Global Trends in the Innovation and Diffusion of Climate Change Mitigation Technologies

Benedict Probst (bsp26@cam.ac.uk)
University of Cambridge https://orcid.org/0000-0002-1149-8938
Simon Touboul
MINES ParisTech, PSL University
Matthieu Glachant
MINES ParisTech
Antoine Dechezleprêtre
OECD

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Abstract

Increasing the development and diffusion of low-carbon technologies on a global scale is critical to mitigating climate change. Based on over two million patents from 1995 to 2017 from 106 countries in all major climate mitigation technologies, our analysis shows an annual average low-carbon patenting growth rate of 10 percent from 1995 to 2013. Yet, from 2013 to 2017 low-carbon patenting rates have fallen by around 6 percent annually, likely driven by declining fossil fuel prices and, possibly, a readjustment of investors' expectations and a stagnation of public funding for green R&D after the financial crisis. The Paris Agreement does not appear to have reversed the negative trend in low-carbon patenting observed since 2013. Innovation is still highly concentrated, with Germany, Japan, and the US accounting for more than half of global inventions, and the top 10 countries for around 90%. This concentration has further intensified over the last decade. Except for China, emerging economies have not caught up and remain less specialised in low-carbon technologies than the world average. This underscores the need for more technology transfers to developing and emerging economies, where most of the future CO2-emissions increases are set to occur. Existing transfer mechanisms, such as the UN Technology Transfer Mechanism and the Clean Development Mechanism, appear insufficient given the slow progress of technology transfer.

Main Text

Increasing the development and diffusion of climate change mitigation technologies (CCMT) on a global scale is critical to mitigating climate change. Historically, most CCMT have been developed and deployed in industrialised countries [1,2,3]. Yet, fast-growing emerging and developing economies urgently need to adopt these technologies to decarbonise their economies. While emerging economies, such as China and India, are building domestic CCMT industries, developing countries are often reluctant to bear the additional cost of CCMT compared to "brown" alternatives [1,4]. Within the United Nations Framework Convention on Climate Change (UNFCCC), several instruments – such as the Technology Transfer Mechanism and the Clean Development Mechanism – have attempted to address this challenge and encourage the CCMT transfer [5].

Continued innovation in CCMT is critical to reaching net-zero emissions in the second half of this century as envisaged by the Paris Agreement [6]. While it is often stated that existing technologies are sufficient to reach net-zero emissions, a range of modelling results indicates otherwise [7,8]. For instance, the IEA estimates that current progress in CCMT is insufficient to reach net-zero emissions by 2070. According to its Sustainable Development Scenario, three-quarters of technologies needed for net-zero are not mature yet. Whereas 25% are mature (such as wind and solar power generation technologies), 41% are in the early adoption stage, 17% in the demonstration phase, and 17% in the prototype stage. [9].

While existing research has provided a clear picture of CCMT invention and diffusion from 1978-2005 [2], there is a lack of a recent and comprehensive overview of global patenting and transfer trends in CCMT. Using data from the European Patent Office (EPO) Worldwide Patent Statistical Database (PATSTAT), we examine patents in the seven climate-change mitigation technologies identified by the EPO under the Y02 classification, which provides the most comprehensive and standardised low-carbon patent classification to date [10].

To provide a cross-country comparison of low-carbon innovation, we rely on patent families that were filed in at least two countries (a patent family refers to all patents protecting the same invention in a given country). By using international patent families, instead of simple patent counts, we address to challenges inherent in patent data: the propensity to patent differs greatly between countries, and the individual value of patents is highly heterogeneous[11,12]. Using international patent families provides a common metric across countries, and enables us to focus on 'high-value' inventions [13].

Also, as common in the literature, we measure the transfer of patented technologies between countries by counting the families that are invented in country A and subsequently patented in country B.[14] As patenting is costly [15], inventors tend to protect their inventions with a patent only in countries where they plan to use the technology. It permits us to analyse technology transfers between the inventor and all non-inventor countries where the patent has been filed. While patents do not capture all inventions, they currently represent the best available proxy for cross-country innovative activity (see Methods section for a detailed discussion).

We provide an up-to-date analysis of CCMT patenting and transfer trends in two steps. First, we document global patenting rates based on more than two million patents – of which 286,997 are high-value international patent families – filed across 106 countries from 1995 to 2017 in all major climate mitigation technologies (see Table 1). Second, we investigate to what extent international technology transfer trends have changed over the last decade with the introduction of the Technology Transfer Mechanism and other political instruments to increase the diffusion of CCMT.

