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How collaboration with G7 countries drives environmental technology innovation in ten Newly Industrializing Countries

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ABSTRACT

The development and deployment of environmental technologies (ETs) is critical to avert further environmental destruction, to significantly reduce emissions and to halt climate change. Innovation in ETs is particularly pertinent in newly industrializing countries (NICs), since they will soon overtake developed countries in terms of aggregate greenhouse gas emissions, but also have the economic strength required to scale up ETs rapidly. Even though NICs now supply a substantial share of low-carbon technologies, multilateral climate change policies continue to focus narrowly on technology transfer rather than collaboration and co-invention. In addition, G7 countries have vocalized their intention to collaborate with developing countries to innovate and diffuse ETs, suggesting that collaboration can be a key driver of developing country innovations. Against this background, we conduct an empirical analysis of ten NICs from 1990 to 2017 and demonstrate that technological collaboration with G7 countries significantly increases ET innovation in NICs.

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Introduction

To combat runaway greenhouse gas (GHG) emissions—the main culprit of climate change—environmental and climate policies have induced global demand for innovations in Environmental Technologies (ETs)[1] (Johnstone et al., 2010). However, much of the research thus far has focused on ET innovation in the developed world, particularly OECD economies (Blind, 2012; Nesta et al., 2014; Polzin et al., 2015). If developing countries are the focus, the question tends to be on technology transfer rather than domestic innovations (Herman, 2021; Lema et al., 2015).

Moreover, of the research that does sufficiently explore ET innovation in the developing countries, most fail to ask the most pressing question of *how* these innovations have occurred (Binz et al., 2017; Lema & Lema, 2013; Never & Betz, 2014). If, as evidence suggests, Newly Industrializing Countries (NICs) have been responsible for over one third of environmental technology innovations in recent years (Dechezleprêtre & Glachant, 2014; Walz et al., 2017), then policymakers may need to reassess how climate technology finance, innovation, and transfer are currently framed within multilateral climate change negotiations (e.g., the Paris climate agreement and the Kyoto Protocol) (Bazilian et al., 2008; Binz et al., 2017). Therefore, shedding light on this important research question would have important ramifications for policy and policy makers—in both multilateral negotiations within the United Nations Framework Convention on Climate Change (UNFCCC), as well as within local policy spheres in developing countries (Dechezlepretre et al., 2020; Herman, 2021). These salient policy issues are highlighted throughout our paper; indeed, our empirical results underscore the need to develop new conceptual and policy approaches, especially for multilateral climate policy and research collaboration in light of the findings.

Domestic innovation in emerging economies will also be instrumental to stay in line with the Paris Climate agreement (Acemoglu et al., 2016; Pegels & Altenburg, 2020). In addition, ETs in developing countries are critical to economic development and to ensure innovations match well with local technological capacities and needs (Cimoli et al., 2009; Lema et al., 2015; Quitzow, 2015). But cross-country collaborations are vital. As recently outlined by Lord Nicholas Stern (*G7 leadership for sustainable, resilient and inclusive economic recovery and growth*), G7 countries have expressed much support for cross-country collaboration on green growth and technological innovation for environmental technologies. Following the COVID crisis, there is a "unique opportunity for the G7 to take bold action to 'build back better' –to realise the growth and jobs story of the 21st century and ensure environmental sustainability" (Stern, 2021: 5). Indeed, the recently announced "Clean Green" and the "Build Back Better for the World" G7 initiatives directly

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[1] Environmental technologies, according to the OECD (OECD, 2017), include 187 different technology domains such as air pollution abatement, waste management, environmental monitoring, as well as climate change mitigation technologies (CCMTs).

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address collaboration for the climate transition to counter China's Belt and Road Initiative.[2]

In this paper we investigate an important group of developing economies, the Newly Industrializing Countries (NICs)—defined here as Brazil, China, India, Indonesia, Malaysia, Mexico, Philippines, South Africa, Thailand, and Turkey—and ask a salient question: does technological collaboration between G7 and NICs induce ET innovations in the latter? In the following section, How collaboration drives innovation in NICs and why it matters, we discuss how and why collaboration can drive innovation in NICs. We situate our theoretical framework within the Technological Innovation Systems (TIS) literature, followed by a discussion of the IEA's technology-oriented agreements (TOAs), which have explicitly sought to increase collaboration on environmental technologies across countries. Thereafter, the Data and method section introduces our data and model. The Results and discussion section discusses the empirical results, which span a 26-year period from 1990 to 2015. The final section closes with a discussion of the relevant policy implications.

How collaboration drives innovation in NICs and why it matters

Since the early 2000s, environmental technology patents have accelerated in step with the ratcheting up of climate and environmental policy stringency in countries throughout the world (Dechezleprêtre et al., 2013; Matsuo & Schmidt, 2019; Noailly & Ryfisch, 2015). Indeed, research shows that some of these NICs have progressed markedly in recent years with respect to ET innovations (Binz et al., 2017; Mealy & Teytelboym, 2020; Quitzow, 2015; Quitzow et al., 2017). Innovation in ETs in NICs, at the same time, is shown to catalyse technological and economic "catch-up" (Matsuo & Schmidt, 2019; Rodrik, 2014; Walz et al., 2017; Wu & Salzman, 2014). Technological catch-up—an outgrowth of the endogenous growth literature (Romer, 1990)—rests on mechanisms such as "learning-by-doing" and "learning-by-interacting."

