INTERNATIONAL MONETARY FUND

Green Innovation and Diffusion

Policies to Accelerate Them and Expected Impact on Macroeconomic and Firm-Level Performance

Prepared by Zeina Hasna, Florence Jaumotte, Jaden Kim, Samuel Pienknagura and Gregor Schwerhoff

SDN/2023/008

2023
NOV

STAFF DISCUSSION NOTE

 SDN/2023/008

IMF Staff Discussion Notes
Research Department

Green Innovation and Diffusion: Policies to Accelerate Them and Expected Impact on Macroeconomic and Firm-Level Performance

Prepared by Zeina Hasna, Florence Jaumotte, Jaden Kim, Samuel Pienknagura, and Gregor Schwerhoff*

Authorized for distribution by Pierre-Olivier Gourinchas
November 2023

ABSTRACT: Innovation in low-carbon technologies (LCTs), which is essential in the fight against climate change, has slowed in recent years. This Staff Discussion Note shows that a global climate policy strategy can bolster innovation in, and deployment of, LCTs. Countries that expand their climate policy portfolio exhibit higher (1) climate-change-mitigation-patent filings, (2) LCT trade flows, and (3) "green" foreign direct investment flows. Importantly, boosting innovation in, and deployment of, LCTs yields medium-term growth, which mitigates potential costs from climate policies. This note stresses the importance of international policy coordination and cooperation by showcasing evidence of potential climate policy spillovers.

RECOMMENDED CITATION: Hasna and others. 2023. *Green Innovation and Diffusion: Policies to Accelerate Them and Expected Impact on Macroeconomic and Firm-Level Performance*. Staff Discussion Note SDN/2023/008. International Monetary Fund, Washington, DC.

ISBN:	979-8-40025-695-0
JEL Classification Numbers:	F21, F64, H23, O33, O44, Q55, Q56, Q58
Keywords:	Low-carbon technologies, green innovation, technological diffusion and deployment, environmental policies, economic performance
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* The authors thank Pierre-Olivier Gourinchas and Antonio Spilimbergo for feedback and guidance. Shane Mahen provided superb research assistance. The views expressed herein are those of the authors and should not be attributed to the IMF, its Executive Board, or its management. Any remaining errors are the responsibility of the authors.

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Executive Summary

Green innovation, a key ingredient in the fight against climate change and its adverse consequences for economic and financial stability, has slowed in recent years, calling for renewed efforts to reignite it. Green innovation, by making new low-carbon technologies (LCTs) available, is a powerful tool in curbing emissions and helping firms and households adapt to the adverse impacts of climate change. While green innovation has already made great advances, reaching net zero emissions will require substantial additional innovations in several areas.

Green innovation is also essential for economic activity, to buffer potentially direct adverse impacts of climate policies. An acceleration in green innovation is found to have a positive impact on economic activity in the short to medium term, which can mitigate the potential costs of compliance with climate policies. It also has a positive impact on firm revenue. This pro-growth effect is comparable to that of patents that are not green and to growth effects of previous technological breakthroughs, such as the information and communications technology (ICT) revolution. However, the channels through which green and nongreen patents affect growth are different—the former work initially mostly through higher investment, whereas the latter also have a positive short-term impact on productivity. Because the restructuring of production processes takes time, the productivity benefits of green innovation could materialize beyond the horizon considered, thanks to greater energy efficiency and cheaper energy sources. Finally, climate policies also lift overall innovation—not just green innovation—suggesting a further boost to growth.

Domestic and international climate policies play an important role in boosting green innovation. Green patenting increases with increases in domestic climate policies: a major jump in climate policies (equivalent to one standard deviation of the distribution of changes in the number of climate policies) boosts green patent filings by 10 percent in five years. Regulations, emissions-trading systems that limit emissions, and expenditure measures such as R&D subsidies and feed-in tariffs are particularly impactful. Importantly, global climate policies affect domestic green patent filings even more than domestic policies do, and international climate agreements (such as the Kyoto Protocol and Paris Agreement) amplify the impact of domestic policies. These results point to the role of policy certainty, global market size, and technology spillovers as important determinants of innovation.

Implementing climate policies is also essential for increased deployment of LCTs through trade and foreign direct investment (FDI) inflows and should be complemented by efforts to reduce trade barriers. Countries that introduce climate policies see a rise in LCT imports and higher green FDI inflows, with stronger effects in emerging market and developing economies. Climate policies, significantly, do not appear to depress total FDI, which could further limit potential adverse effects on activity. Lowering tariffs is also found to raise both LCT trade and green FDI inflows, pointing to the importance of reducing the cost of technologies that are key to the green transition. This is especially relevant for middle- and low-income countries, where LCT tariffs remain high. These findings also point to the risks protectionist measures pose for the diffusion of LCTs more broadly, an important consideration amid concerns of rising geoeconomic fragmentation.

The positive effects of innovation are enhanced by international coordination and cooperation. Overall, climate policies introduced in advanced economies result in stronger deployment of LCTs in the rest of the world through trade and green FDI outflows. However, some policies, most notably green subsidies, reduce green FDI outflows. While subsidies may be needed to address externalities and market failures in the development of certain technologies and could lower the price of LCTs in the long term, they may create tensions between domestic and global climate objectives. Advanced economies must weigh their potential negative spillovers, especially for emerging market and developing economies with less fiscal space; avoid a race to the bottom; and ensure the consistency of their policies with international rules, including by avoiding local content requirements. Given evidence of positive climate policy spillovers on innovation across countries, a fragmented world—with ultimately smaller potential markets—could stifle incentives for green innovation and slow the transfer of LCT goods to emerging market and developing economies.

I. Introduction

Curbing greenhouse gas emissions is a global priority to prevent catastrophic climate change, and a strategy that prioritizes the development and deployment of low-carbon technologies (LCTs) is instrumental in achieving this goal. The availability of LCTs is crucial to accelerating emissions reductions (Rogelji, Shindell, and Jiang 2018).[1] Expanding LCTs entails innovation aimed both at making new technologies available and reducing the cost of existing LCTs. Equally important is the deployment of such technologies on a global scale, especially to emerging market and developing economies, where the adoption of already available LCTs could have a large impact in terms of reducing the emissions intensity of economic activity (Capelle and others, forthcoming; Glennerster and Jayachandran 2023).

Green innovation is also crucial to reduce potential short-term costs from climate policies. While climate policies will yield long-term growth dividends by steering the economy away from a trajectory of growing disasters (Acemoglu and others 2012), their short-term economic impact is not obvious. Indeed, policies may force economic agents to use more costly inputs or production processes, thus reducing efficiency in the short term and adding to the potentially high transition costs faced by firms and sectors that rely heavily on carbon-intensive inputs. Green innovation provides alternative, low-carbon technologies, and over time makes them less expensive, thereby reducing these transition costs. It could even temporarily boost economic activity as economic agents make the investments needed to use the new low-carbon technologies and new firms are created (Finkelstein Shapiro and Metcalf 2023)—or by increasing energy efficiency and providing cheaper energy sources. Renewable energy is already cheaper than fossil-fuel-based energy (IRENA 2022). Yet the evidence on the short- to medium-term impact of green innovation is mixed. Some studies have found that green patents, as defined in patent classification schemes, do not affect firms' performance (Dechezleprêtre and Kruse 2022); others have found a positive effect on growth over the medium term (Fernandes and others 2021). Further understanding the net short-term aggregate economic impact of green innovation is important given concerns by policymakers about potential short-term growth costs of the green transition. The evidence suggests that climate strategies perceived to entail economic costs receive less support than those with positive or no apparent economic impact (Dabla-Norris and others 2023).

As countries embark on the green transition, how to bolster green innovation effectively and how to deploy it remain key questions, especially in a context of growing geoeconomic fragmentation. Recent evidence from advanced economies shows that climate policies can stimulate green innovation (Eugster 2021; Battarelli and others 2023). Yet policy instruments may vary in terms of their effectiveness, ease of implementation, and potential side effects. For example, carbon prices can promote innovation in, and the adoption of, new low carbon technologies (Acemoglu and others 2012; IMF 2023a). However, carbon taxes typically face higher public resistance than other policies (Dabla-Norris and others 2023). Meanwhile, subsidies, which have garnered attention after the passage of the US Inflation Reduction Act and the Green Deal Industrial Plan proposed by the European Commission, help tackle market failures that typically hamper the creation of new alternatives to fossil fuels and the diffusion of mature clean technologies. Yet subsidies can also be seen as protectionist and can lead to retaliation and geoeconomic fragmentation, in turn potentially muting global decarbonization efforts. Indeed, the dramatic cost reductions of solar panel technologies over the

[1] Low-carbon technologies (LCTs) are those whose emissions are lower than those of their counterparts and are essential to the green transition. Parts of this Staff Discussion Note (SDN) use the term "green technologies" to refer to LCTs and mitigation technologies.

past two decades have highlighted the importance of integrated global markets for the advancement of technologies.

Finally, there has been recent emphasis on the importance of boosting LCT deployment to accelerate emissions reductions in emerging market and developing economies. These economies have much higher emissions per unit of output than advanced economies. International forums, such as the 2022 Group of Twenty Summit, the United Nations Climate Change Conference (COP27), and multilateral institutions have emphasized the importance of facilitating climate-related financing and the deployment of LCTs to emerging market and developing economies. Together with more action in the climate policy arena, such actions can help curb their emissions. Yet many obstacles prevent the deployment and adoption of LCTs. For example, low levels of education and poor governance hamper LCT trade (Pigato and others 2020), and structural factors constrain climate financing (IMF 2023b). Recent work shows that structural reforms can promote green investment and LCT adoption, as well as reduce the cost of financing and increase FDI inflows (Budina and others 2023). Less is known, however, about the potential catalytic role that climate policies can play in promoting LCT trade and FDI.