Table 1: Technology field, EPO classification, definition, and number of inventions. Please note: The sum of all categories does not equal the total number of high-value CCMT inventions, because some inventions may be part of several CCMT technology classes. Source: PATSTAT (2019) and definitions directly cited from EPO (2013) and EPO (2019)

Technology Field	European Patent Office classification	Definition	Number of high-value inventions 1995-2017
Buildings	Y02B	"Integration of renewables in buildings, lighting, HVAC (heating, ventilation and air conditioning), home appliances, elevators and scalators, constructional or architectural elements, ICT, power management"	33,633
Carbon capture and storage (CCS)	Y02C	"CO2 capture and storage, also of other relevant GHG"	4,585
Energy	Y02E	"Renewable energy, efficient combustion, nuclear energy, biofuels, efficient transmission and distribution, energy storage, hydrogen technology"	88,631
Information and communication technologies (ICT)	Y02D	"information and communication technologies aiming at the reduction of their own energy use".	24,635
Manufacturing	YO2P	"Metal processing, chemical/petrochemical industry, minerals processing (e.g. cement, lime, glass), agro-alimentary industries"	67,109
Transportation	YO2T	"e-mobility, hybrid cars, efficient internal combustion engines, efficient technologies in railways and air/waterways transport"	88,684
Waste Management	YO2W	"Wastewater treatment, solid waste management, bio packaging"	16,072
All mitigation			**286,997**

We find an average increase of 10% in annual patenting rates from 1995 to 2013. Yet, from 2013 to 2017, low-carbon patenting rates have fallen by around 6 percent annually, likely driven by declining fossil fuel prices and the financial crisis. Innovation is highly concentrated geographically: Germany, Japan, and the US account for more than half of global inventions and the top 10 countries for around 90%, while the contribution of most emerging economies is still marginal. While patenting activity has increased substantially in China over the last years, China only accounts for only 5% of (high-value) inventions. This underscores the need for more transfers to developing and emerging economies where most of the future CO2-emissions increases are set to occur.

Global innovation trends

Figure 1 shows the annual high-value patent count for both CCMT and all technologies (indexed at 1 in 1995). The period 1995-2013 saw an almost fivefold increase in yearly patenting rates in CCMT, and substantially higher growth of CCMT compared to all patented inventions from 2002 onward. Over the period 1995-2013, the average annual growth rate was 10.4 percent. Yet, during the period 2013-2017, there has been a general decline in CCMT technologies by 5.5 percent annually.

There are several potential reasons for the decline in CCMT-patenting since 2013. The first likely explanation is the massive fall in fossil fuel prices. Historically, the proportion of global innovations targeted at CCMT has closely followed oil prices as shown in Figure 2. Oil prices also tend to be strongly correlated with other fossil fuel prices. Existing research confirms a causal and not merely correlational relationship: CCMT inventors respond rapidly to changes in fossil fuel prices [17,18]. That patenting responds so quickly is plausible, as patents may cover inventions that have already been developed, but were not yet profitable due to market factors (such as low CO_2 or oil prices). Carbon prices have not compensated for the decrease in fossil fuel prices, with allowances in the European Union Emissions Trading System (the largest carbon market in the world) falling from a peak of almost 30 EUR/t CO_2 in 2008 to around 5 EUR/t CO_2 in 2017, further weakening market incentives to abate CO_2 [19]. Past econometric evidence shows that the EU ETS increased patenting in regulated firms vis-à-vis unregulated firms by up to 10% [20], but low carbon prices likely weaken that effect. While EU ETS prices have risen since 2018, the recent decline in oil and gas prices due to the COVID-19 pandemic may continue to weaken incentives for CCMT-inventions until fossil fuel prices fully recover [21].

The decline in CCMT innovation can also be related to the stagnation in public funding for low-carbon R&D since 2012 after a doubling observed between 2000 and 2012. [22] Also, it is noteworthy that the 2015 Paris Agreement does not seem to have modified substantially inventors' expectations on the returns of low carbon innovation. Another potential reason could be that the increasing maturity of CCMT has led to a decrease in patenting. As technologies mature, the patenting intensity could decline as the focus of innovation shifts from product to process innovations, which may be protected by secrecy rather than patenting [23]. Yet, while some technologies are becoming more mature – such as solar photovoltaics – others are constantly emerging, such that, on average CCMT inventions have not become less original over time [24]. Therefore, there is no empirical indication that the maturity of CCMT is driving the decline in innovation.