To be sure, collaboration for climate technology development has been recognized as a priority within global climate governance (de Coninck et al., 2008). For example, in the UNFCCC's founding agreement, Article 4.1 and Article 9 address cooperation in environmental innovations; Articles 2.1 and 10 of the Kyoto Protocol call for cooperation on innovation of "environmentally sound technologies" while, most recently, the Paris Agreement's Articles 10 and 13 call for "cooperative action on technology development and transfer" as well as "capacity-building" for developing countries. Yet, the empirical research remains largely silent on the issue of collaboration (Giuliani et al., 2016; Schmid et al., 2016), levying much greater emphasis on inward technology transfers (Das, 2011; de Coninck et al., 2007; Dechezleprêtre et al., 2008; Haites et al., 2006), specifically through the UNFCCC's Clean Development Mechanism (CDM) (Haščič & Johnstone, 2011; Murphy et al., 2009; Ockwell et al., 2010; Schneider et al., 2008; Seres et al., 2009; Youngman et al., 2007). This somewhat narrow focus on North-South technology transfer might require major revision given the remarkable progress in NICs' innovation systems and growing trends in collaboration (Binz et al., 2017; Brewer, 2008; Byrne et al., 2012). In addition, studies which focus squarely on technology transfer are largely silent on local innovative capacities of NICs—which is perhaps a more pressing issue due in large part to unique technological needs and capacities, as well as the important economic role that innovation can play (Behuria, 2020; Lema et al., 2018; Perkins & Neumayer, 2005).

While much of the prior research focuses on the Kyoto Protocol's CDM and how it helped to transfer ETs and other climate technologies from developed to developing countries (Haščič & Johnstone, 2011; Karakosta et al., 2010; Schneider et al., 2008; Seres et al., 2009), a much smaller group of studies pay attention to domestic innovative capacities in NICs (Herman, 2021; Lema et al., 2015). An even smaller group of studies investigate how such innovations have occurred (Never & Betz, 2014), although some empirical evidence suggests that, indeed, collaborations and other bilateral relationships are instrumental (Herman & Xiang, 2022). Indeed, in a related paper, Herman (2022) explores how developing countries collaborate with Germany and the US to innovate in climate change mitigation technologies (CCMTs).

There are some other weaknesses with the predominant focus on the CDM. First, many technologies transferred under the CDM were *ozone* mitigation technologies, which met the demands of the Montreal Protocol rather than agreements set forth under the UNFCCC; such technologies represent an entirely different technology domain since the latter do not explicitly deal with the transition to a climate-neutral world (Dechezleprêtre et al., 2008; Doranova et al., 2010; Murphy et al., 2009). This implies that, from the perspective of NICs, the CDM largely failed to deliver the technologies required to combat climate change. Additionally, the technologies transferred were not very innovative (Falkner, 2016), nor was domestic technology development a main concern for both the Kyoto Protocol and the CDM (Karakosta et al., 2010). While not invalidating previous research on the CDM and NICs, the research attention given to the CDM and technology transfer is slightly out of step with current realities (Walz et al., 2017).

Why is ET innovation in NICs important?

Innovation in ETs in NICs is not only a climate imperative, it is also an economic imperative (Lema et al., 2018). NICs can leverage domestic innovation as a tool for technological and economic "catch-up"—meaning that they can improve their economies and their environment simultaneously (e.g., the achievement of green growth) (Matsuo & Schmidt, 2019; Rodrik, 2014; Walz et al., 2017; Wu & Salzman, 2014). In this vein, researchers have begun to examine these important concepts under the rubric of green growth for developing economies (Blohmke, 2014; Perkins & Neumayer, 2005; Yap & Truffer, 2019), discussed in more detail below. Indeed, well-crafted climate and green growth policies—because they meet development, environmental, and economic needs all at once—can create "win-wins" for both the environment and the economy (Goldthau & Hughes, 2020).

Beyond economic catch-up, innovation in ETs can also enable NICs to "leapfrog" straight past high-emissions technologies (e.g., coal power) and directly to renewable energy technologies, with considerable emissions mitigation potential (Gosens & Lu, 2013; Hansen & Lema, 2019; Watson & Sauter, 2011). Leap-frogging is important because it would help NICs to bypass heavily-polluting fossil fuel industries, industries which have contributed to rampant GHG emissions since the dawn of the industrial revolution. Considering the above, finally, innovation in ETs in NICs has important implications for meeting the Paris Climate Agreement of limiting global average temperature rise to below two degrees Celsius by the end of the century (Pegels & Altenburg, 2020).

Technological innovation systems

The broader body of literature on technological innovation has already provided much evidence that international collaboration can significantly increase the rate of inventions (Asheim & Herstad, 2005; Carlsson, 2006; Guerrieri & Pietrobelli, 2006; Ma & Lee, 2008). But this subject is not widely researched for ETs, despite their obvious importance for meeting global climate targets. Research on Technological Innovation Systems (TIS) and low-carbon transitions suggests that developing countries can nurture their own innovation systems rather than exclusively relying on inward knowledge or technology transfer from the developed countries (Bergek et al., 2008; Geels et al., 2017; Nill & Kemp, 2009). Initially developed by evolutionary economists (Nelson & Winter, 1982), TIS expands the National Innovation Systems (NIS) concept to encompass innovations that are globally dispersed and induced by targeted environmental and climate policies (Bergek et al., 2008). This means that the TIS concept, differently than NIS, more

[2] https://www.natlawreview.com/article/clean-green-to-counter-belt-and-road.

effectively accounts for collaborative efforts across different countries and jurisdictions, and therefore better addresses innovations in specific technologies, such as ETs (see Geels, 2014 for a review of TIS).

Indeed, Gosens and Lu (2013) demonstrate that NICs innovate in renewable technologies through effective development in TIS capacities. Similarly, Furtado and Perrot (2015) point out that the strong TIS's in China and India have led to much more wind energy innovation than in Brazil and South Africa. Quitzow (2015) explains how inward knowledge spillovers and domestic absorptive capacities play a crucial role for TIS's with respect to ETs. Absorptive capacities increase the likelihood that knowledge spillovers are integrated into the domestic economy, which also has the effect of reducing reliance on foreign technologies (ibid).