Against this backdrop, this SDN aims to quantify the short-term economic impact of green innovation and study the role of policies in fostering innovation and deployment of LCTs. The note combines several data sources gauging green innovation, via patent filings, and deployment, through trade and FDI, with a comprehensive dataset of climate policies covering a large set of advanced and emerging market and developing economies to address the following questions:

- *What is the short- to medium-term impact of green innovation on economic activity, and what are the key channels through which it affects growth?*
- *Can climate policies yield higher green innovation and catalyze green FDI and trade in LCTs?*
- *Does the choice of policy instruments matter for accelerating green innovation and deployment?*
- *What are the cross-border spillover effects of climate policies for domestic innovation and deployment?*

The note contributes to the literature in five areas. First, while previous studies have focused on the impact of green innovation on firm-level value added (Dechezleprêtre and Kruse 2022) and on medium-term growth (Fernandes and others 2021), or on the impact of climate policies on total factor productivity (TFP) (Albrizio, Koźluk, and Zipperer 2017), this note explores the channels through which green innovation affects economic activity (investment and productivity) and compares the impact of green innovation with that of nongreen innovation and another major innovation—namely, ICT. Second, unlike other studies, which have focused mostly on advanced economies (Eugster 2021; Battarelli and others 2023), this SDN assesses the impact of climate policies on both advanced and emerging market and developing economies. Third, the SDN gives special consideration to the role of global policies and key global climate events, in addition to domestic policies, to investigate the importance of synchronization of climate policy actions across countries in driving green innovation. Fourth, the SDN provides evidence on the role of climate policies and trade policies to further the deployment of LCTs through trade and FDI, an area that, to the best of our knowledge, is unexplored in the literature. This is critical for the diffusion of green technologies to emerging market and developing economies and for their ability to access foreign capital for investments in the green transition. Building on this evidence, the note also sheds light on cross-country climate policy spillovers, notably how policies in advanced economies can impact green FDI flows to emerging market and developing economies, an area for which evidence is scant but that has received increased attention with the passage of the US Inflation Reduction Act. Finally, compared with existing climate policy databases, such as the Organisation for Economic Co-operation and Development's (OECD's) Environmental Policy Stringency (EPS) database, the policy database used in this SDN offers more comprehensive and granular coverage of policy instruments across countries, sectors, and types of instruments. The last two points are particularly important given recent climate policy packages proposed by some advanced economies, which rely heavily on expenditure measures that favor domestic producers and could therefore affect deployment to emerging market and developing economies.

The rest of the SDN is organized as follows. Section II presents relevant stylized facts on green innovation and estimates its impact on economic activity using aggregate cross-country data for a set of OECD countries and for Brazil, Russia, India, China, and South Africa (BRICS), as well as firm-level data from US publicly listed firms. In doing so, the note explores the key transmission channels through which green innovation affects economic activity and compares it with nongreen innovation. Section III presents results of analyses showcasing the impact of climate policies on green innovation and deployment through trade in LCTs and green FDI. The section provides a granular analysis of the impact of different policies, distinguishing between revenue measures (such as taxes and emissions-trading systems), expenditure measures (such as subsidies), and revenue-neutral measures (such as regulation). Section IV concludes and discusses the policy implications of the SDN's results.

II. Innovation in LCTs: Recent Trends and Economic Impact

Accelerating emissions reductions hinges on innovation that expands the availability of LCTs. This entails devoting research efforts to the development of new technologies and to reducing the cost of existing LCTs. The role of innovation in the development and cost reduction of LCTs is clearly displayed in the case of solar energy (Box 1). In an initial phase, resources—mostly from the government—were invested into basic research for solar technology. In a second phase, efforts were directed to making the technology cost-effective by scaling up its deployment. Solar energy today is one of the cheapest forms of electricity generation in terms of levelized cost (IRENA 2022). Achieving current climate objectives will require both the development of technologies, such as new negative emissions technologies, and reducing the cost of key clean energy options (for example, green hydrogen).

Importantly, innovation in LCTs can counteract the potential adverse effects of climate policies and improve public support for the transition. One concern about the adoption of ambitious climate policies is their potential adverse economic effects, especially in the short term, as households and firms are forced to adopt alternative inputs or production processes that can be initially more costly. The effects of climate policies on economic activity remain uncertain. Most model-based studies tend to project small negative effects on short- to medium-term growth, while some studies highlight the potential double dividend of climate policies (namely, better positive economic outcomes and reduced climate impacts). Empirical studies have been inconclusive so far, potentially reflecting that policies have been either limited in scope or implemented very gradually. Some studies find either zero or small positive impacts of reforms implemented in Europe (Barker and others 2009; Enevoldsen, Ryelund, and Andersein 2009; Metcalf and Stock 2020) and North America (Murray and Rivers 2015; Bernard and Kichian 2021; Metcalf 2019), and others find negative impacts (Kanzig and Konradt 2023). However, as countries introduce more stringent policies and move toward deeper decarbonization of their economies, innovation that increases the availability and affordability of alternative LCTs will be crucial to reduce the costs of the transition.

This section documents recent trends in green patent filings—a gauge of green innovation—and quantifies their short- and medium-term economic impact. The primary measure of green innovation used in this SDN is the count of climate-change-mitigating patent families filed in a given country-year. Using data from the European Patent Office's Worldwide Patent Statistical Database (PATSTAT), the SDN constructs a measure of green patent filings using the patent's technical classification. Green patents are related to climate-change-mitigating technologies and cover selected technologies that (1) control, reduce, or prevent greenhouse gas emissions or (2) help adapt to the adverse effects of climate change. Two limitations of patents as a gauge of innovation are that they capture only technological—product and process—innovations and thus miss organizational and managerial innovations that could result in reduced emissions and that they fail to capture innovations that are not patented for strategic reasons. Most of the analysis focuses on patents filed and granted in at least two application authorities, labeled as "family size 2," which are regarded as higher-quality patents. Using this data, the section presents trends in global patent filings, quantifies the economic impact of green patent filings on GDP, and explores channels of transmission. The section also combines patents filed by US publicly traded firms with the firms' financial information to assess the impact of green patents on firm-level performance.

II.1. Patenting Trends: The State of Innovation

Green patent filings increased steadily since the early 1980s, until hitting a plateau in recent years. The number of green patents granted increased steadily from the 1980s until the mid-2010s, when they plateaued, while total patent filings continued on a steady increase. As a share of total innovation, green filings peaked in 2010 but have experienced a small decline since. They account for an average share of 6.6 percent of total filings since 2010 and, restricting patent filings to family size 2, they account for 10 percent of total filings, which is about 1.5–2 times their initial share of total filings in 1980 (Figure 1, panel 1). In levels, green patent filings of family size 1 averaged about 115,000 annually between 2010 and 2018; green patents of family size 2 averaged about 19,000 annually over the same time period. The gap in levels between green patents of family sizes 1 and 2 is driven largely by the surge in patents resulting from the Chinese government's subsidization programs to incentivize local innovation, which are typically filed only in China.[2] The rest of this SDN focuses on granted patents of family size 2 to avoid contaminating the results with single-country patent filings that are, on average, of lower quality.

Most green patents are filed in a few technology subfields and mainly in advanced economies, albeit with growing patenting in emerging market economies in the past two decades. There are eight subcategories of green patent filings (which are not mutually exclusive): (1) adaptation to climate change; (2) buildings; (3) carbon capture and storage of greenhouse gases; (4) ICT aimed at the reduction of energy use; (5) production, distribution, and transport of energy; (6) industry and agriculture; (7) transportation; and (8) waste management and wastewater. Energy, transport, and production account for the lion's share of overall green patent filings, with energy alone constituting 35 percent of green patent filings and 2.5 percent of total filings on average (Figure 1, panel 2). Significantly, the slowdown in patent filings is evident across subcategories. Turning to cross-country patterns, more than 90 percent of green patents were filed in advanced economies during 1980–2000, and more than 60 percent were filed in nine countries (Group of Seven, China,

[2] For example, China's National Indigenous Innovation Campaign in 2006 aimed to boost domestic innovation, and the 12th and 13th five-year plans offered subsidies to increase the number of patent applications. Recent evidence, however, shows that efforts can produce negative returns if regulators do not differentiate for the quality of innovations (Wei and others 2023).

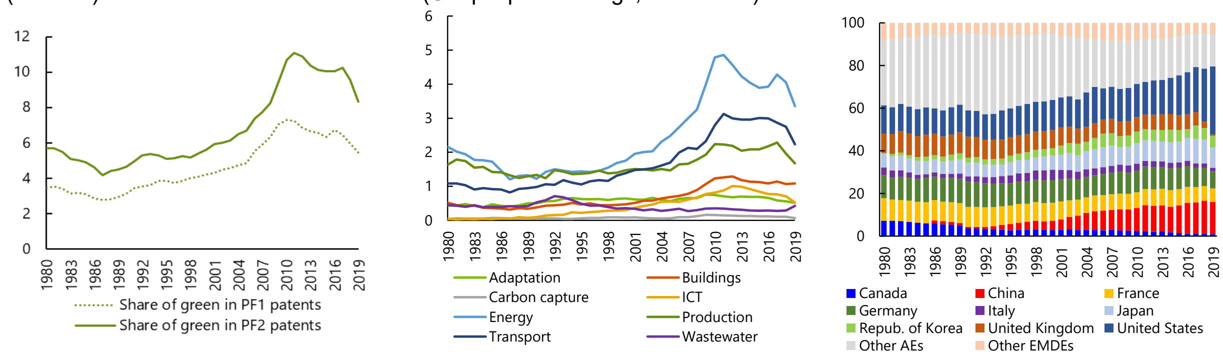
and Korea). However, since the 2000s, emerging markets have been gaining momentum in terms of green patent filings, driving down the share of filings in advanced economies to about 80 percent by 2019 (Figure 1, panel 3).

Figure 1. Trends and Composition of Green Patents

1. Evolution of Granted Green Patents as Share of Total Filings (Percent)

2. Green Patent Filings by Subcategory as Share of Total Filings (Unique patent filings, thousands)

3. Breakdown by Country (Percent)



Sources: European Patent Office Worldwide Patent Statistical Database (PATSTAT); and Hasna and others (forthcoming).
Note: AE = advanced economy; EMDE = emerging market and developing economy; ICT = information and communications technologies; PF = patent family.

The slowdown in the share of green patents in the past few years raises concerns about the ability to tackle climate change in due time. One potential factor behind the green innovation slowdown is the rise of hydraulic fracking, which has lowered oil prices and diverted attention from clean energy technologies. In addition, recent International Energy Agency analyses suggest that the decline reflects in part technological maturity, which reduces the pace of innovation (see also Popp and others 2020). This is evident in the field of solar photovoltaic (PV) energy, which now accounts for almost half of total global electricity generation investment. The rapid deployment of PV is a result largely of improved know-how and cost efficiency in exploiting existing technology rather than of new solar PV-related inventions. Indeed, a recent study argues that more than 80 percent of the emissions reductions needed by 2030 can be achieved by scaling up existing technologies, which means shifting from innovation to deployment (Pigato and others 2020). The slowdown in green innovation is, however, evident in all technology fields. And, as discussed in Box 1, key technologies to bring the global economy to net zero emissions by mid-century are still missing or are only at a very early stage of development (see also IEA 2020a).[3] The fact that innovations take time—often decades—to reach maturity makes it urgent to rekindle green innovation efforts in this decade.