Compared to all other CCMT, energy-saving innovations in the information and communication technologies (ICT) sector saw the lowest decline compared to all other technologies (Figure 3). The growing importance of ICT in the energy sector may signal a shift towards a greater reliance on this fast-moving high-tech sector (e.g., power net metering, digitally-controlled home heating) [24]. This trend is reflected in manufacturing more generally, in which ICT plays an increasingly important role in driving innovation[25]. For instance, Branstetter et al.[25] show that more software-intense firms generate more patents per R&D dollar.

In contrast to ICT-related CCMT, inventions in energy generation (including renewable energy, nuclear energy, and biofuels) have seen the highest decline in 2013-2017. This particular decline in technologies that compete with fossil-based energy is suggestive of the significant role that the decline in fossil fuel prices has likely played in the recent fall in CCMT innovation. The substantial reversal in patenting rates in carbon-capture and storage (CCS) is also noteworthy: in the period 1995-2012 it saw a large increase of 11%, yet, CCS also registered a sizeable decline since 2013 of -6.7%. This decline is potentially due to overblown expectations on the large-scale deployment of CCS in the early 2000s and low carbon prices over the last decade in Europe and elsewhere [19]. Besides, carbon utilisation has also struggled to demonstrate a viable business model over the last decade beyond its use in enhanced oil recovery.[26] The transport and storage of CO2 in deep underground rock formations have also faced technical, economic, and societal setbacks.[27] Yet, at least in Europe, two new CO2-storage sites off the coast of the Netherlands (Porthos[28]) and Norway (Northern Lights)[29] may contribute to the revitalisation of CCS innovation dynamics over the next decade.

We now investigate the patenting trends across countries (Figure 4). As the majority of carbon emissions increases in the next 30 years will come from emerging and developing economies [30], understanding whether these countries are 'catching up' in CCMT inventions is critical. Yet, our analysis shows that CCMT innovation remains highly concentrated in few industrialised countries: Japan, the U.S.A, and Germany account for 59% of global CMMT inventions, whereas the top-10 inventing countries account for 87%. The concentration of CCMT invention in few countries has even further intensified over the last decade compared to the 2000s (in the period 2000-2005, the top 10 accounted for around 85%). The major difference is that China and Taiwan have substantially increased in their ranking over the last decade. Yet, apart from China, no other emerging economy has leaped into top-10 inventing countries. It is important to note that many emerging economies perform better when analysing the mere count of patented inventions (in contrast to high-value inventions that we measure), which indicates that a sizable share of their patented inventions has a low quality, but this may change in the future.

Also, emerging countries do not only innovate less, they are less specialized in CCMT than industrialised countries (Figure 5). Emerging economies roughly kept the same level of specialization over the last three decades, while industrialized countries have redirected their innovation efforts towards CCMT (in the mid-nineties, the share of CCMT in all innovation was roughly 4% everywhere). Most industrialised countries are now highly specialised in CCMT. For instance, in Denmark, around 20 percent of all patents are filed in CCMT. In contrast, Mexico is the only emerging economy that has an above-average specialisation in CCMTs, whereas South Africa, Russia, Brazil, Turkey, and China have a below-average specialisation compared to the global average.

Global diffusion trends

To adopt CCMT technologies, countries can invent them but also import them from foreign countries, this is why studying the diffusion of CCMT is also important. Historically, patent transfers and import and FDI of CCMT have been correlated. There is a high concentration of CCMT technology transfer between high-income countries. This concentration is not specific to CCMT, but it is particularly worrying as the majority of increases in future CO2-emissions are expected to come from low- and middle-income countries. Figure 6 shows the geographical distribution of cross-country patent transfers by income groups. High-income economies constitute around 93% of all CCMT inventions and around two-thirds of global transfers are transferred to other high-income countries. In contrast, only one-third is transferred to medium-income countries. Yet, the majority of inventions transferred from high- to middle-income countries go to China, which constitutes on average 72% of all transfers from high-to-middle income countries between 2013-2017. Strikingly, low-income countries do not play a role in either invention or international technology transfer of CCMT, with less than 1% of both.

This low rate of transfer to emerging economies and developing countries alike suggests that political and economic factors appear not to be sufficient to substantially accelerate the rate of transfer. Transfer mechanisms, such as the Clean Development Mechanism and the UN Technology Transfer Mechanism, which have been established under the UNFCCC, appear insufficient. Given the slow progress that has been made since 1992, several experts have noted that it may be impossible for the UN to ultimately deliver on its technology transfer commitments, particularly to low-income countries [31].

Despite the low transfer to middle-income countries, CCMT technologies still see a much higher diffusion than the global average. The transfer rate – defined as the share of patented inventions that have been transferred to at least one foreign country – is shown in Figure 7. The level of CCMT transfer (23% of CCMT inventions) is higher than the average non-CCMT technology (17%) and this gap has widened over time. This widespread diffusion indicates the existence of a lively international market for CCMT, but largely limited to the developed world and China.