Due in part to strong TIS's, a small yet growing body of scholarship on innovation in developing countries demonstrates that Brazil, India and China (the "BICs") have significantly improved their competitiveness in these technologies in recent years (Chandra et al., 2009; Kim & Kim, 2015; Mathews, 2009). Indeed, the BICs economies now supply a large share of renewable energy technologies including biofuels, wind, solar, and energy storage (Lema et al., 2018; Lema & Lema, 2013; Mealy & Teytelboym, 2020; Yu et al., 2016). Assuming a strong TIS exists, NICs can leverage "international information exchange and collaboration on the generation and diffusion of knowledge and innovation" for ETs (Pietrobelli & Rabellotti, 2011: 1261). In what follows, we discuss specific policy tools and multilaterl agreements which have enabled greater collaboration for ET innovation throughout both developed and developing economies, with attention given to how TIS and NIS have enhanced such collaborations.

Technology oriented agreements

Environmental and climate change technologies are complex and require substantial dedication to research, funding, and developmental collaboration (Blohmke, 2014). A relatively small group of scholars have explored Technology Oriented Agreements (TOAs) and how these have driven learning and knowledge transfers for environmental technologies (de Coninck et al., 2008; Justus & Philibert, 2005; Newell, 2010). TOAs can help to induce innovation in these technologies by "fostering RD&D or [driving] efforts that 'pull' technologies into the market" (de Coninck et al., 2008: 337). In addition, given that "firms may find a demand-pull to innovate coming from international actors rather than from national ones" (Peñasco et al., 2017: 61), the growing importance of cross-border innovation inducement and collaboration is likewise recently explored (Herman & Xiang, 2019; Herman & Xiang, 2020; Herman & Xiang, 2022).

Similarly, the International Energy Agency (IEA) has made important policy contributions to collaboration on climate technology development. For example, its Implementing Agreements (IAs) focus on collaboration across borders (Haščič et al., 2012; Haščič & Migotto, 2015; Philibert, 2004); as early as the 1970s, such agreements have enabled countries to collaborate on energy technologies through exchange of scientific information and thereby provide "a unique platform for fostering co-invention" (Haščič et al., 2012: 9). More specifically, IAs help to coordinate and plan energy technology innovation, development and deployment. They promote joint evaluation and pooling of scientific and technical information. Further, they help to set up research and pilot facilities, as well as promoting the exchange of policy information, technological developments, and energy regulations which are beneficial to ET development and deployment. Finally, the IAs help develop joint innovation programs for energy technologies (Article 2, IEA IAs).

Consequently, the IEA's IAs promote knowledge exchange and generate new research synergies among developed and developing countries (de Coninck et al., 2007; Figueroa, 2010; Haščič et al., 2012; Wang et al., 2013). Accordingly, Haščič et al. (2012) assert that IAs have been particularly important to help share knowledge about climate technologies "across borders and creat[e] research collaboration synergies…[and] potentially contribute to achieving faster technological innovation at lower cost" (Haščič et al., 2012: 10). More recently the IAs have been rebranded as the Technology Collaboration Programme (TCP), with a more concerted focus on renewable energy technologies. The TCP brings together 6000 experts from 55 countries and 300 public and private organisations with the aim to advance R&D and commercialisation of energy technologies.[3] For renewable energy, the current technological focus is on bioenergy, concentrated solar power, geothermal energy, hydrogen, hydropower, ocean systems, solar photovoltaic, solar heating and cooling, and wind energy systems (ibid).

Haščič et al. (2012) and Justus and Philibert (2005) are among the few studies to analyse the role of the IAs in driving collaboration and innovation in ETs and CCMTs. In an empirical analysis, Haščič et al. (2012) find that collaboration on R&D and information exchange has significantly reduced costs for solar energy technologies. Further they show in a panel of 33 OECD countries from 1970 to 2009 that IAs have, indeed, been significant drivers of co-invention of CCMTs—leading to an increase in co-inventions of 90% for two CCMTs in particular, wind energy and fuel cells. The rate of co-invention is even higher for solar PV, biofuels, and Carbon Capture and Storage (CCS). In line with our investigation here, they also find that BRICS (Brazil, Russia, India, China, South Africa)—which includes four countries we include in our NICs sample—are highly innovative in renewable energy technologies due in large part to collaboration agreements. However, despite these interesting findings, surprising little research has been conducted since then to examine the effects of collaboration for climate technology innovation in developing countries. Bearing in mind this research gap, below we discuss the importance of collaboration across borders for ET innovation in NICs, which grounds our hypothesis and empirical approach.

Collaboration and innovation

As discussed above, collaboration is an important focal point for enacting more swift policy approaches to climate change (Fernandes et al., 2021; Golombek & Hoel, 2011). This is true in developed and developing countries alike (Ockwell & Mallett, 2013), and suggests that technological cooperation and collaboration can become paramount to achieving global climate policy objectives. Consistent with our approach in this paper, researchers have also explored collaboration through co-invention from a geographical perspective (Archibugi & Pietrobelli, 2003; Cowan et al., 2007; Jaffe et al., 1993). Indeed, co-invention is widely prevalent in the global cleantech innovation paradigm due to widespread demand and high costs of innovation (Acemoglu et al., 2016). As such collaboration can be an invaluable "conduit" for domestic innovation in developing countries (Laursen & Salter, 2006; Zoo et al., 2017).

The broader literature on innovation shows that economies as diverse as Brazil, Italy and Taiwan have successfully collaborated with other countries to become more technologically innovative (Bazan & Navas-Alemán, 2004; del Río et al., 2015; del Río et al., 2016; Guerrieri & Pietrobelli, 2006; Horbach, 2016). For instance, Ma and Lee (2008) show, using a sample of South Korea, Taiwan, and eight OECD countries, that collaboration and co-patenting have steadily increased since the mid-1980s, implying that collaboration is becoming increasingly more sophisticated and globally dispersed. They assert that these trends are likely to continue as the "world has begun to embrace the paradigm of the globalization of technology resulting from increased collaborative efforts" (Ma & Lee, 2008: 379). Indeed, within the economies that have risen the fastest (Korea, Singapore, Taiwan, etc.), collaboration with foreign entities has been crucial (ibid). These findings suggest

[3] https://www.iea.org/programmes/technology-collaboration-programme.

that the international dimension of innovation is perhaps as important as the national system of innovation (Asheim & Herstad, 2005; Carlsson, 2006).