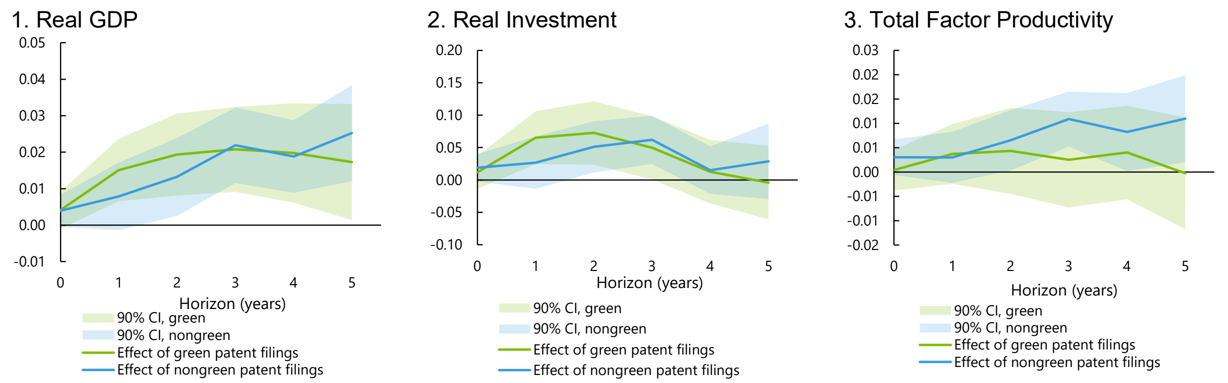
II.2. The Economic Impact of Green Innovation

While climate models point to long-term benefits of green innovation and climate policies, the short- and medium-term economic impacts of green innovation have been studied less. The long-term benefits of green innovation for economic activity, as a result of a reduction in damages from climate change, are well understood (Acemoglu and others 2012; Fernandes and others 2021). However, what is also critical for the

[3] IEA (2020a) argues that about 75 percent of the cumulative CO_2 emissions reductions needed for a sustainable path come from technologies currently at the prototype or demonstration phase or not yet commercially deployed on a mass-market scale.

public debate is the economic cost of the green transition (Pisani-Ferry 2021). In this context, we examine the impact of green innovation on economic activity in the short to medium term. On one hand, green innovation could disrupt existing production processes, since current economic systems are still based mostly on carbon-intensive energy, which points to path-dependency arguments (Aghion and others 2016; Acemoglu and others 2016). On the other hand, green innovation could initially lead to higher investment and progressively raise productivity by increasing energy efficiency and reducing the cost of inputs (especially energy, given recent advancements in renewables) (Ambec and Lanoie 2008). In addition, there is evidence that green innovation generates larger knowledge spillovers than its carbon-intensive counterparts and could therefore lead to higher innovation overall, as well as facilitate the manufacture of new products and access to new markets (Porter and van der Linde 1995; Dechezleprêtre, Martin, and Mohnen 2017).

Figure 2. Gauging the Impact of Green and Nongreen Patent Filings on Economic Activity
(Percent)



Sources: European Patent Office Worldwide Patent Statistical Database (PATSTAT); and Hasna and others (forthcoming, a).
Note: The analysis is based on a local projection framework in which the dependent variable is the log difference in real GDP over the horizon considered and the independent variable is the logarithm of green patent filings. For more details on the econometric specification and additional controls see Online Annex II. CI = confidence interval.

At the macroeconomic level, green patent filings have a positive impact on economic activity, especially over the medium term, that is not statistically distinguishable from that of nongreen patent filings. Drawing on data on patent filings in OECD and BRICS countries between 1990 and 2019, econometric analysis shows that an increase in climate-change-mitigation patent filings boosts real GDP, with effects peaking after three years. The estimated coefficients imply that an increase in the *flow* of patent filings—that is, an acceleration in patenting—of 7 percent (the annual growth rate observed in the data) leads to a 0.14 percent increase in GDP after five years relative to the baseline scenario. A similar analysis shows that the impact of nongreen patent filings on GDP is quantitatively similar to that observed for green patents, but the timing differs. The pro-growth impact of nongreen patents materializes after two years and peaks after five years (Figure 2, panel 1). These estimates represent a lower bound, since they increase twofold when controlling for climate policies and fourfold when instrumenting domestic patent filings to control for the potential reverse impact of economic growth on patenting activity. In all exercises, the effects of green patent filings on economic activity are comparable to those of nongreen patent filings (see Online Annexes II and III for more details).[4]

Green patent filings boost output initially through higher investment; however, they do not enhance aggregate TFP over the horizon considered. Green patents yield a short-term increase in real investment,

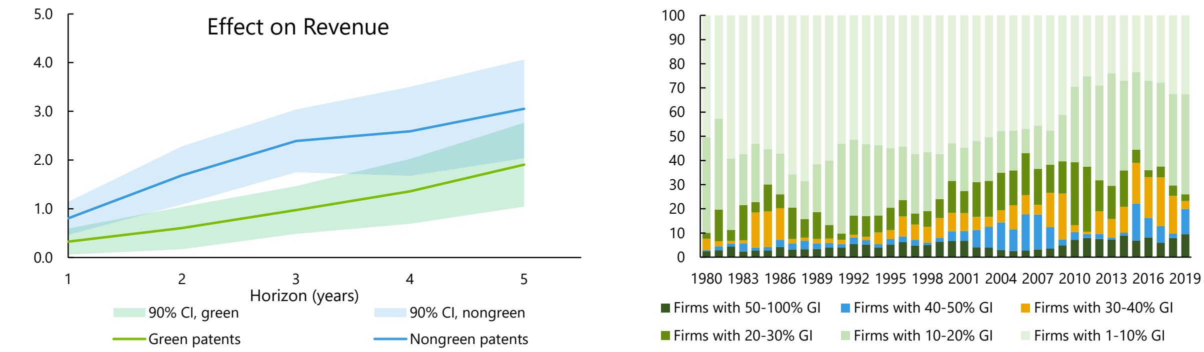
[4] Details on econometric specifications and additional results are found in online Annexes II and III, respectively. Additional robustness exercises control for growth expectations and both types of patents.

which is slightly larger than the increase caused by nongreen patent filings (Figure 2, panel 2). This confirms the previous discussion on the role LCTs can play in increasing growth by boosting investment. However, when it comes to aggregate productivity, green patent filings do not have a significant effect on TFP over the horizon considered, unlike nongreen patent filings (Figure 2, panel 3). This could reflect path dependency—arguments raised by Acemoglu and others (2016) and Aghion and others (2016). Incorporating new technologies may initially disrupt existing production processes, thus reducing potential TFP benefits from these new technologies in the short to medium term. Next, we further assess whether evidence of such effects can be found at the firm level.

Figure 3. Green Patents at the Firm Level: Impact and Green Intensity
(Percent)

1. Impact of Green and Nongreen Patents on Firm Revenue

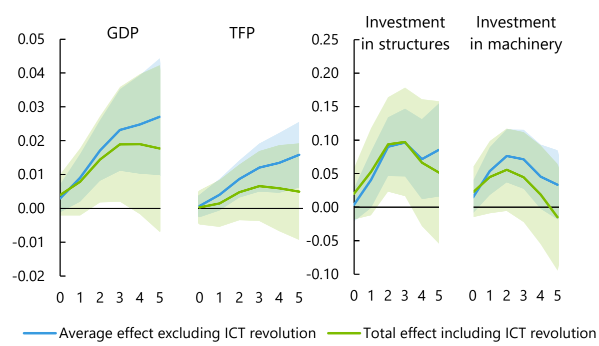
2. Firm-Level Heterogeneity: Breakdown along Green Intensity



Sources: Compustat; Hasna and others (forthcoming, b); and US Patent Trademark Office.
Note: In panel 1, the analyis is based on firm-level local projections in which the dependent variable is the log difference in firm revenue and the independent variables of interest are the the citation-adjusted firm-level patent flows divided by the firm's book value. For more details on the econometric specification and additional controls in each panel, see Online Annex II. CI = confidence interval; GI = green intensity.

At the firm level, green patents boost revenue—but not as much as nongreen patents, which may reflect production systems' continued reliance mostly on nongreen technologies. Analysis for US public firms shows that new green patent filings have a positive impact on firms' revenue. A one standard deviation increase in the quality-adjusted measure of patents held by firms yields a 2 percent increase in revenue after five years (Figure 3, panel 1). The effect of green innovation on revenue is initially smaller than that of nongreen innovation, which may reflect path dependency. Indeed, most firms introducing green patents have low green intensity, defined as a firm's ratio of green patents to total patents (Figure 3, panel 2; Ferreira and others, forthcoming). This implies that most firms still rely on nongreen technology and that the productivity benefits of emerging green technologies may take time to materialize, as production processes adjust progressively.

Figure 4. The impact of ICT Patents
(Percent)



Sources: European Patent Office Worldwide Patent Statistical Database (PATSTAT); Penn World Tables version 10.1; and World Economic Outlook database.
Note: The analysis is based on a local projection framework in which the dependent variable is the log difference in real GDP over the horizon considered and the independent variables of interest are the logarithm of green patent filings. For more details on the econometric specifiication and additional controls in each panel, see Online Annex II. ICT = information and communication technology; TFP = total factor productivity.

The green transition seems to be at least as promising as the ICT revolution. To benchmark the green transition against previous major technological breakthroughs, Figure 4 presents the impact of ICT patent filings. There are important differences to keep in mind when comparing the two. On one hand, information and communications technologies were general purpose technologies, with potential applications throughout the economy, and were adopted mostly in response to profit motives. On the other hand, LCTs are more sector-specific and are being deployed in response to policies that mandate the reduction of carbon-intensive technologies. Nevertheless, LCTs have the potential to affect vast sectors of the economy, as they typically benefit key upstream sectors such as energy and transportation. Dechezleprêtre, Ménière, and Mohnen (2017) argue that, like ICT and other new technologies, LCTs have strong knowledge spillover effects as measured by the number of citations they receive. This SDN's results show that ICT patents have an impact on real economic activity comparable to that of green patents. The analysis also looks at how ICT patents affected economic activity during the ICT revolution period (1995–2005), when these technologies were first introduced, and finds that the impact of ICT patent filings on GDP in that period was lower than in subsequent years. Much as is observed with respect to green innovation today, ICT filings initially boosted economic activity primarily through higher investment, whereas TFP gains accumulated more progressively. In fact, the impact on TFP was almost half to two-thirds lower during the ICT revolution than its average impact over the whole sample period. Overall, the findings suggest that new technologies initially increase economic activity mostly through investment rather than productivity, arguably as a result of transition costs. They also point to potentially higher productivity benefits once the technologies have been incorporated on a larger scale in the economy.

III. Environmental Policies as a Conduit of Green Innovation and Deployment

This SDN focuses next on the role of policies in boosting green innovation and its deployment through trade and FDI. Countries have introduced climate policies to address the challenges of climate change.[5] This process accelerated in high-income countries following the Kyoto Protocol and the third Intergovernmental Panel on Climate Change (IPCC) assessment report. Around the time of fourth assessment report the process sped up in middle-income and low-income countries, but there are still noticeable differences in the number of policies per country across income groups (Figure 5, panel 1). Climate policies target multiple sectors, especially energy, transportation, and to a lesser extent, industry. Against this backdrop, a key question is the extent to which these policies have stimulated green innovation and the deployment of LCTs.