CCMT inventions related to transport, CCS, and ICT exhibit particularly high rates of international transfer compared to the average CCMT. Transport markets are inherently global, as European car manufacturers sell around 20% of their cars in China alone [32]. Interpreting these cross-sector differences is difficult, but this result suggests that additional incentives for cross-country transfer may be particularly important in energy production, manufacturing, and waste-related technologies, which underperform in terms of transfer compared to other mitigation technologies.

Discussion

After almost two decades (1995-2013) of increasing patenting rates in low-carbon technologies, our analysis shows an overall decline in CCMT-patenting trends since 2013. Low fossil-fuel and carbon prices, as well as lower private and public funding for low-carbon technologies after the financial crisis, have likely contributed to the decline. This decline is worrisome, particularly because a range of studies shows that the availability of low-carbon technologies is critical for mitigating dangerous climate change [33]. While there is an overall decline in patenting, our analysis also shows that the least affected is the ICT-sector.

Over the last decade, the concentration of CCMT innovation in few (mostly high-income) countries has remained largely stable. This concentration indicates that existing climate policies and market forces have not led to a more diverse set of CCMT-inventing countries. Nonetheless, both China (ranked 5th in global CCMT inventions) and Taiwan (7th) have caught up substantially over the last decade. China is also the major recipient of CCMT from high-income countries, receiving 72% of transferred technologies from high to middle-income countries from 2013-2017. Yet, overall emerging economies remain less specialised in CCMT technologies than the global average. The lack of specialisation of emerging economies in CCMT also points towards a more fundamental challenge: many emerging economies may be hesitant to fully engage in a low-carbon transition if there are few jobs in the low-carbon sector of the economy to which existing jobs in high-carbon sectors can be shifted (e.g., coal mining).

Our findings indicate two important lessons: First, there is a dangerous downward trend in low-carbon inventions. It is particularly worrisome that the Paris Agreement does not appear to have reversed the downward trend in low-carbon patenting. Second, our findings underscore the need for more transfers to developing and emerging economies where most CO2-emissions increases are set to occur. While global transfers do not merely occur between industrialised countries, most of the transfers from high-income to middle-income countries go to China. Hence, transferring more technologies to other emerging economies – such as South Africa, Brazil, and Russia – is critical to mitigating climate change.

Data & Methods

Data

To measure innovation and transfer of technologies, we use patent data from PATSTAT, a database provided by the European Patent Office (EPO). The database includes more than 100 million patents filed in 169 patent offices. The data used in our study can be found in Table 1.

EPO experts have created a new classification system (the “Y02” classification) specifically targeted at climate change-related technologies. Except for the Y02A class, dedicated to climate adaptation technologies, all categories within this Y02 classification refer to mitigation technologies.

EPO experts identified seven categories of mitigation technologies. The first one is the *‘Buildings’* category, which refers to “climate change mitigation technologies related to buildings, e.g. housing, house appliances or related end-user applications”. The *‘CCS’* category groups all technologies for the “capture, storage, sequestration or disposal of greenhouse gases [GHG]”. *‘ICT’* technologies are “climate change mitigation technologies in information and communication technologies [ICT], i.e. information and communication technologies aiming at the reduction of their own energy use". The *'Energy'* class groups all technologies targeting a "reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission or distribution". The fifth category, *'Manufacturing'*, gathers "climate change mitigation technologies in the production or processing of goods", whereas the category *"Transportation"* puts together "climate change mitigation technologies related to transportation". Finally, we called the last category *'Waste management'*, which targets "climate change mitigation technologies related to wastewater treatment or waste management".

Altogether, these categories contain more than two million patents related to mitigation technologies for the period 1995-2017, corresponding to 286,997 'high-value' inventions (i.e., international patent families).

Methods

Economists regularly use patents to measure innovation [18,34,35]. A patent grants the inventor the exclusive property of the new technology but forces the inventor to partly describe and reveal the technology content of his invention. Inventors patent their inventions only at the end of the innovation process when they plan to use or diffuse their invention. Patents as an indicator reflect the output of the innovation effort. Other indicators, such as R&D expenditures, or the average number of researchers per capita, can also be used as proxies for innovation, but they reflect the inputs into the innovation process (e.g., a country could have many researchers but fails to commercialize these findings). Patent documents contain detailed information on the inventor, including their country of residence which we use to determine the inventor country of the technology, but also the date of application of the patent. Patents also include a detailed description of the technology itself. This allows us to precisely identify the scope of potential applications of the technology. In particular, patent experts use this information to classify technologies, as mitigation technologies for instance. Finally, because patents are filed in all patent offices where the inventor wants to protect the technology, it provides information on all countries where the technology is expected to be used.