Along these lines Gereffi et al. (2005) show that developing countries leverage global value chains to enhance knowledge spillovers and learning, with an important analysis of China and solar PV technologies given by Zhang and Gallagher (2016). Elsewhere this phenomenon is referred to as "the co-evolution of domestic and international knowledge linkages" (Guerrieri & Pietrobelli, 2006: 22). Consequently, the signing of bilateral cooperation agreements on Intellectual Property Rights with developed countries is likewise shown to lead to more co-invention and learning-by-interacting effects (Barton, 2007; Ryan, 1998). Indeed, intellectual property protection enables not only innovation in developing countries but also the ability for innovations to be exported to developed economies, with positive economic and technological benefits (Hudson & Minea, 2013). Conversely, Rai et al. (2014) show that weak intellectual property regimes in developing countries tend to reduce the diffusion of climate technologies, with negative implications for their economies and innovation inducement.

The hypothesis

The logic behind collaboration is relatively straightforward: to increase technological specialisations and to garner economic and financial advantages in global markets (Nepelski & De Prato, 2012). From a quantitative empirical approach, Guellec and van Pottelsberghe de la Potterie (2001) are among the first to examine the internationalization of patenting and R&D. They suggest that collaboration is sensible during firm acquisitions (which necessitate R&D collaboration), mergers, and adaptation of products to foreign markets to gain competitive advantages and to take advantage of lower wages. Their empirical results show that from 1980 to 1995 R&D collaboration, co-patenting and co-invention nearly doubled. With respect to renewable energy, Tang and Popp (2016) draw attention to the benefits of accruing knowledge from other countries to spur on wind technology innovation. In what they refer to as "learning-by-interacting," they show how firms in China incrementally innovate in wind technologies through technological collaborations with OECD firms. From this evidence Tang and Popp suggest that collaboration is, likewise, a key element for increasing the rate of renewable energy innovation in developing economies. A recent patent network analysis, moreover, demonstrates that ET innovation has become highly collaborative (Li et al., 2021), especially when countries share similar TIS elements. Another recent study by Herman (2022) shows that collaboration between eight emerging economies (Brazil, China, India, Israel, Mexico, Russia, South Africa, and Turkey) and two developed countries (Germany and the US) significantly improves innovation in CCMTs in the former.

In short, while the studies mentioned previously mark important contributions to the literature, the consistent and stable increase in innovation in NICs in recent years calls for deeper empirical analysis to shed light on how this remarkable progress has happened (Bunnell & Coe, 2001; Fromhold-Eisebith, 2007; Lema et al., 2015; Walz et al., 2017). Indeed, collaboration and co-invention between developing and developed countries marks a fertile research domain (Bagchi, 2011; Kahrobaie et al., 2012; Singh, 2005; Tseng, 2009). Therefore, the outsized research and policy focus on question of how to transfer ETs from developed countries to developing countries seems less relevant in light of technological shifts and more visible collaborative efforts. A more important question becomes how technological collaborations increase the rate of innovation in the NICs. This leads us to our hypothesis:

Technological collaboration between G7 countries and NICs leads to increasing rates of environmental technology innovation in NICs.

Data and method

Sample of analysis

The sample of countries in our analysis includes ten NICs (Brazil, China, India, Indonesia, Malaysia, Mexico, Philippines, South Africa, Thailand, and Turkey). Their collaboration partner countries consist of the G7 countries (Canada, France, Germany, Italy, Japan, the UK, and the US). As remarked in the introduction, we select the G7 countries because these countries have specifically stated their intent to finance and collaborate with developing economies in order to innovate and diffuse key climate technologies (Stern, 2021). To reiterate, we are interested in assessing how collaboration between G7 countries and ten NICs can induce innovation in ETs in the latter. Due to data availability and the lag structure employed in our analysis, the time period covers the years from 1990 to 2017 for the dependent variable and from 1990 to 2015 for the independent variables.

Dependent variable

Our dependent variable is patents in environmental technologies (ETs) by NICs. As mentioned above ETs, according to the OECD (OECD, 2017), include 187 different technology domains such as air pollution abatement, waste management, environmental monitoring, as well as CCMTs. Patents are an important proxy for innovation since they are a store of knowledge and have an intrinsic value to inventors and firms (Griliches, 1989; Griliches, 1998; Hall et al., 1984; Hall et al., 2001). Indeed, patent data are widely used to examine innovation in climate and environmental technologies (Brunnermeier & Cohen, 2003; de Vries & Withagen, 2005; Kittner et al., 2017; Lanjouw & Mody, 1996; Popp et al., 2011). The data for our dependent variable is obtained from the OECD statistics website.[4]

Independent variable of interest

In line with the empirical models developed by Haščič et al. (2012), Guellec and van Pottelsberghe de la Potterie (2001), and Justus and Philibert (2005), we proxy collaboration with co-invention data, which is also supplied by the OECD statistics website. A co-invention is defined as an invention that is patented by residents in two or more countries. The data, therefore, has important implications for the geographical dispersion of invention (Haščič et al., 2012). For instance, if a Chinese resident or firm patents an invention alongside a German resident or firm, this is considered a co-invention. Finally, a co-invention also signifies knowledge flows and knowledge spillovers, which are pertinent to the eventual success of a local TIS (Cowan et al., 2007; Durán-Romero & Urraca-Ruiz, 2015; Ejermo & Karlsson, 2006; Guellec & van Pottelsberghe de la Potterie, 2001; Jaffe et al., 1993).

