statistically significant. Specifically, the time-lag model shows that a 3-year time lag for the synergetic effect has a significant effect on GHG mitigation at a 5% significance level despite the lack of significance for ratification and overall green innovation. Because the model employs log variables for both the dependent and independent variables, the results can be interpreted as reflecting the presence of elasticity. Thus, if the degree of technical innovation increases by 1%, GHG emissions decrease by 0.015% in the long-term perspective.

These results provide empirical evidence for the long-term propensity of the synergetic effect of innovation on GHG emission reduction via the Kyoto Protocol. This means that those countries party to the Kyoto Protocol that exhibit high technological innovation in climate change mitigation more effectively reduce their emissions. In this regard, the time-lag models present interesting results that support the second hypothesis from a long-term perspective. These findings are also in accordance with previous research that has identified the dynamic relationship between climate change policies, innovation, and environmental pollution [16–20]. The present study indicates that this dynamic effect can potentially be applied to international policy.

The results for the other variables in the synergetic model are consistent with the general model. In all the versions of the time-lag model, \widehat{GDPP} is highly significant and

positive. Economic development increases GHG emissions, with a 1% rise in GDP leading to approximately 0.5–0.7% more emissions. The tradeoff between economic development and emission reduction is in line with previous studies [3,6]. Energy use and energy production from fossil fuels also negatively affect the reduction of GHG emissions, while renewable energy effectively strengthens GHG mitigation. This result supports previous studies that insist energy use and energy structure are important determinants of GHG emissions [44–46]. Thus, to effectively mitigate GHG emissions, a comprehensive strategy that considers economic and energy structure policies is required both internationally and domestically.

4. Discussion

4.1. Technological Innovation in the Kyoto Protocol

The evaluation of the impact of international regimes related to climate change on domestic environmental performance and consideration of their impact on the economy are crucial to ensuring their effectiveness. Even though many international environmental regimes have been established to promote environmental quality, their effectiveness is still open to debate. The characteristics of international policies, including the diversity of their stakeholders, differences in the socioeconomic situation of the parties involved, and the significant economic burden for implementation, strongly influence their effect [3,6,42,58,59].

In this respect, this study focuses on green technological innovation associated with the Kyoto Protocol, which is a representative climate change regime that adopts flexible market-based mechanisms such as the CDM [1,29,30]. Based on a descriptive investigation, this study finds interesting historical trends in the number of patents for climate change mitigation technologies. There has been a significant increase in the number of patents related to GHG mitigation during the first commitment period for the Kyoto Protocol. This trend highlights the potential for technical diffusion due to international regimes, which is in line with previous studies that have argued that flexible market-based mechanisms stimulate technological improvement [15,29]. In particular, energy and transportation-related technologies are likely to be strongly promoted by the Kyoto Protocol.

Based on the historical trend in climate change-related patents, this study empirically investigates their impact on GHG mitigation and on the effectiveness of the Kyoto Protocol. The results find a positive and significant impact of innovation associated with buildings and production-related technologies on reducing GHG emissions. This empirical evidence supports the first hypothesis that green technological innovation is effective in mitigating emissions. Moreover, the time-lag model reveals a synergetic effect between participation in the Kyoto Protocol and technological innovation in reducing emissions. This finding highlights the beneficial and synergetic effect of environmental policy on green innovation and environmental performance at both the domestic and international level. Even though previous studies have reported a beneficial effect of environmental policy on green innovation and environmental performance [16,17], only a few have attempted to investigate this at the international level [23–28]. Therefore, the present study extends previous literature on the relationship between environmental policy and innovation at the international level.

The present study also offers implications for enhancing the effect of the Paris Agreement, which has targeted a universal reduction in GHG emissions, for the parties involved. Countries around the world are struggling to devise countermeasures to respond to this new system. In particular, developing countries, which generally have low adaptive capacity to climate change but are greatly affected by the negative externalities of environmental problems, have expressed concern about the negative impacts of the ratification of international environmental regimes [4,6–9]. The findings show that participating in an international regime can promote green technological innovations, which leads to environmental improvement for the parties involved. Based on the Porter hypothesis, it is also expected that innovation can alleviate any inefficiencies inherent to international policies and moderate the tradeoff between economic development and emission reduction, which is illustrated in the results for the fitted GDP (Table 2). Moreover, from a long-term perspec-

tive, the synergetic effect of innovation enhances the regime effectiveness for environmental improvement.

Given the potential of technological innovation at the international level highlighted by the present study, it can be argued that green technological innovation can encourage participation in international climate change regimes and reinforce their effectiveness. To ensure sustainable development, future global climate change frameworks should establish strategies and provide guidelines for countries so that they can pursue and develop the most appropriate types of technical innovation. This would act as an effective incentive for countries with a low capacity for adaptation.