To further delve into the role of policies, this SDN distinguishes three types of climate policies: those that generate government expenses, those that generate government revenue, and those that do not have a pronounced effect on the government budget. Economists, including those at the IMF, recommend carbon pricing as the key building block for climate policy (IMF 2019), but in practice countries apply a broad set of policy instruments to each sector (Nascimento and others 2022; Linsenmeier, Mohommad, and Schwerhoff 2022). Exploiting the rich information of the Climate Policy Database (CPD), Figure 5, panel 2,

[5] Data on climate policies are from the Climate Policy Database (CPD). The CPD offers the most comprehensive inventory of climate policies, but it is not exhaustive. For details see Nascimento and others (2022) and Online Annex I.

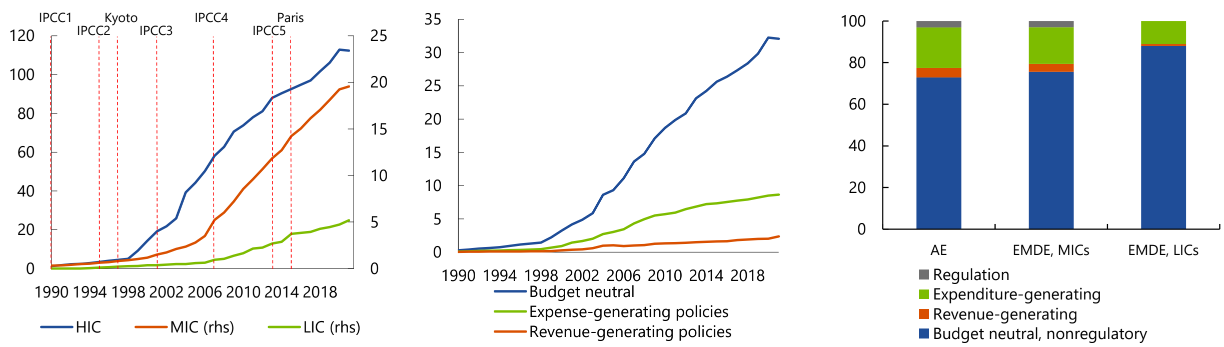
shows that regulations and other government-budget-neutral policies[6] are the most frequently used policies, followed by expenditure policies (including
subsidies). There are only a few revenue policies. The advantage of the CPD is its broad coverage of countries and policies and its granularity by types of policies and sectors of application. The limitation, however, is that it does not reflect the stringency of policies. This can hide the importance of revenue measures such as carbon taxes as a driver of climate policy stringency, as these measures tend to cover a large share of the economy. For example, countries covered by countrywide carbon taxes or emissions trading systems[7] are higher on the OECD's Environmental Policy Stringency (EPS) Index in 2020 than countries without carbon taxes. To tackle this concern and for robustness, some parts of this SDN present additional evidence using the EPS Index, which has much smaller country and policy coverage but captures stringency better.

Figure 5. Evolution and Composition of Climate Policies

1. Evolution by Income Group (Average number of policies)

2. Heterogeneity by Policy Instrument (Average number of policies)

3. Heterogeneity across Income Groups by Policy Instrument (Percent)



Sources: Climate Policy Database; IMF, *World Economic Outlook;* World Bank; and World Bank, World Development Indicators.
Note: EU policies are tallied for each country. Policy instruments are classified based on their impact on governments' budgets. EU policies are counted by country and sector. AE = advanced economy; EMDE = emerging market and developing economy; HIC = high-income country; IPCC = Intergovernmental Panel on Climate Change; LIC = low-income country; MIC = middle-income country; rhs = right hand side.

There are notable differences in the composition of climate policy portfolios across income groups. Figure 5, panel 3, shows that although budget-neutral measures are the most common in all countries, almost one-fifth of policies in advanced economies generate government expenditure (compared with 17 percent and 10 percent in middle-income and low-income countries, respectively). This may reflect greater fiscal space in advanced economies. In addition, revenue-generating measures are used more frequently in advanced economies and, to a lesser extent, in middle-income countries. This may reflect the more advanced stage of climate policies in these countries (Linsenmeier, Mohommad, and Schwerhoff 2022).

This SDN also looks at the impact of trade policies, which are especially relevant for diffusion through trade and FDI. Using the definition provided in Pigato and others (2020) and Howell and others (2023), Figure 6 shows the average applied tariff for LCT goods and other goods across income groups for three periods—before the global financial crisis (2000–07), after the global financial crisis and before the Paris Agreement (2010–15), and after the Paris Agreement (2015–21). Three patterns emerge from the analysis. First, tariffs on

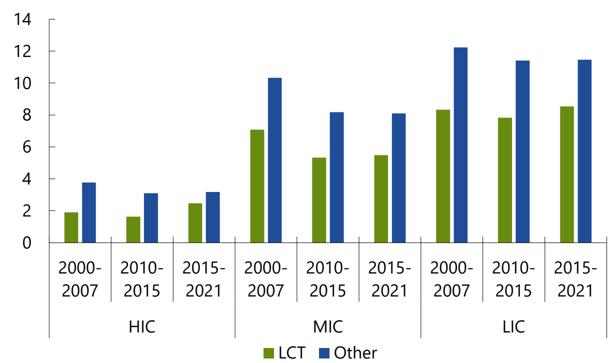
[6] These include legally binding and nonbinding targets related to energy efficiency, greenhouse gas emissions, and clean energy use; voluntary measures; information and support measures; and tendering programs, among others.

[7] There are 39 countrywide carbon taxes or emissions-trading systems and 73 active carbon pricing initiatives at the national and subnational levels.

LCT goods are typically lower than those on non-LCT goods across all income groups (Figure 6). Second, LCT tariffs (and other tariffs) are noticeably higher on average in middle- and low-income countries than in high-income countries. Finally, progress in terms of tariff reductions has stalled in recent years (LCT applied tariffs have actually increased), and nontariff barriers for LCT goods are higher than for non-LCT goods in upper-middle-income countries (Howell and others 2023).

Results, especially those related to the impact of different policies, should be viewed as qualitative, given data shortcomings. As discussed, CPD data, while comprehensive in its coverage of policies and countries, do not capture intensity nor the impact of policies on emissions. This makes it difficult to compute shocks to policy subcategories that can be interpreted as of similar magnitude (for example, from an emissions-reduction perspective), thus complicating the comparison across policy instruments. The results, therefore, give a good indication of the direction of the relationship between policy subcategories and the variable of interest but do not provide an accurate comparison of the magnitude of effects across instruments.

Figure 6. Applied Tariffs across Regions
(Percent)



Sources: IMF, Climate Change Indicators Dashboard; and United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) database.
Note: HIC = high-income country; LCT = low-carbon technology; LIC = low-income country; MIC = middle-income country.

III.1. Climate Policies and Patent Filings

To assess the dynamic impact of climate policies on patent filings, this SDN follows a local projection approach. The sample consists of 42 countries comprising OECD countries and BRICS, excluding India,[8] during 1990–2019. Consistent with previous empirical studies (Eugster 2021; Battarelli and others 2023), the framework uses the local projection method proposed by Jordà (2005) to estimate the effects of an additional climate policy on green patent filings over time. The green patent filings at the domestic patenting authority include both new innovations and existing innovations in other countries that are later patented at the domestic patenting authority. It is thus a more encompassing measure of a country's adoption of new technologies. The framework contributes to the literature by focusing on this comprehensive measure (instead of a more narrowly defined innovation), with a particular focus on the differentiated impact of different types of policy measures within the country, as well as on the impact of global policies and key global events in shaping patent filings. Thus the specification abstracts from time fixed effects and includes instead a time trend and global oil prices (Eugster 2021; Battarelli and others 2023), key dates of major climate policy events, and a measure of global policies. As suggested earlier, lower oil prices—as experienced with the fracking revolution in the 2010s—are

[8] India is excluded from the analysis because of significantly incomplete coverage of patent filings in the European Patent Office database.

found to be associated with less green innovation, which reflects fewer incentives for firms to find cheaper, more efficient energy sources and helps explain the observed slowdown in green innovation.

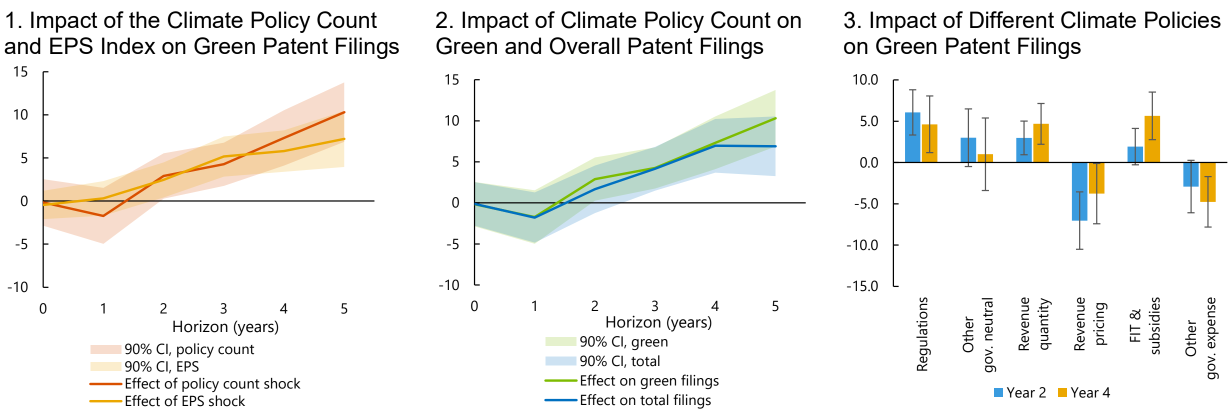
Regression analysis shows that adopting climate-change-mitigating policies is associated with higher green patent filings in the medium term. A one standard deviation increase in climate policies boosts green patent filings by 2.9 percent in two years and up to 10.3 percent in five years, on average (Figure 7, panel 1). The delayed effect is expected, as it takes time for people to develop innovations and file their patents in the country adopting new policies. Nevertheless, the response is still relatively quick, since applications to the domestic patent authority include existing patents in other countries for which patent owners are seeking protection in new markets. The figure also presents results of similar analysis tracking the impact of changes in the Environmental Policy Stringency Index, which captures the relative stringency of different policies across and within countries. A one standard deviation increase in the index raises green patent filings by 2.5 percent in two years and up to 7.2 percent in five years. The qualitative and quantitative similarity in results suggests that the number of climate policies is an adequate measure of policy effects, even though it does not capture stringency. Results are also robust to an instrumental variables exercise that addresses the potential endogeneity of climate policies (see Online Annex III).