Since the dependent variable and the independent variable of interest are both measured by patents, it is essential not to double count the same patents in these two variables (Haščič et al., 2012). To remedy this potential issue, we subtract the overlapping patents from the calculation of the independent variable. As a result, the independent variable of interest is constructed as co-invention between a NIC and all G7 countries in all technologies except environmental technologies. Mathematically, the independent variable of interest is given by

$$\sum_{j=1}^{7}\left(\text{All Technologies}_{ijt}-\text{ETs}_{ijt}\right)$$

where i denotes a NIC, j denotes a G7 country, and t denotes a year. In addition, All Technologies and ETs indicate co-invention between NICs and G7 countries. Here we aggregate co-invention between a NIC and

[4] https://stats.oecd.org/.

all G7 countries, instead of using seven individual co-invention variables, to avoid the potential multicollinearity problem (Fagerberg, 1987).

To better understand the independent variable of interest we plot this variable over years by each NIC. The plots are shown in Fig. 1. In each plot the horizontal axis denotes the year ranging from 1990 to 2015. The vertical axis indicates collaboration with G7 in all technologies except ETs. Since the values of this variable vary significantly from country to country, we divide the sample into three groups, given by three different rows. The y-axis ranges from 0 to 100 for the first row, from 0 to 400 for the second row, and from 0 to 5000 for the third row. The first row includes Indonesia, Philippines, South Africa, and Thailand, and collaborations with G7 for these four countries are the lowest, usually with not more than 100 per year. Brazil, Malaysia, Mexico, and Turkey are listed in the second row, and their collaborations with G7 are somewhat higher than the first group, with values around 200 per year in many cases. The third row shows China and India, and they demonstrate much higher levels of collaboration with G7, with China close to 5000 and India over 3000 in certain years. In addition to the significant cross-country heterogeneity among the ten NICs, collaboration with G7 varies greatly across different years as well, with a general increasing trend over time.

Control variables

Consistent with previous literature on environmental technology innovation (Böhringer et al., 2017; Dasgupta & De Cian, 2018; Herman & Xiang, 2020; Johnstone et al., 2010), we include a number of control variables. These six variables can be considered to measure important TIS characteristics of NICs, and include GDP, civil liberties, trade (as % of GDP), inflow of foreign direct investment (as % of GDP), electricity production from renewable sources excluding hydroelectric (as % of total), and a Kyoto Protocol dummy. All the control variables, except for civil liberties and the Kyoto Protocol dummy, are taken from the World Bank's World Development Indicators. GDP indicates a NIC's total economy size, which is expected to positively affect its innovation capacity. Civil liberties measure a NIC's institutional quality, with the data downloaded from the Freedom House. As argued in related literature, institutional quality improves a country's innovative capabilities (Herman & Xiang, 2020; North, 1993). Both trade and foreign direct investment signal the competitiveness of NICs on the international market as well as their level of globalization (Herman & Xiang, 2022). Therefore, trade and foreign direct investment are likely to increase innovation. Electricity production from renewable sources—with the exception of large hydropower, which is not often considered a sustainable energy source (Sipahutar et al., 2013)—is expected to be positively correlated with innovation in environmental technology, as renewable energy technologies are an important component of environmental technologies. Lastly, Kyoto Protocol dummy equals one if a NIC has signed and ratified the Kyoto Protocol and zero otherwise, mirroring the approach by Johnstone et al. (2010).

Regression model

To summarize, we build a regression model to empirically evaluate our hypothesis that technological collaboration between G7 countries and NICs is likely to increase ET innovation in ten NICs. Because the dependent variable is continuous, a linear model is estimated. In addition,