While patents offer many advantages to study global innovation, they are not a perfect proxy to investigate innovation and technology transfer. First, there are several ways – apart from patenting – to protect an invention. Industrial secrecy or lead-time advantages constitute other options inventors may use to ensure ownership of their technology[36]. Yet, most widely used technologies have been patented [37,38]. As the filing of a patent forces the host country to ensure the property of the invention, inventors file patents only in countries that can guarantee intellectual property. This is a second drawback of using patents as institutions in the least developed countries are not strong enough to ensure intellectual property rights (IPR). Yet, in the context of our study, it is not problematic as we focus on mitigation technologies primarily deployed in industrialised and emerging economies, which are responsible for the bulk of historical and future CO2-emissions. Another limitation of patents is the vast differences in value among them[12]. As patent offices are independent to decide what is or is not a patentable innovation, important differences in the value, but also the propensity to patent across countries exist. Using mere patent counts does not accurately capture the quality of patents.

Several methods can be used to compare innovation between countries and account for differences in patent value [13]. One of the usual methods is to weigh patents by the number of citations received from other patents. However, citations are only observed with a lag, hence this method cannot be used to investigate recent trends. Another option is to use international patent families, which are patents that protect the same invention across several countries. Using patent families accounts for differences in the breadth of patents across countries (each family is counted as one invention, irrespective of how many patents protect the invention in each country). We only use patent families that were filed in at least two countries, as these are considered high-value inventions. High-value patent families provide a common measure of innovation across countries while accounting for differences in the quality of inventions.

To disentangle innovation trends specific to mitigation technologies from trends observed in similar technologies not specifically dedicated to climate change mitigation, we build a benchmark for each technology field (Figure 3). We first selected all International Patent Classification (IPC) codes corresponding to mitigation patents by technology field (note that mitigation patents have other IPC codes apart from the Y02 classification). Next, we extracted the first three characters of each IPC code, and those with the largest number of observations, until we covered at least 80 percent of the patents in that field. We finally retain as a benchmark for this technology field all patents with three matching characters in their IPC codes.