4.2. Open Innovation and International Regimes

As highlighted above, participating in an international climate regime promotes green technological innovation, which improves environmental performance and even eases inefficiencies, such as negative economic impact. The question is, then, why does this work and how can global climate governance strengthen the effectiveness of further international regimes? This study's empirical results provide a meaningful answer in the form of open innovation through international regimes, even though, because of its macro perspective, this study did not delve deeply into the micro internal mechanism of Kyoto Protocol-driven technological innovation.

The Kyoto Protocol could encourage innovation, especially open innovation, both domestically and internationally across countries. The open innovation paradigm makes it possible to solve problems and generate new ideas using internal and external collective intelligence, whereas traditional innovation theory, such as "closed innovation," emphasizes innovation within a certain sector [31,33,60–62]. In this respect, it is possible to consider the Kyoto Protocol as a window through which mitigation technology or knowledge crosses boundaries within and outside sectors, leading to green technological innovation. Specifically, domestically, parties with emissions reduction obligations establish green-focused domestic policies or regulations to mitigate GHG emissions, and various markets and businesses also pursue a green strategy because of social responsibility or business opportunities. Internationally, flexible mechanisms, for example the CDM, transfer mitigation technologies and knowledge from high- to low-capacity countries and sectors, usually from countries with emission reduction targets to non-obligated countries.

Thus, the following implications regarding the effectiveness of international regimes from the perspective of the open innovation can be derived from this study. First, further global climate governance should facilitate network creation and matchmaking of climate change mitigation technology. The Climate Technology Centre and Network (CTCN), which was established under a Technology Mechanism to promote action on climate change technology development and transfer [1,63], has great potential for this role. As Lee and Mwebaza [63] mentioned, the CTCN's collaborative approach focuses on open innovation to facilitate diffusion of climate technologies based on developing countries' requests and attract technology experts and providers. Thus, effective international regimes can expand their role as facilitators of open innovation by looking to existing institutions like CTCN as examples. If international regimes provide active platforms for the integration of mitigation capabilities from continuous interaction among diverse countries, institutions, and stakeholders through open innovation, dynamic open innovation can contribute to achieving effective GHG emissions reduction and sustainable development. Second, in highlighting the beneficial impact of open innovation through international climate regimes, sharing risks should be considered. While innovation brings more resources, it can also bring more scientific and practical risk [64]. In particular, for developing countries, the platform for open innovation by international regimes can reduce the cost and time of the development process of green technologies [65–67] and inspire them to participate in international climate regimes.

5. Conclusions

This study examined the role of technological innovation in improving the effectiveness of the Kyoto Protocol in terms of GHG mitigation. Using existing data on patents, whether technological innovation is effective in mitigating GHG emissions and whether it generates a significant synergetic effect with the Kyoto Protocol were investigated. To determine the degree of technological innovation for each country, this study employed patents for climate change mitigation technologies and established a country-based panel dataset from 1990 to 2015 that included 54 countries.

The results showed that the number of patents related to GHG mitigation significantly increased during the first commitment period for the Kyoto Protocol, indicating a strong relationship between the protocol and technological innovation. It was also found that mitigation technologies related to energy and transportation were strongly promoted by the protocol. Findings from the research models suggested that innovation in mitigation technologies related to buildings and the production or processing of goods were effective in reducing GHG emissions. Furthermore, the synergetic effect between ratification and innovation was significant for GHG emission mitigation in the long term, but it was not significant in the model with no time lag. The results also revealed that energy-related variables were strongly associated with emission reduction. As a whole, these results underline the importance of international and domestic energy policies.

This study contributes to international climate change governance by suggesting that the influence of an international regime on the member countries' socioeconomic conditions needs to be more strongly considered. In addition, by utilizing patents as an indicator of technological innovation, this study provides empirical evidence for the relationship between international regimes and green innovation. The findings can serve as a foundation for the advancement of technological and socioeconomic development through the adoption of the Porter hypothesis and open innovation theory at the international level. The findings of the present study also offer implications for international regimes in terms of promoting GHG mitigation targets. In particular, policies and strategies for technology transfer and assistance should focus more on specific mitigation technologies, and the synergetic effect between international policies and domestic technological improvement should not be ignored. Furthermore, through technology development, future international regimes should provide active platforms for the open innovation process so that climate change mitigation technology resources can be integrated, and risks shared.

Furthermore, this study's findings suggest a useful and realistic new direction for developing countries seeking to mitigate GHG emissions in the future under the new Paris Agreement framework. In this framework, all countries need to establish new mitigation efforts, which can lead to negative economic externalities. The empirical evidence from this study supports the positive impact of participation in international regimes and of innovations on the reduction of emissions.

Future research should consider the impact of technological innovation on economic performance in more detail, particularly whether green innovation can benefit the economy. In addition, follow-up studies with larger datasets over a longer time period that include the entire second commitment period are required. Furthering the understanding of the virtuous cycle of innovation opens up new possibilities for global sustainable development.

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