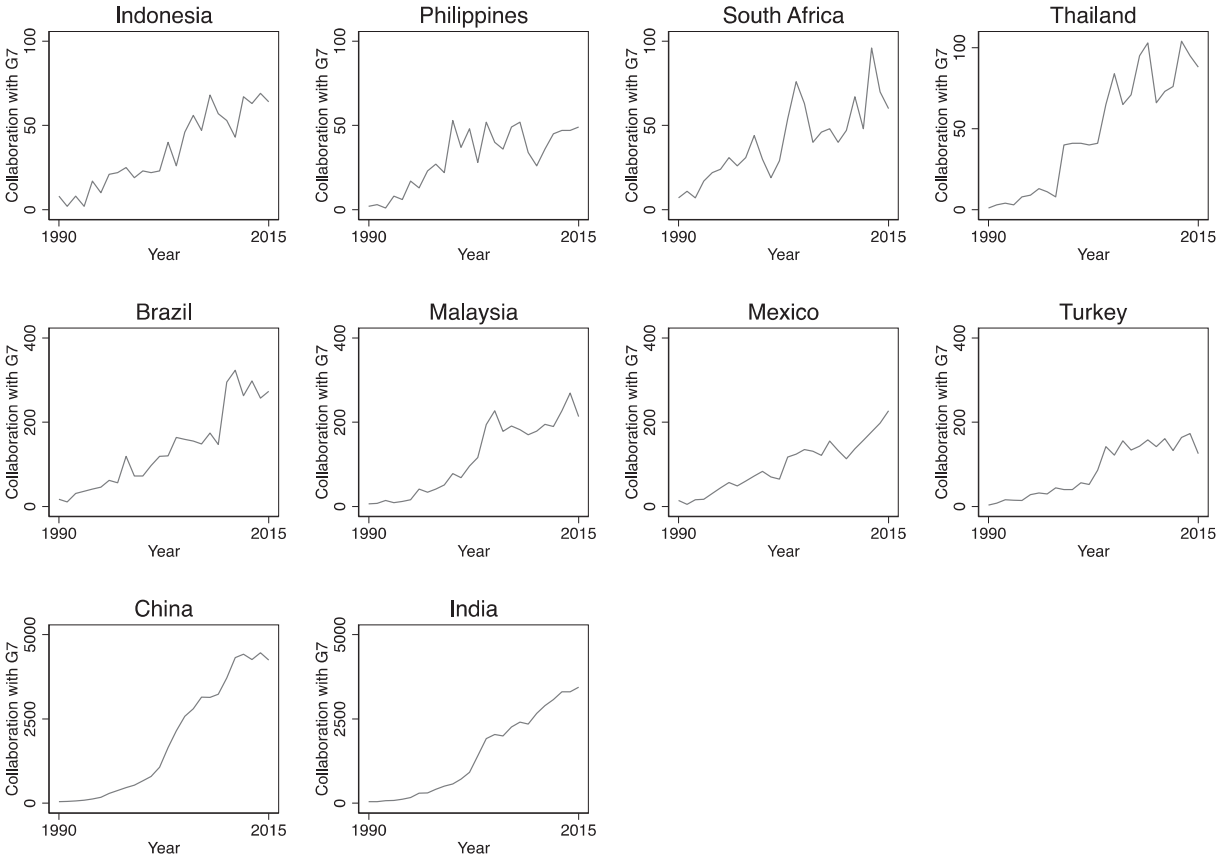


Fig. 1. Collaboration with G7 in all technologies except environmental technologies, by NIC.
Notes:
First row: y-axis ranges from 0 to 100; second row: y-axis ranges from 0 to 400; third row: y-axis ranges from 0 to 5000.
The vertical axis collaboration with G7 denotes co-invention between a NIC and all G7 countries in all technologies except ETs.

since research and development, and in turn new innovations, take time to occur, we lag all independent variables between 0 and 2 years in different models to demonstrate robustness. To account for unobservable country-specific heterogeneity, country fixed effects are included in the estimation.[5] The specific regression model we run is shown in the following:

$$Y_{it} = Collaboration_{i(t-x)} + Z_{i(t-x)} + U_i$$

- Where i indexes a NIC, t indexes a year, and x specifies a year lag.
- Y is the dependent variable, representing patents in ETs by NICs.
- Collaboration denotes co-invention between a NIC and all G7 countries.
- Z represents a vector of control variables, which include GDP, civil liberties, trade (% of GDP), inflow foreign direct investment (% of GDP), electricity production from renewable sources excluding hydroelectric (% of total), and Kyoto Protocol dummy.
- U denotes country fixed effects.

Results and discussion

We present the empirical results in this section. Before showing the multivariate regression results, it is useful to examine the bivariate relationship between each independent variable and the dependent variable. Therefore, seven plots are displayed in Fig. 2. In each plot the horizontal axis indicates an independent variable and the vertical axis denotes the dependent variable patents in ETs by NICs. In addition, each dot is an observation for a total of 260 observations, and the line represents the predicted linear relationship between the two variables. Several interesting findings emerge. First, the positive correlation between collaboration with G7 and patents in ETs by NICs provides some preliminary evidence to support our hypothesis. GDP, FDI net inflows (% of GDP), and the Kyoto Protocol dummy all demonstrate a positive correlation with the dependent variable, as expected. Since a larger value of Freedom House's civil liberties indicates less freedom, the positive correlation between civil liberties and the dependent variable runs counter to our expectation, which is probably due to China as a non-democracy and the largest innovating country in the group. Finally, contrary to the expectation, both trade (% of GDP) and electricity production from renewable sources show a slightly negative correlation with the dependent variable.

While the plots in Fig. 2 show interesting preliminary findings, the bivariate analysis is subject to the potential omitted variable bias problem. Therefore, in the remaining part of this section, we test our hypothesis using a multivariate regression analysis. As previously mentioned, a linear model is estimated since the dependent variable is continuous. To account for unobservable country-specific heterogeneity, country fixed effects are included in the estimation. The regression results are displayed in Table 1. In the table, three models are estimated to demonstrate robustness of the results when the independent variables are lagged 0, 1, or 2 years.

In Table 1, our independent variable of interest—collaboration with G7 countries—shows positive and statistically significant coefficients in all three models. That is, collaboration with G7 countries increases innovation in ETs for NICs. Note this collaboration variable excludes ETs, meaning that the increase in the dependent variable is not due to counting ETs from the independent variable collaboration. The coefficient size of collaboration reduces when the independent variables are lagged for more years, suggesting the effect of collaboration diminishes over time. As far as we know, this is the first systematic evidence that demonstrates collaboration between G7 and the ten NICs exhibits positive effects on innovation in ETs in the latter over a long time period.

Several other important findings emerge from Table 1. First, GDP increases innovation in ETs, but its coefficient is statistically significant only when the independent variables are lagged by two years. This finding provides some weak evidence that a larger economy is likely to innovate more. When a NIC trades more with other countries, it is more likely to innovate in ETs. Put differently, a more open and competitive country is better equipped to innovate in ETs. This comports with findings in the broader technological innovation systems literature on developing countries (Arocena & Sutz, 2002; Metcalfe & Ramlogan, 2008). Interestingly, after controlling for other variables, the effect of trade changes from negative in Fig. 2 to positive in Table 1, which exemplifies the omitted variable bias. Contrary to our expectation but consistent with the plot in Fig. 2, electricity production from renewable sources shows a negative effect on the dependent variable, with its coefficient statistically significant in two models. This finding is interesting because it suggests that electricity production from renewable sources does not go side-by-side with innovation in ETs for the ten NICs—perhaps due to a focus on export markets from NICs to other more stringent environmental policy countries (Herman & Xiang, 2019). On the other hand, the remaining independent variables fail to show an effect on the dependent variable. Civil liberties do not influence innovation in ETs in NICs. Again one possible explanation is that China has poor civil liberties but it is the most innovative country among the NICs. After taking into account the influence of trade, FDI shows no additional effect on the dependent variable. Likewise, the Kyoto Protocol dummy demonstrates no independent effect on innovation in ETs. Finally, the estimated country fixed effects show that China has significantly higher values than the rest NICs.[6] That is, the estimated intercept for China is substantially larger than the estimated intercepts for the other NICs, suggesting that a large part of China's ET innovation is attributed to certain unobservable characteristics in China.