Climate policies also increase total patent filings. An interesting question is whether a push toward green innovation will simply replace innovation in carbon-intensive technologies or boost overall innovation, at least for a while. An increase in overall innovation could result from ongoing parallel research in both high- and low-carbon technologies as carbon-intensive technologies are still widely used in the economy. Or it could reflect the need for complementary non-LCT innovations triggered by the incorporation of new LCTs into upstream sectors of the economy as well as the knowledge spillovers of green innovation to other technology fields, as highlighted by Dechezleprêtre, Ménière, and Mohnen (2017). Figure 7, panel 2, shows the impact of changes in climate policies on total patent filings and finds that a one standard deviation increase in the stock of climate policies increases total patent filings by 6.9 percent after five years. Consequently, evidence suggests that climate policies do not simply cause substitution between high- and low-carbon technologies but lead to greater overall innovation, a point that must be taken into account when quantifying the net economic impact of the green transition. Note, however, that climate policies have a stronger impact on green patents, whereby a change in the stock of climate policies leads to an increase in the share of green filings in total filings (Online Annex III). Zooming into the energy sector, evidence points to a greater number of green and gray patents (that is, innovations to reduce emissions from carbon-intensive technologies) as a share of total energy patents filings following an increase in the stock of climate policies; the share of carbon-intensive energy patents, however, decreases.

Regulations, revenue-generating policies that target the quantity of emissions, R&D subsidies, and feed-in tariffs effectively foster overall green patent filings. Leveraging the classification based on policies' impact on government budgets, Figure 7, panel 3, studies how effectively different climate policies stimulate patent filings. Government-neutral policies, and particularly regulations, are effective at stimulating green patent filings: a one standard deviation increase in the stock of regulations can increase green patent filings by 5 percent four years after the change. Within revenue-generating policies, only instruments that limit emissions quantities—such as emissions-trading schemes —are found to boost green patent filings, by 4.7 percent after four years. The weak result for revenue measures operating through prices (such as carbon taxes and fees) is consistent with findings of other studies (Eugster 2021; Battarelli and others 2023) and may result from the short horizon of the analysis and aggregate nature of the data employed. Theoretical models highlight the role of carbon taxes for emissions reductions and innovation over the long term (Acemoglu and others 2012); other studies have found that high energy prices spark innovation in alternative energy sources (Popp 2002). On the expenditure side, feed-in tariffs and subsidies increase green patents by 5.6 percent in four years, whereas other expenditure measures are not conducive to innovation (Figure 7, panel 3). This is consistent with Battarelli and others (2023), who find that the technological support component of the Environmental Policy Stringency Index, covering R&D subsidies and feed-in tariffs, has a positive impact on renewable energy patents. Box 1 elaborates further on the role of expenditure measures in fostering key technologies.

Figure 7. Climate Policies and Green Patent Filings

(Percent)



Sources: Climate Policy Database; European Patent Office Worldwide Patent Statistical Database (PATSTAT); and Hasna and others (forthcoming, a).

Note: All panels estimate the impact of climate policies following the local projection framework in which the dependent variable is the log of patents per capita over the horizon considered and the variable of interest is the change in the stock of climate policies, or in the EPS. In panel 3, the analysis considers the change in the stock of each policy type and shows results of impacts two and four years after the change. For more details on the econometric specification and additional controls in each panel see Online Annex II. CI = confidence interval; EPS = Environmental Policy Stringency Index; FIT = feed-in tariff.

Green patent filings are also positively affected by key international climate policy landmarks and global policies. The local projection framework is augmented by identifying key dates in the climate policy nexus (plus the two-year window succeeding the event) and interacting those events with the policy change to capture the marginal effect of the climate events. The events, as defined in Figure 5, panel 1, start with the issuance of the first IPCC report in 1990 and end with the Paris Agreement in 2015. Figure 8, panel 1, shows that key events boost the impact of domestic policies on green patent filings, especially over the medium term, during which they almost double their effect. This may reflect the fact that climate policy landmarks create more policy certainty about the resolve of governments to embark on the green transition and make climate policies more credible, thus reinforcing their impact on innovation. The importance of global climate policy action is also visible when comparing the effect of domestic policies with that of a weighted count of global policies. Global policies have a larger effect than domestic policies (Figure 8, panel 2), whereby a one standard deviation increase in distance-weighted global policies increases domestic patent filings by close to 20 percent after five years. The inclusion of global policies does not affect the size and significance of most domestic policies, except for weakening the medium-term effect of regulations and nonregulatory revenue-neutral policies (the latter include less binding measures, such as government strategy documents and voluntary emissions-reduction targets). The significance of global policies for domestic green patenting points to the large potential effect of synchronized global climate action.

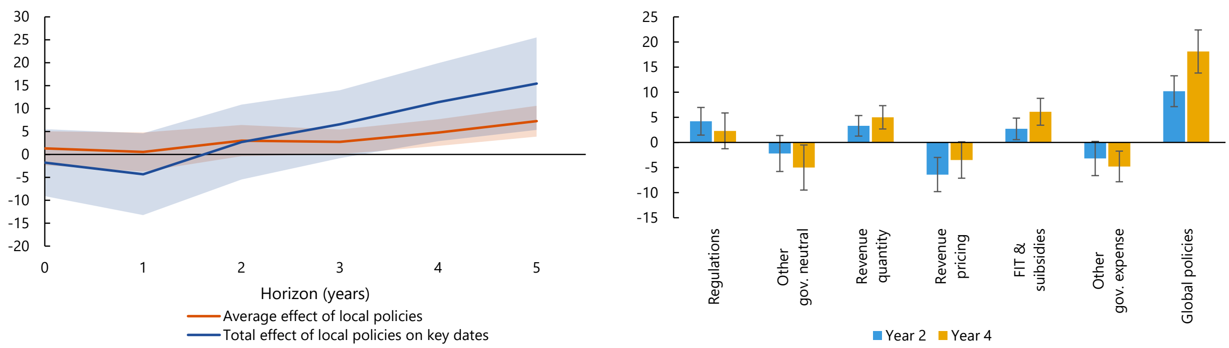
There are two channels through which global policies can have a strong impact on domestic patenting of LCTs: the market size effect and technology spillovers. Given the global nature of markets, firms respond both to policies in the country of their headquarters and to policies in large countries or markets. Their incentives to develop LCTs increase with the size of the potential market in which these technologies can be sold. The automobile market is a case in point. The recent announcements by a growing number of governments, including those of large countries, of bans on future sales of internal combustion engine vehicles bodes well for an acceleration of technological progress for electric vehicles, whose sales have been rising sharply. The second channel is technology diffusion, through which domestic green patent filings capture and build on inventions from other countries. Green patents are subsequently filed in the domestic economy; such inventions depend on the policies of the inventors' countries.

Figure 8. Effect of Global Events and Policies on Green Patent Filings

(Percent)

1. Impact of Key Climate Events on Green Patent Filings

2. Impact of Domestic and Global Climate Policies on Local Green Patent Filings (Effects after Four Years)



Sources: Climate Policy Database; European Patent Office Worldwide Patent Statistical Database (PATSTAT); and Hasna and others (forthcoming, a).
Note: All panels estimate the impact of climate policies following the local projection framework, in which the dependent variable is the log of patents per capita over the horizon considered and the variable of interest is the change in the stock of climate policies. Key climate events are defined as in Figure 5. In panel 2, bars indicate the effect on patents 4 years after the shock. All coefficents capture a one standard deviation change in each variable of interest. For more details on the econometric specification and additional controls in each panel see Online Annex II. FIT = feed-in tariff.

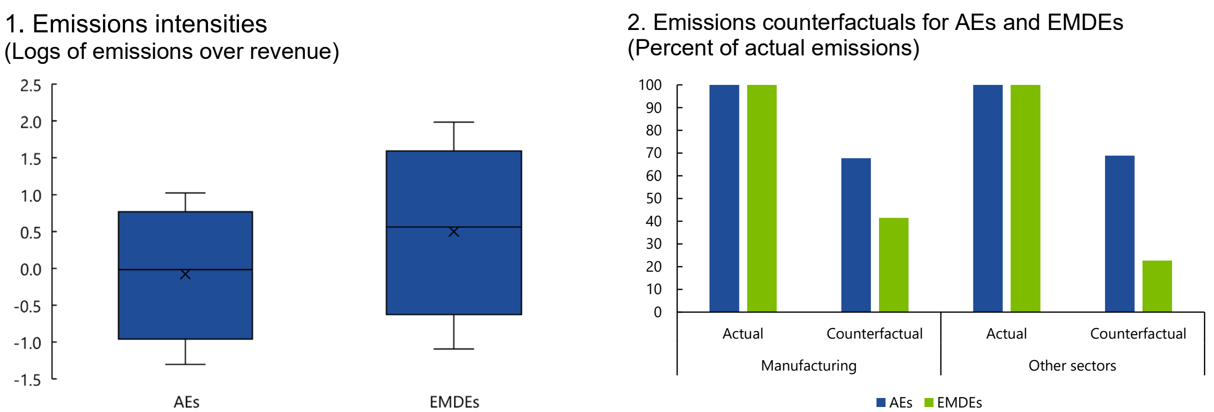
Beyond the indirect impact of policies, governments have a key role in directing innovation and funding research in technologies that will be needed but are too risky for private actors to invest in. Climate policies create a market for particular LCTs and set expectations for future business opportunities, which allows firms to invest in LCTs. Through climate policies, governments can help direct research toward areas that are socially desirable (Johnson and Acemoglu 2023). In addition, government-funded basic research has played a key role in developing key technological breakthroughs (Mazzucato 2013) and continues to do so. As discussed in Box 2, early-stage government-funded research was instrumental in the development of solar energy. A more recent example is the large-scale government effort to finance COVID-19 vaccines in 2020 (Celasun, Jaumotte, and Spilimbergo 2021). The contribution of large-scale and long-term government support for research is essential for the global economy to reach net zero emissions. Examples of critical technologies in need of substantial development are negative emissions technologies and technologies to reduce emissions in the agricultural sector.

III.2. The Impact of Climate Policies on LCT Trade and Green FDI

An important factor to reach net zero emissions is the global deployment of technology, which can take place through different channels—namely, trade and FDI. Patents are only one way in which knowledge flows across borders. In fact, as documented earlier, patent filings are seen only in a relatively small share of countries. Two alternative vessels for technological transfers are trade and FDI. On one hand, trade, in particular imports, gives local producers access to goods produced abroad. These goods, especially when they come from knowledge-producing countries, embody frontier technology. FDI, on the other hand, is both a source of financing, thus easing financial constraints in the local economy, and a vessel for technological transfers through affiliate-parent company interactions (Arnold and Javorcik 2009) and through direct and indirect linkages between affiliates and local firms (Javorcik 2004). Foreign-owned firms in emerging markets exhibit lower carbon intensity than domestic firms in high-emissions sectors (Borga and others 2023) and use less energy than local firms (Brucal, Javorcik, and Love 2019). The higher emissions intensity of local firms is driven in part by older physical capital, lower research intensity, and less effective management practices (Capelle and others, forthcoming). Trade in LCTs and FDI may thus be two important ways firms in emerging market and developing economies can close their emissions-intensity gap. Capelle and others (forthcoming) find that, keeping production constant, emissions from firms in emerging market and developing economies could be reduced by 70 percent if those with high emissions intensity converged to the median level observed in advanced economy firms in the same narrowly defined industry (Figure 9). While technological transfer occurs mostly through private sector activity, government-sponsored technological transfer initiatives are another way to transfer technologies, especially to lower-income countries. Box 2 discusses past technology transfer initiatives that have successfully helped achieve global objectives and how such initiatives could play a role in the fight against climate change.