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Figures

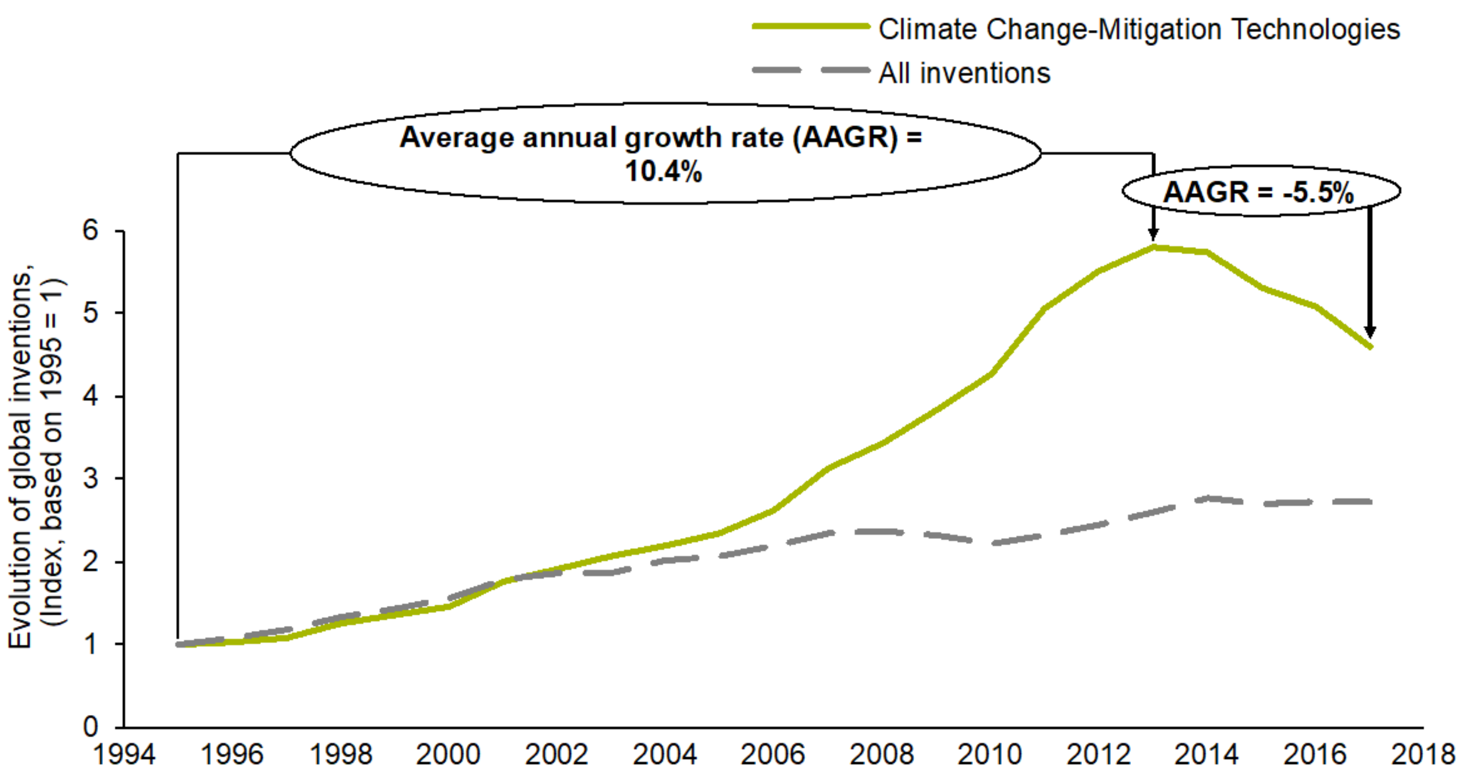

Figure 1

Evolution of global inventions from 1995-2017. Climate-change mitigation technologies include all technologies identified by the European Patent Office under the Y02 classification. These include energy, buildings, carbon capture and storage (CCS), transportation, waste management, manufacturing, and information and communications technology (ICT). Counts are based on patent families registered in at least two countries, which are considered 'high-value' inventions (i.e., our approach avoids counting large swaths of low-value patents). Patent data from 2018-2020 excluded as the patenting process takes around 2 years, potentially truncating the most recent data. Based on PATSTAT (Fall 2019) data.