To reiterate, Table 1 provides strong empirical evidence to support our hypothesis that collaboration with G7 increases ET innovation in ten NICs. To further demonstrate the robustness of this result, we reassess our hypothesis using alternative samples. First, since the US shows significantly more collaboration with NICs than other G7 countries, we treat the US as an outlier and exclude it from G7 countries when calculating the independent variable collaboration with G7. In addition, given China and India demonstrate much higher levels of collaboration with G7 as shown in Fig. 1, we exclude these two NICs from the sample of NICs. The new regression results are presented in Table 2. Note both models are estimated based on independent variables with no lag.

As we can see from model 4 in Table 2, when the US is excluded from G7 in the calculation of the main independent variable, collaboration with G7 increases ET innovation in ten NICs. Likewise, after excluding China and India from the sample of NICs, collaboration with G7 shows a positive effect in model 5. In short, the sensitivity analysis in Table 2 demonstrates further support to our hypothesis. The control variables show similar findings in Table 2, except for trade which becomes statistically insignificant and FDI, which is negative and statistically significant in model 5. This finding suggests that, with regard to how trade and FDI influence ET innovation, China and India exhibit different characteristics than the other NICs. Finally, since China and India are dropped from the sample of analysis, model 5 reduces to 208 observations.[7]

[5] More specifically, we introduce country fixed effects to control for time-invariant unobservable factors that are correlated with the dependent variable and some of the independent variables. In other words, country fixed effects are used to address potential omitted variable bias. Country fixed effects are estimated by country dummy variables. That is, we estimate a different intercept for each country with Brazil omitted as the reference category.

[6] The results of country fixed effects are omitted to save space.

[7] The US is excluded in the calculation of the main independent variable, and therefore model 4 still has 260 observations.

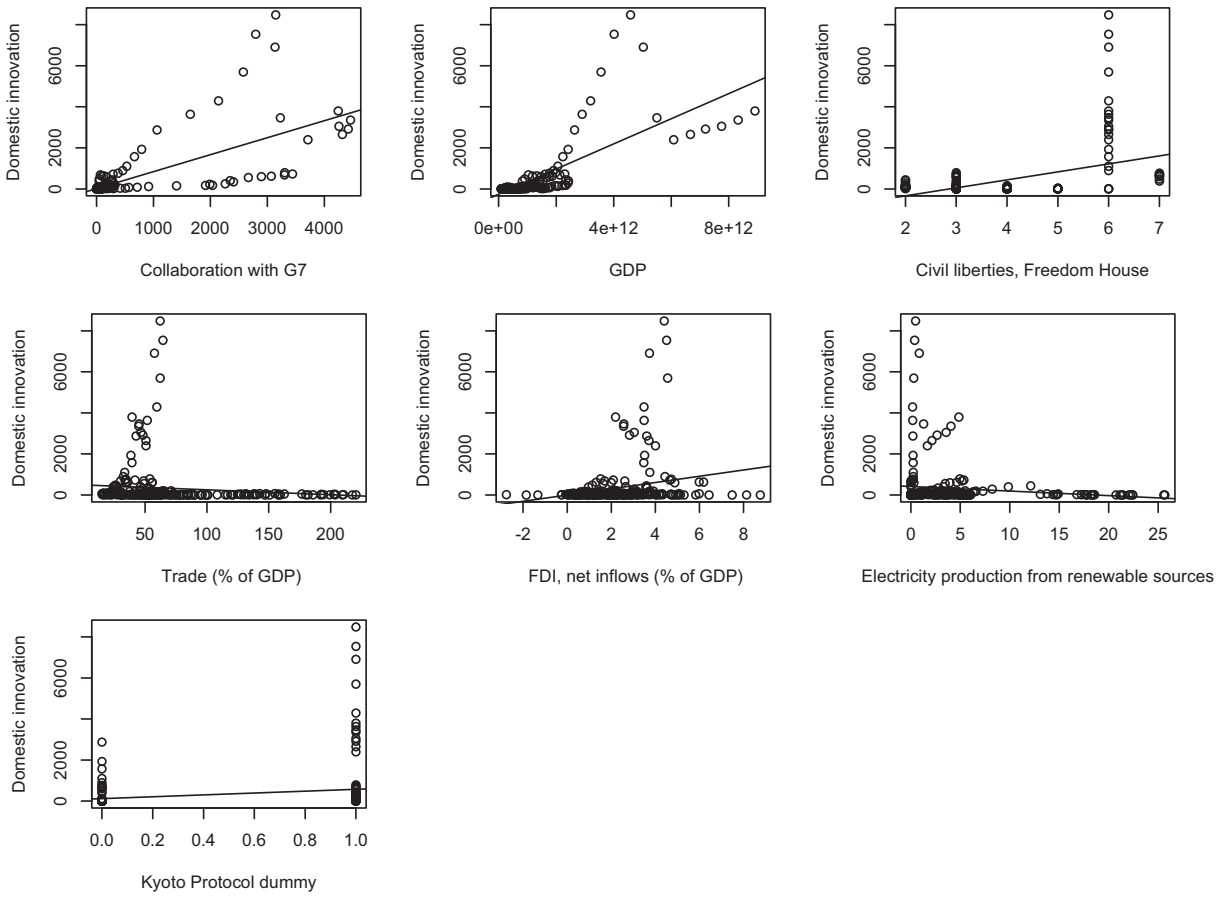


Fig. 2. Bivariate plots between each independent variable and the dependent variable.
Notes:
For the vertical axis, domestic innovation denotes the dependent variable patents in ETs by NICs.
For the horizontal axis, collaboration with G7 measures the number of co-inventions, GDP is in constant 2010 USD, civil liberties show the degree of freedom (larger values indicate less freedom), trade (% of GDP) or FDI, net inflows (% of GDP) computes trade or FDI net inflows as a percentage of GDP, electricity production from renewable sources is calculated as a percentage of total electricity production, and Kyoto Protocol dummy takes the value zero or one.