LCT deployment also has the potential to yield economic benefits in recipient countries. One factor that could mitigate the economic gains from FDI to the domestic economy is the partial accrual of efficiency gains from multinational firms to parent firms through higher profits. However, Capelle and others (forthcoming) find that policies that stimulate LCT deployment can positively affect production and consumption in emerging market and developing economies. More broadly, as discussed, technological transfers and spillovers to local firms as a result of FDI can lead to GDP and productivity gains in the host country.

Figure 9. Emissions intensities in Advanced Economies and Emerging Market and Developing Economies and Potential Emissions Reductions from Closing Emissions-Intensity Gaps

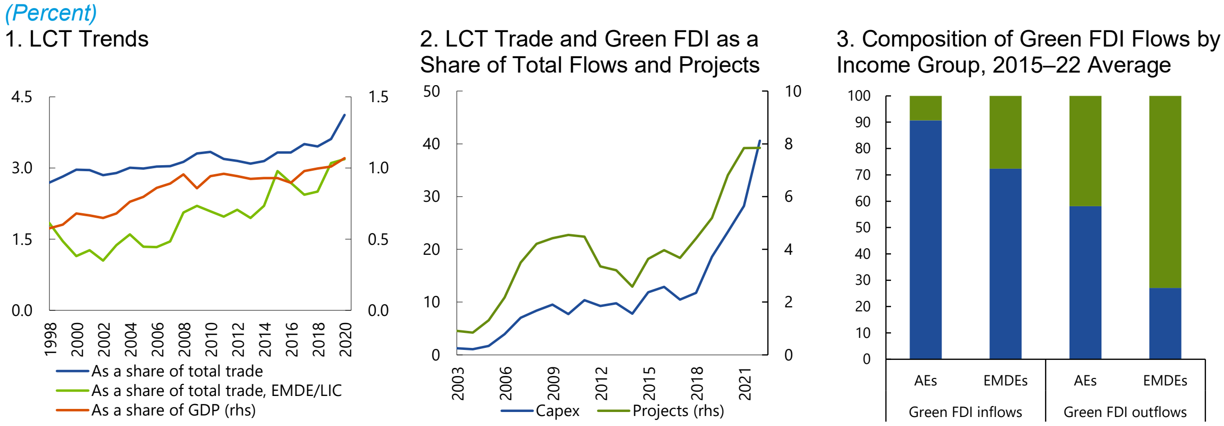


Source: Capelle and others (forthcoming).
Note: The analysis focuses on emissions of scope 1 (direct) and 2 (indirect, from generation of purchased energy). Four-digit Standard Industrial Classification and 2019 data are used. The sample is biased toward large listed firms that report emissions. The financial, utilities, and energy sectors are excluded. In panel 1, each plot shows the 10th, 25th, 50th, 75th, and 90th percentiles of the distribution. Industry fixed effects are included. In panel 2, within-industry counterfactuals are constructed by assuming that all AE and EMDE firms with emissions intensities above the AE median reduce their intensities to the level of the median AE firm, keeping their production constant. AE = advanced economy; EMDE = emerging market and developing economy.

To quantify each form of deployment, this SDN relies on several data sources. To study deployment though trade, it focuses on LCT goods, as defined in Howell and others (2023). These are goods that typically produce less pollution than their traditional counterparts and play a vital role in the transition to a low-carbon economy.[9] LCT goods include wind turbines, solar panels, biomass systems, and carbon capture equipment. When studying green FDI, this SDN focuses on new cross-border investment projects associated with renewable energy and the production or adoption of LCTs (see Online Annex I and Pienknagura, forthcoming, b). Data come from the Financial Times fDi Markets database, which collects data on announced new cross-border investment plans from multiple media and business sources. The data are an imperfect proxy for overall FDI, since they capture only investment projects included in the fDi Markets database, but they offer unique information that makes it possible to identify green FDI. Moreover, Aiyar, Malacrino, and Presbitero (2023) document a strong correlation between FDI market aggregate inflows and official FDI flows.

An analysis of trends shows that, unlike the slowdown in patenting, the diffusion of LCTs through trade and FDI has accelerated. After slowing in the aftermath of the global financial crisis, LCT imports have recovered their dynamism since 2016, especially in advanced economies (see Figure 10 and Pienknagura, forthcoming, a). Low-income countries, which started further behind advanced economies in the early 2000s, had closed most of that gap by 2015. Emerging market and developing economies such as China, Mexico, and Vietnam stand out for their high share of LCT imports.[10] Global green FDI has also accelerated since 2016—even more than LCT trade—and tripled as a share of global GDP between 2014 and 2022. The rising trend in green FDI is also evident when looking at the composition of total greenfield FDI—green FDI flows accounted for 10 percent of total greenfield FDI between 2014 and 2017, and by 2022 it had reached 40 percent of total investment (Pienknagura, forthcoming, b). A large amount of green FDI inflows into emerging market and developing economies still comes from advanced economies, although inflows from other emerging market and developing economies are not negligible (Figure 10).

Figure 10. LCT Trade and Green FDI—Global Trends and Heterogeneity across Income Groups
(Percent)



Sources: IMF climate policy dashboard; World Bank, World Development Indicators; and IMF staff calculations.
Note: AEs and EMDEs are classified according to the IMF income classification. Low-income classifications follows the World Bank classification. AE = advanced economy; capex = capital expenditure; EMDE/LIC = emerging market and developing economy, low income; FDI = foreign direct investment; LCT = low-carbon technology; rhs = right hand side.

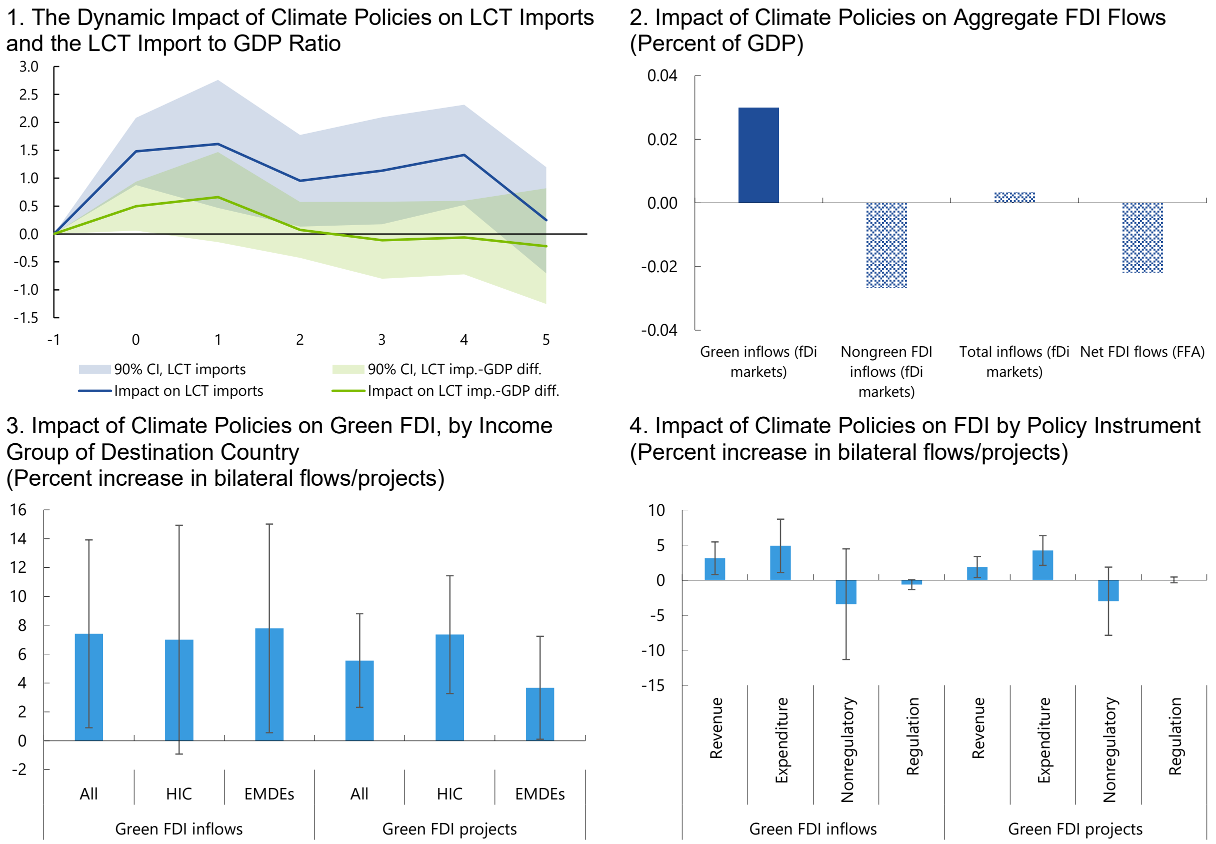
[9] See https://climatedata.imf.org/ for methodological details and definitions.
[10] Emerging market and developing economies lag advanced economies substantially in terms of LCT exports, with notable exceptions such as Hungary, Malaysia, and China—the largest exporter of LCTs in dollar terms globally in 2021 (Howell and others 2023).

The Role of Domestic Policies

Climate policies are found to boost LCT imports significantly. Figure 11, panel 1, shows results from local projections of the impact of climate policies on real LCT imports and the ratio of LCT imports to GDP. Estimates suggest that a one standard deviation increase in the stock of climate policies results in an increase in real LCT imports of about 1.5 percent on impact and an increase in LCT imports to GDP of about 0.5 percent. As time progresses, GDP catches up to imports, returning the share of LCT imports to GDP to its initial level. Turning to the role of specific policies, revenue and expenditure measures are found to yield medium-term increases in LCT imports, while other measures either have a nonsignificant (regulations) or negative (nonbinding neutral policies) effect (see Online Annex III).

Figure 11. The impact of Climate Policies on LCT Trade and FDI Inflows

(Percent)



Sources: Climate Policy Database; Financial Times fDi Markets database; IMF climate policy dashboard; and United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) database.
Note: Panel 1 shows local projection estimations of the impact of a one standard deviation change in climate policies on the log difference of real LCT imports at different horizons and its pre-shock level and on the log difference between LCT imports and GDP. Panel 2 shows panel regression results quantifying the impact of a one standard deviation change in log climate policies on each FDI measure. Solid bars are significant at the 10 percent level; patterned bars are not significant. Panels 3 and 4 shows the impact of a one standard deviation increase in the destination country's log climate policies on bilateral green FDI inflows. Additional details can be found in Online Annex II and Pienknagura (forthcoming, b). CI = climate impact; diff. = difference; EMDE = emerging market and developing economy; FDI = foreign direct investment; fDi Markets = Financial Times fDi Markets database; FFA = foreign financial assets; HIC = high-income country; imp. = imports; LCT = low-carbon technology.