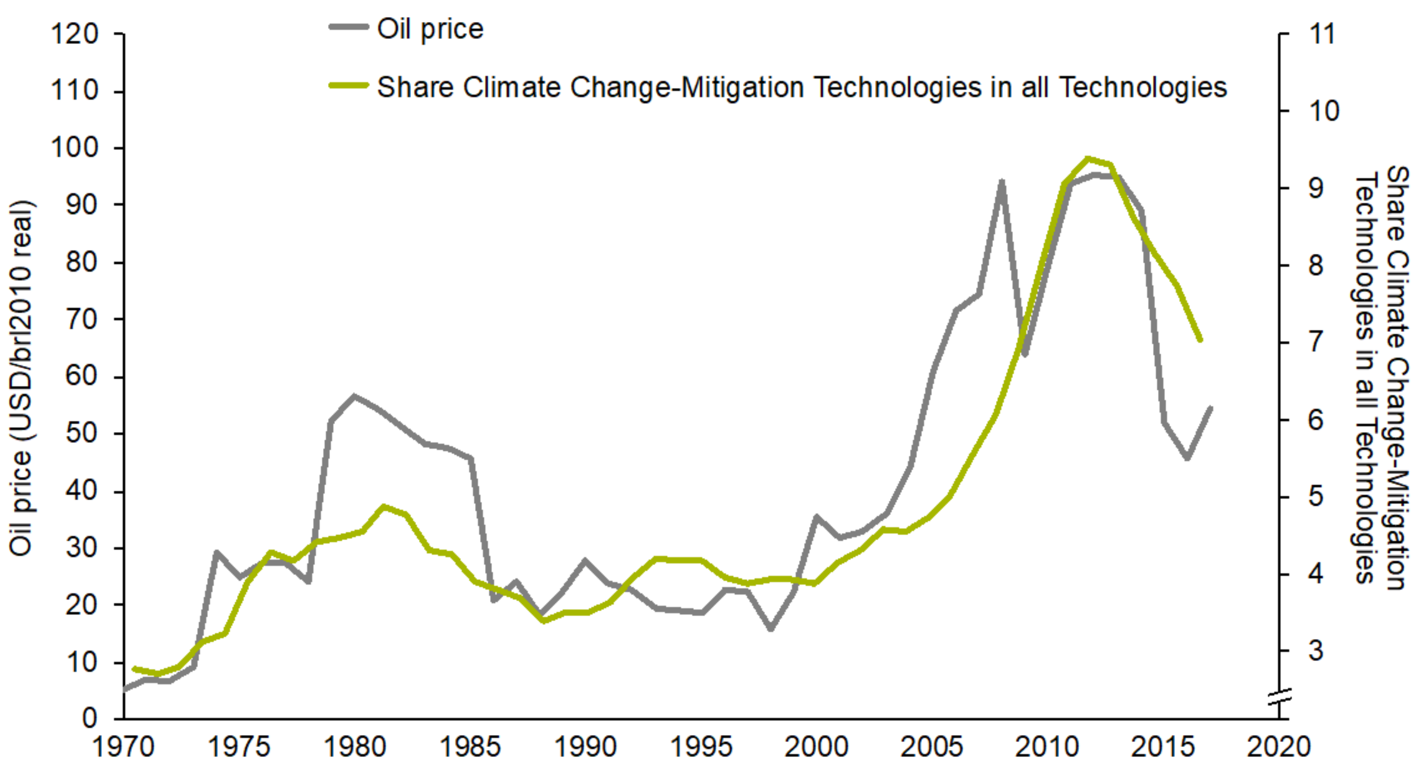

Figure 2

Correlation of oil prices and inventions in climate change mitigation technologies. Patent data is the share of climate change-mitigation technologies in all technologies based on PATSTAT (2019) and oil price based on World Bank (2020)

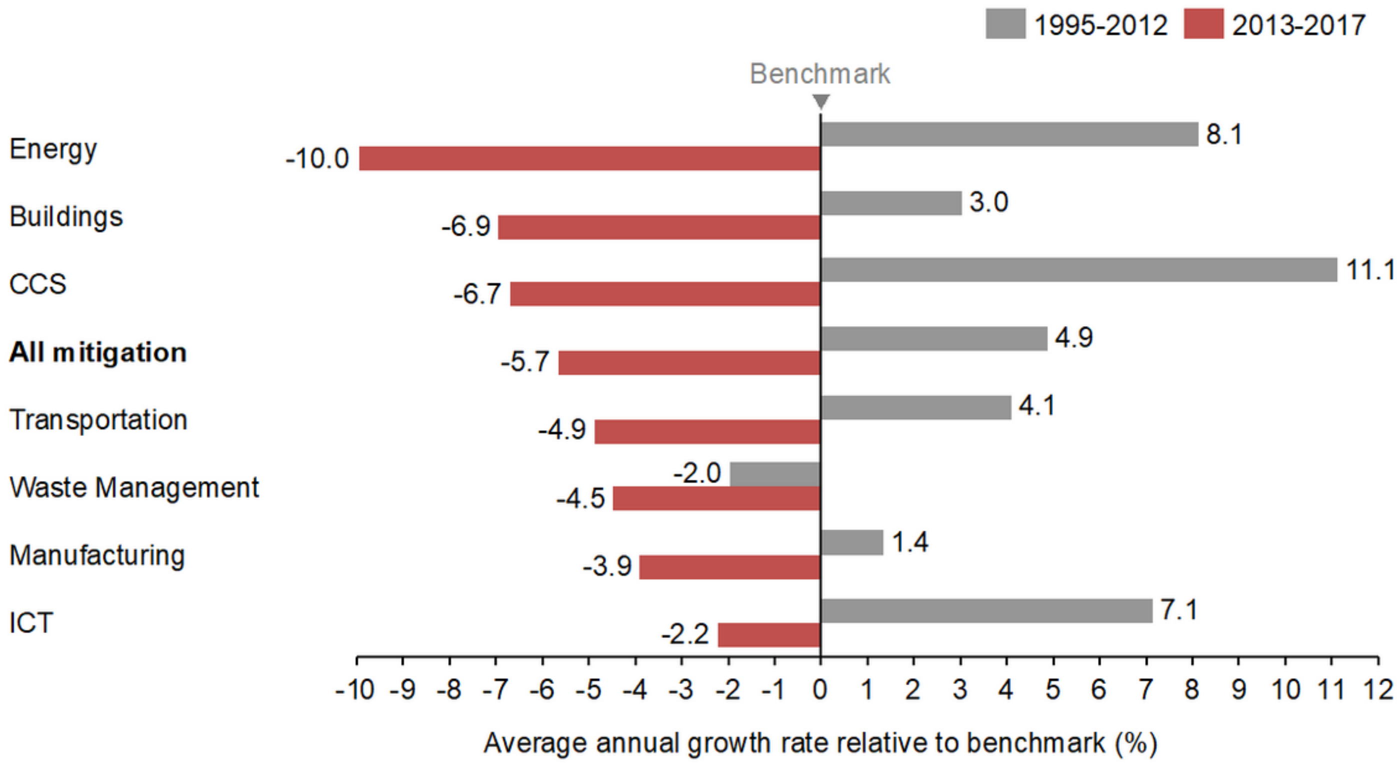

Figure 3

Average annual growth of climate change mitigation technologies. The average growth rate is calculated by dividing the raw growth rate in each technology relative to a technology-specific benchmark (described in detail in the method section). These benchmark categories include patents in the same patent classification categories that are not climate-change mitigation technologies. They account for differences in technology-specific patenting trends. For instance, for transportation, we compare electric vehicles (and other low-carbon transportation modes) to patenting growth in vehicles with an internal combustion engine. All mitigation is compared to all other inventions. Patent data based on PATSTAT (2019).