Generally speaking, our findings suggest that the original framing of environmental technology dependency—that ETs should be innovated in developed countries and transferred to developing economies—is now less universally valid (Lema et al., 2015; Mealy & Teytelboym, 2020). Our results confirm recent research which has shown the precipitous rise in innovation in environmental technologies in developing countries (Bayer et al., 2013; Mealy & Teytelboym, 2020). Indeed, developing economies now provide nearly one-third environmental technologies worldwide (Walz et al., 2017), so it is no surprise that, through collaboration, they are able to enhance their technological innovation capacities in climate and environmental technologies. NICs are experiencing ever greater competence in developing CCMTs (Walz & Marscheider-Weidemann, 2011), even though much of the empirical literature tends to overlook these trends.

Indeed as Golombek and Hoel (2011) suggest, in light of the shortcomings of the Kyoto Protocol and multilateral climate negotiations under the UNFCCC, collaboration and technological innovation to reduce global emissions might be a more fruitful way to directly mitigate emissions in the near-term. The results from our study clearly indicate that collaboration matters for innovation in climate and environmental technologies in NICs. Importantly, our empirical results stand out apart from the literature, which surprisingly does not explore these collaboration effects very deeply. Apart from Ockwell et al. (2015) who conduct an analysis on interview data, an earlier paper by Haščič et al. (2012) and a recent study by Herman (2022), our results are among the first to clearly demonstrate the importance of collaboration for domestic innovation in ETs.

Conclusions and future research

Our results broadly confirm previous research that has shown the precipitous rise in ET innovation in developing countries (Mealy & Teytelboym, 2020; Walz et al., 2017). Going beyond much of the prior research, however, we show that general technological collaboration has driven such innovation. These results are important for three reasons. First, they show that the previously dominant research and policy focus—that ETs and climate technologies are invented in developed countries and transferred to developing countries—requires some revision, as stated elsewhere (Binz et al., 2017; Herman, 2022; Mealy & Teytelboym, 2020; Quitzow, 2015; Quitzow et al., 2017). Second, the results of our empirical analysis illuminate the critical collaborative component of environmental technology innovation, with important implications for economic development as well (Matsuo & Schmidt, 2019; Wu & Salzman, 2014). Considering these first two implications, a third and indeed very important extension of our research is that "green growth win-wins" can indeed be realised in developing economies through enhancing TIS and technological collaborations—which likely will lead to enormous positive consequences on climate change mitigation as well as poverty alleviation and economic development throughout many parts of the world (Jänicke, 2012).

Table 1
Effects of collaboration on innovation in environmental technologies.

Variables	(1)	(2)	(3)
	No lag	Lag 1 year	Lag 2 years
Collaboration with G7, all technologies except	0.583***	0.510***	0.365***
Environmental technologies	(0.126)	(0.128)	(0.132)
GDP	4.24e-11	8.25e-11	1.91e-10*
	(9.84e-11)	(1.00e-10)	(1.03e-10)
Civil liberties, Freedom House	−38.460	−57.033	−77.544
	(66.618)	(67.814)	(69.526)
Trade (% of GDP)	5.557*	5.668*	5.118*
	(2.849)	(2.900)	(2.974)
FDI, net inflows (% of GDP)	0.386	−3.485	−17.940
	(30.954)	(31.509)	(32.305)
Electricity production from renewable sources,	−58.849**	−49.438**	−37.175
Excluding hydroelectric (% of total)	(23.196)	(23.613)	(24.209)
Kyoto Protocol dummy	31.348	22.229	8.518
	(97.137)	(98.881)	(101.377)
Constant	175.149	157.232	67.740
	(335.062)	(341.077)	(349.687)
Country fixed effects	Yes	Yes	Yes
Number of observations	260	260	260
R-squared	0.713	0.725	0.736

Standard errors in parentheses.
*** p < 0.01.
** p < 0.05.
* p < 0.10.

There are some limitations to this study, which suggest several future research directions. First, the matter of what actually constitutes a "co-invention" is subject to some debate (Giuliani et al., 2016). For example, company ownership as well as company R&D structures are very complex (Bergek & Bruzelius, 2010). This can lead to much difficulty in assessing the degree to which co-invention signifies collaboration between two separate countries (Haščič et al., 2012). For instance, even though an innovation may be labelled as a co-invention, it could be from the same company operating across borders. To ameliorate some of these potentially spurious findings, future research could use firm-level patent data to corroborate the patent data at country level. Nevertheless, our country-level analysis constitutes some of the first systematic evidence to demonstrate how collaboration between G7 and NICs improves climate and environmental technology innovation in the latter. One more limitation is worth mentioning: the rate of innovation does not necessarily mean that innovations have been successfully diffused and integrated into NICs' infrastructure and, consequently, patent data is not necessarily indicative of technological adoption and deployment (Lanjouw & Mody, 1996). Therefore, we have not demonstrated that collaboration in ETs will reduce emissions or directly lead to low carbon development in NICs. We leave this important question for future research.

Table 2
Effects of collaboration on innovation in environmental technologies, alternative samples.

Variables	(4)	(5)
	Excluding the US from G7	Excluding China and India from NICs
Collaboration with G7 (excluding the US), all	3.131***	
Technologies except environmental technologies	(0.561)	
Collaboration with G7, all technologies except		0.190**
Environmental technologies		(0.075)
GDP	−2.02e-10	1.63e-10***
	(1.24e-10)	(2.40e-11)
Civil liberties, Freedom House	−36.821	1.705
	(65.342)	(3.773)
Trade (% of GDP)	4.890*	−0.008
	(2.802)	(0.153)
FDI, net inflows (% of GDP)	7.148	−3.404*
	(30.356)	(1.868)
Electricity production from renewable sources,	−47.760**	1.733
Excluding hydroelectric (% of total)	(22.799)	(1.457)
Kyoto Protocol dummy	23.972	−5.554
	(95.283)	(7.076)
Constant	439.889	−190.443***
	(340.300)	(36.171)
Country fixed effects	Yes	Yes
Number of observations	260	208
R-squared	0.723	0.750

Standard errors in parentheses.
Models 4–5 are based on independent variables with no lag.
*** p < 0.01.
** p < 0.05.
* p < 0.10.

Declaration of competing interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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