More action on the climate policy front also increases green FDI inflows, without adverse effects on total FDI. Figure 11, panel 2, shows the impact of climate policies on greenfield FDI inflows (green, nongreen, and total) and net FDI as a share of GDP. The analysis uses FDI as a share of GDP as its dependent variable to facilitate comparison with previous work (see, for example, Gu and Hale 2022). An increase in the number of climate policies leads to higher green FDI inflows as a share of GDP. The evidence suggests, however, that climate policies may reduce FDI inflows in nongreen projects, although the effect is statistically insignificant. This pattern may reflect the fact that nongreen FDI includes both carbon-intensive projects (such as those associated with fossil fuels), which are likely hampered by climate policies, but also activities that complement green projects and thus benefit from more stringent climate policies (for example, those providing inputs to green projects or those reliant on the output of green projects). Overall, the combined impact of climate policies on green and nongreen FDI flows yields a relatively negligible impact on total greenfield investment. This does not preclude FDI inflows into some sectors from being adversely affected by climate policies; it just points to a lack of aggregate effects. Similar conclusions emerge when studying the relationship between climate policies and net aggregate FDI inflows, a result that is consistent with Gu and Hale (2023), and when using the Environmental Policy Stringency Index instead of the climate policy count. Significantly, these patterns are based on historical data and may change as the balance between green and nongreen FDI changes.

Using data on bilateral FDI flows confirms that the implementation of climate policies incentivizes green FDI inflows. To gain further insights into the role of climate policies for green FDI, the rest of the analysis turns to bilateral gravity estimations. The methodology allows to control for destination-country, source-country, and country-pair characteristics that could affect FDI flows. For example, geographic and cultural proximity are two attributes associated with larger FDI flows, and the gravity framework makes it possible to take these factors into account. Baseline results confirm that a larger portfolio of climate policies in the destination country is associated both with a higher number of green projects and with greater value of investment in green projects (Figure 11, panel 3). A one standard deviation change in the stock of climate policies in the recipient country is estimated to increase bilateral green FDI inflows by 7 percent, on average.

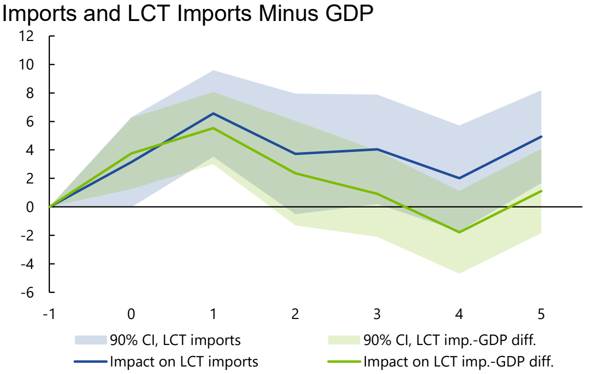
The positive impact of climate policies on green FDI inflows is not, however, driven exclusively by advanced economies; in fact, effects are somewhat stronger in emerging market and developing economies. As argued in Pigato and others (2020), weak fundamentals (such as low human capital or weak rule of law) may hamper emerging market and developing economies' ability to leverage climate policies to boost LCT deployment, including through FDI. Against this backdrop, Figure 11, panel 3, explores potential differences between advanced and emerging market and developing economies in terms of the elasticity of green FDI inflows with respect to climate policies. In both income groups climate policies act as a catalyst for green FDI inflows, with somewhat larger effects in emerging market and developing economies for the value of inflows, but smaller effects for the number of projects. This indicates that foreign investors may be less constrained than domestic firms by absorptive capacity, since they can partially overcome these barriers by transferring firm-specific know-how and deploying qualified personnel to their foreign affiliates.

Among climate policies, government expenditure and revenue measures have a strong positive impact on green FDI in the recipient country. Figure 11, panel 4, shows results of an augmented gravity specification that, in addition to controlling for the total number of climate policies, includes the share of each policy type (revenue, expenditure, or regulation) in the total. In line with results for LCT trade, revenue and expenditure measures have a positive and significant effect on green FDI inflows (Figure 11, panel 4). Other policies, including nonbinding neutral policies, have a nonsignificant impact. This points to the importance of more binding and specific policies in the design of climate policies when pursuing higher green FDI inflows.

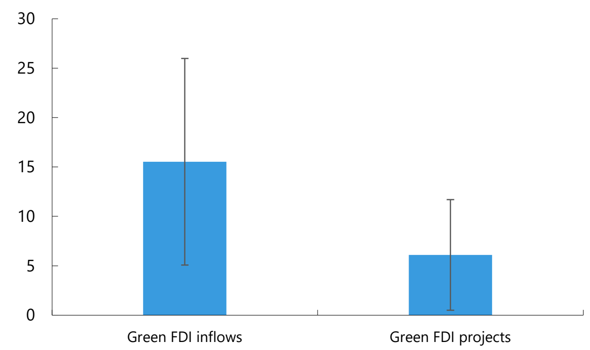
Another important policy tool available to policymakers to accelerate LCT imports and green FDI inflows is lower tariffs on LCT goods. Results from local projections show that LCT imports rise substantially in response to a decline in LCT tariffs (Figure 12, panel 1). As in the case of climate policies, the initial acceleration in imports outpaces GDP growth, yielding a temporary increase in the difference between LCT imports and GDP, after which GDP catches up to the higher level of imports. The estimated magnitudes imply that a one standard deviation reduction in LCT tariffs, which is equivalent to closing one-third of the gap between emerging market and advanced economies in one year, is associated with a 4 percent increase in the LCT-trade-to-GDP ratio and a 6 percent increase in LCT imports. Similarly, lower LCT tariffs are found to increase green FDI inflows (Figure 12, panel 2). Trade protection can have opposing effects on FDI inflows a priori. It can induce multinational corporations to relocate to protected markets to circumvent tariffs (tariff-jumping FDI; see Bloningen 2005) , but it can also increase the cost of imported inputs and discourage FDI in activities that rely heavily on such goods, especially when there is scarcity of cheaper domestically sourced alternatives. Results point to the latter effect dominating when it comes to green FDI—lower tariffs for LCT goods are associated with higher values for both green FDI inflows and green projects (for which LCT imports are presumably crucial inputs). As with imports, the economic effect of lower LCT tariffs is large—a one standard deviation decrease in LCT tariffs in the recipient country yields an increase of 15 percent in bilateral FDI flows. Trade policy thus appears to be a key lever to boost LCT diffusion through both LCT imports and green FDI inflows, by reducing the cost of the technology. Emerging market and developing economies, in particular, have substantial room to reduce tariffs on LCT goods.

Figure 12. The Impact of Trade Policies on LCT Trade and Green FDI
(Percent)

1. The Dynamic Impact of Lowering Green Tariffs on LCT Imports and LCT Imports Minus GDP



2. The Impact of Lowering Green Tariffs on Bilateral Green FDI Inflows



Source: Climate Policy Database; IMF climate policy dashboard; United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) database; and IMF staff calculations.
Note: Panel 1 plots the estimated impact of a one standard deviation change in tariffs from two local projections: one of the log difference of real LCT imports at different horizon and its pre-shock level and one of the log difference of LCT imports and GDP. Panel 2 shows the impact of a one standard deviation change in tariffs on bilateral green FDI (values and projects) from gravity estimations. Additional details are in Online Annex II. CI = confidence interval; diff. = difference; imp. = imports; LCT = low-carbon technology.

Cross-Border Effect of Policies

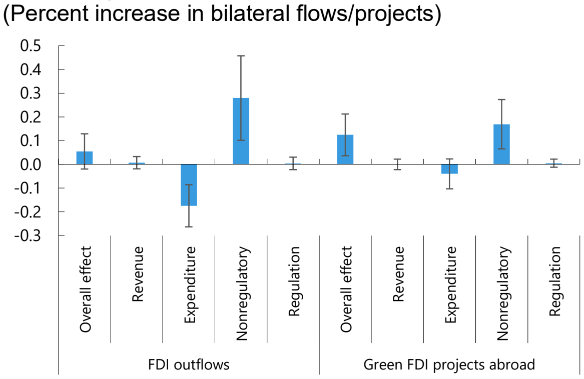
The introduction of green subsidies and industrial policies by the US Inflation Reduction Act has sparked concern in emerging market and developing economies—and in other advanced economies as well—about potential negative cross-border effects on their green industries. Support for LCTs can ultimately benefit the global fight against climate change by helping overcome externalities and market failures that hinder the introduction of LCTs. However, in the short to medium term, countries that do not have equivalent expenditure measures—sometimes because of lack of fiscal space—are concerned that these policies could move new green industries to the countries implementing the subsidies, at their expense. The concern is especially high when, in an effort to avoid the emergence of dominant foreign producers, the provision of the subsidies is conditional on the requirement that the goods be produced in the country implementing the subsidies ("local content requirement"). As shown earlier, subsidies are an important lever for attracting green FDI inflows; the analysis next examines how the implementation of climate policies, including subsidies, affects green FDI outflows from countries implementing them.

Overall, climate policies implemented in countries that are the source of FDI are found to boost their green FDI outflows, pointing to positive green spillovers to other countries. In addition to assessing the impact of policies in the destination country, gravity models make it possible to gauge the impact of climate policies in the source country. Figure 13 shows results of a gravity specification that controls for the characteristics of the source country's climate policy portfolio. The figure shows that a larger number of climate policies in the source country is linked to higher green FDI outflows and more green projects abroad (Figure 13, panel 1, overall effect). Similarly, a higher Environmental Policy Stringency (EPS) Index value, which is available for many source countries in the analysis, is associated with higher green FDI outflows (Figure 13, panel 2). All this points to positive cross-border policy spillovers. This is important for two reasons. First, it shows that the enactment of climate policies in high-income countries, typically the source of green FDI outflows, can boost the deployment of LCTs to emerging market and developing economies and help overcome current climate policy gaps. Second, it stresses the importance of international efforts to accelerate climate policies, as they can spark the adoption of LCTs on a global scale.

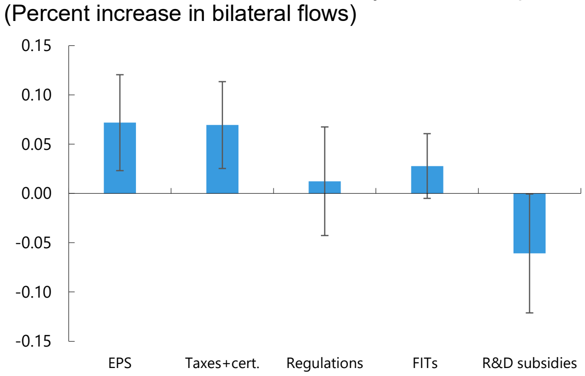
One exception, however, is expenditure measures, which appear to reduce green FDI outflows, at least in the short to medium term. Figure 13, panel 1, shows that higher levels of expenditure measures (such as subsidies) are associated with lower green FDI outflows and fewer green FDI projects abroad. By contrast, other policy instruments have either a positive or statistically insignificant impact. A similar analysis breaking down the impact of different EPS subcomponents shows that countries with higher R&D subsidies exhibit lower green FDI outflows, while countries with a higher intensity in the "certificates and taxes" category have higher green FDI outflows (Figure 13, panel 2). As mentioned earlier, the analysis captures mostly the short-term impact of subsidies, which may otherwise be important for the development of new LCTs and for future deployment. Thus, the analysis points to potential trade-offs between short- and long-term deployment objectives. This trade-off appears less strong with other types of subsidies, such as feed-in tariffs, which have a positive, albeit only marginally significant, effect on green FDI outflows.

Figure 13. The Impact of Climate Policies in the Source Country on Green FDI

1. The Impact of Climate Policies in the Source Country (Percent increase in bilateral flows/projects)



2. The Role of the Source Country's EPS Components (Percent increase in bilateral flows)



Sources: Climate Policy Database; Financial Times fDi Markets database; and United Nations Conference on Trade and Development (UNCTAD) Trade Analysis Information System (TRAINS) database.
Note: Panel 1 shows results of a regression estimating the effect of a one standard deviation increase in the log of climate policies in the source country on bilateral green FDI and one gauging the effect of a one standard deviation change in each policy type. Panel 2 shows results of a regression estimating the effect of a one standard deviation change in the source country's EPS and one estimating the effect of a one standard deviation change in each subcomponent. For details see Online Annex II. EPS = environmental policy stringency; cert. = certificates; FIT = feed-in tariff.

IV. Conclusions and Policy Implications

In addition to its essential role in curbing emissions and reducing the macro-critical risks associated with climate change, green innovation can boost medium-term economic growth, especially through higher investment. Innovations that introduce new low-carbon technologies or lower the cost of those that already exist are key to the green transition. Still, while the long-term economic benefits of higher green innovation are well understood, there is still debate over potential transition costs. Green innovation can promote economic activity in the short to medium term by stimulating investment and total innovation and buffer potential adverse effects of climate policies. The prospects of such positive effects are particularly appealing at a time of weak medium-term economic outlook (IMF 2023a) and could ease societal concerns about the adoption of a more vigorous climate agenda (Dabla-Norris and others 2023). The analysis in this SDN does not find a positive impact of green innovation on aggregate productivity, but this may reflect the relatively short horizon of analysis. Evidence from the information and communications technology revolution suggests that the pro-productivity impact of technological breakthroughs may take time to materialize.

Boosting green innovation and accelerating the deployment of low-carbon technologies (LCTs) require expansion in the stock of climate policies and lower trade costs for LCTs. Advancing climate policies will play a critical role as countries seek technology-based solutions to fight climate change. Climate policies can accelerate patenting in clean technologies and can spark higher diffusion through trade and FDI. Revenue measures (specifically those restricting emissions quantities, such as emissions-trading systems) and expenditure measures associated with R&D subsidies and feed-in tariffs bolster both green patents and green FDI inflows; regulations also lead to more green patents. Efforts on the climate policy front should be complemented with lower trade costs for LCTs, especially in emerging market and developing economies: lower tariffs on LCT goods strongly promote deployment through both trade and FDI.

International coordination and cooperation are crucial to accelerate innovation and the deployment of LCTs, as there are significant cross-border climate policy spillovers. First, domestic patenting reacts to global climate policies, pointing to benefits from synchronized climate action through market size effects (Aghion and others 2022) and technology spillovers. Second, countries that implement climate policies also increase the share of green FDI in their overall outflows, which suggests that they export the low-carbon technologies to other countries. Yet some policies may create tension between domestic and global climate objectives. For example, the use of subsidies—which may be warranted in the presence of externalities and market failures and could boost LCT trade if they lead to lower production costs—results in reduced green FDI outflows. The potentially harmful effects of subsidies could be exacerbated if they are accompanied by protectionist measures, as shown by the adverse impact of LCT tariffs on the deployment of green technologies. International coordination and cooperation in the design of climate strategies will thus be crucial to (1) mitigate the adverse impact of subsidies; (2) prevent a subsidy race, which could hamper the deployment of LCTs to emerging market and developing economies, given their reduced fiscal space (Aligishiev and others 2023); and (3) ensure that policies are consistent with World Trade Organization rules, including by avoiding local content requirements. This is particularly important given growing concerns of geoeconomic fragmentation, which can erode incentives for green innovation and slow the diffusion of green technologies.

Box 1. Innovating toward Net Zero Emissions: The Role of Government

Governments need to pursue a dual approach of scaling up the use of existing low-carbon technologies (LCTs) and investing in basic research for LCTs, which may take a long time to develop. Over 80 percent of the emissions reductions needed *by 2030* can be achieved if the use of existing technologies can be scaled up (Pigato and others 2020). The use of the technologies will further reduce the costs through learning by doing. At the same time, 75 percent of the LCTs needed *by 2050* either need to be developed beyond the prototype level or require R&D investment to become commercially viable (IEA 2020a). To address this, governments should engage in long-term support for technology development.

In the early LCT development stage, the government has a key role in funding basic research. Developing solar energy, one of the cheapest current forms of electricity generation, is an example of the key role of government support (Nemet 2019). In a first phase, the government invested in basic research for the technology. For example, the US government provided crucial support for solar energy by investing in research following the 1979 oil crisis and incorporating it in niche markets (for example, space flight).[11] Another example of the importance of government support in early technology development is the research for a COVID-19 vaccine in 2020. Although private companies were deeply engaged, the government had a role in coordination and funding. An important consideration in early technology support is assuring innovators that there will be a market for the technology. Developing a technology with a substantial market size can open considerable opportunity for domestic firms' growth and job creation.

When an LCT is viable, but not yet economically competitive, subsidies can help scale up production and achieve further cost reductions. Even while it was still more expensive than conventional energy production, solar energy began to be used for terrestrial electricity generation. In this phase, subsidy programs in Japan and Germany allowed for scaled-up use of the technology and learning by doing until the technology became competitive. In contrast, the US government did not provide sufficient policy certainty to its industry to maintain the early advantage. In a third phase, mass production by China allowed that country to reap further cost reductions through economies of scale, which contributed to global deployment of the technology. Solar energy is now one of the cheapest forms of electricity generation in terms of levelized cost (IRENA 2022).

Key technologies that will require active government intervention are green hydrogen and negative emissions technologies (NETs). Energy use for long-distance flights and maritime transportation cannot be electrified as can road transportation (Englert and others 2021; IEA 2020b). These uses call for zero-carbon fuels, which can be produced from hydrogen, which is labeled "green" if it is generated with renewable energy. Government intervention is needed to coordinate global supply and demand increases. The European Union, for example is requiring aircraft fuel suppliers at EU airports to use an increasing share of sustainable fuels.[12] Direct government research support is also needed for NETs; that is, technologies that can withdraw greenhouse gases from the atmosphere. These technologies will be necessary to compensate for unavoidable emissions and possible temperature overshoots. An example of a NET is direct air capture, which can extract carbon dioxide from the atmosphere. NETs will most likely be scaled up in the middle of this century, but given the currently high cost, investment must start very soon (Nemet and others 2018).

[11] Government investment and risk taking are crucial in the development of many new technologies (Mazzucato 2013).
[12] https://www.consilium.europa.eu/en/infographics/fit-for-55-refueleu-and-fueleu.

Box 2. Technology Transfer and the Role of International Organizations

International technology transfer may play a key role in very large emissions reductions and could enhance the economic benefits from green innovation accrued by emerging market and developing economies. Emissions intensity per unit of output within narrowly defined sectors varies substantially across firms and countries. If all firms with emissions intensity above the 25th percentile could improve to the 25th percentile, emissions in advanced economies could decrease by 55 percent, assuming an unchanged level of production. Within emerging market and developing economies the emissions reduction would be larger, because these economies' firms emit more per unit of output (Capelle and others 2023). Capelle and others (2023) also find substantial economic benefits for emerging markets from a scenario in which the latest capital vintages are subsidized, which can be viewed as partial transfer of intellectual property rights. The transfer of technology between firms and countries is challenging, but this analysis highlights its potential.

Although most technology transfer happens through private sector activity, the Montreal Protocol and the Green Revolution in agriculture are examples of successful government-led technology transfer. Technology transfer and cooperation is a broad term, and it "usually occurs via the private sector" (Kirchherr and Urban 2018). However, there are examples of government-sponsored international technological transfers in which international organizations play a key implementation role. The Montreal Protocol was signed in 1987 to protect the ozone layer from harmful chemicals. A portion of this international agreement was a transfer from advanced to emerging market and developing economies of technologies that made it possible to avoid the use of such chemicals.[13] The transfer was organized by the World Bank, which administered a fund for technology transfer that was bankrolled by advanced economies (Kelly 2004), and the United Nations. Another successful example was the Green Revolution, which tripled the production of cereal crops between 1966 and 2005 with only 30 percent more land area cultivated. This was achieved through international organizations such as the Consultative Group on International Agricultural Research. Given the important role of international organizations in these two cases, there are attempts to achieve technology transfer in a similar way for low-carbon technologies. Examples of such organizations are the Climate Technology Centre and Network, the Green Climate Fund, and the Technology Executive Committee—all of which support the transfer of low-emissions and climate-resilient technologies.

An important concern regarding transfers of existing technology is the compensation of private sector innovators. Private sector innovation investments must be financed through profits on products based on the innovation (Aghion and Howitt 1992). The ability to obtain these profits depends on the exclusive use of a patent. If the right to exploit a patent is granted to producers other than the innovator, the innovator needs to be compensated in order to preserve the incentive for future innovations. Governments wishing to donate the use of a patent would thus need to buy that right from the innovator. Depending on the patent, this can be very expensive. When India and South Africa requested a temporary suspension of intellectual property rights on COVID-19 vaccines (Usher 2020), a much weaker patent waiver was implemented by the World Trade Organization, which did not have much effect.[14] For this reason, research conducted directly by international organizations such as the Consultative Group on International Agricultural Research—as in the case of the Green Revolution—is an important alternative to donation of patent access.

[13] https://ozone.unep.org/treaties/montreal-protocol/articles/article-10a-transfer-technology.
[14] https://blog.petrieflom.law.harvard.edu/2022/11/08/what-happened-to-the-covid-19-vaccine-patent-waiver.

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Green Innovation and Diffusion: Policies to Accelerate Them and Expected Impact on Macroeconomic and Firm-Level Performance
Staff Discussion Note No. SDN/2023/008