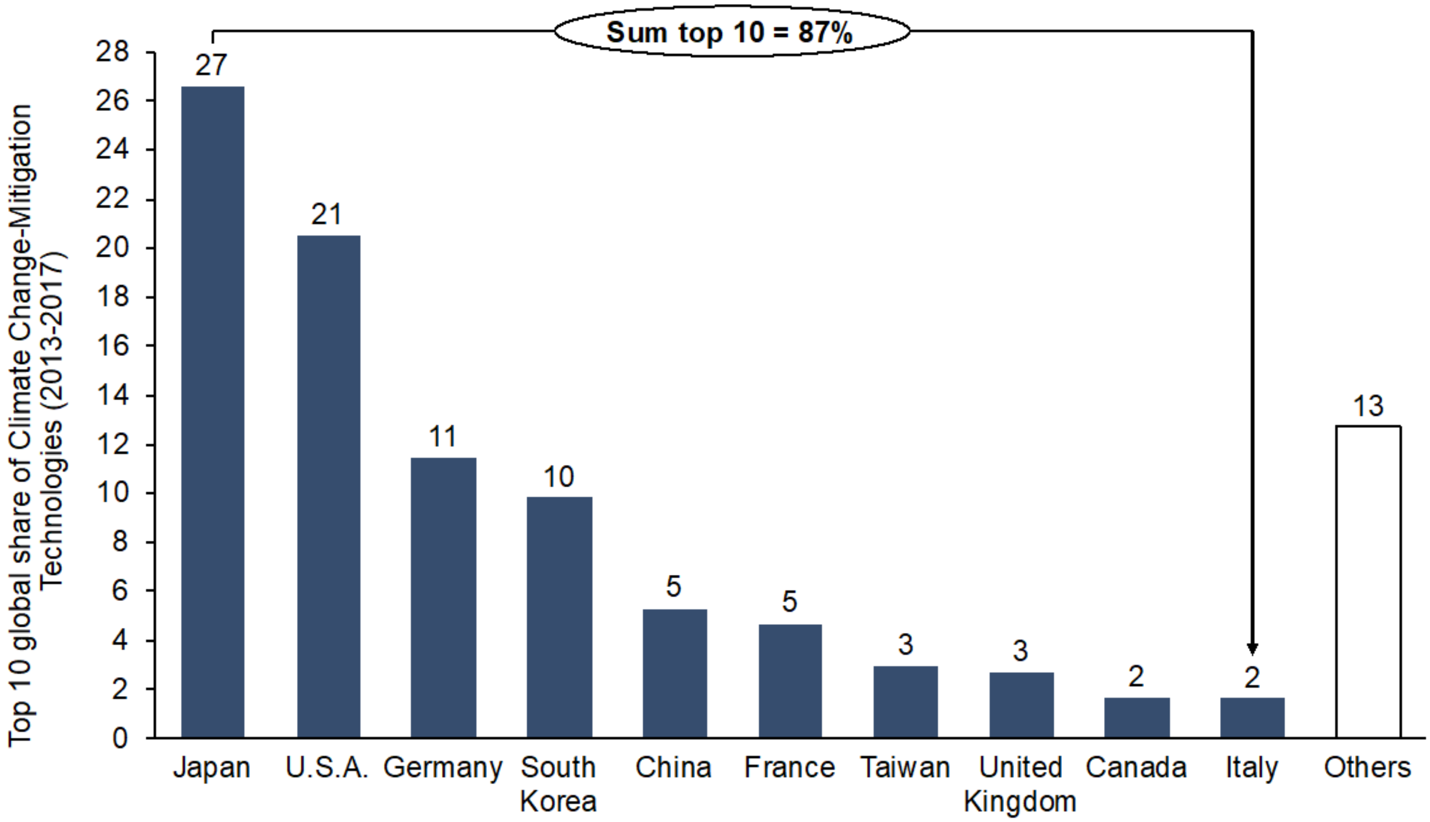

Figure 4

Top-10 inventor countries in CCMT. Patent data based on PATSTAT (2019).

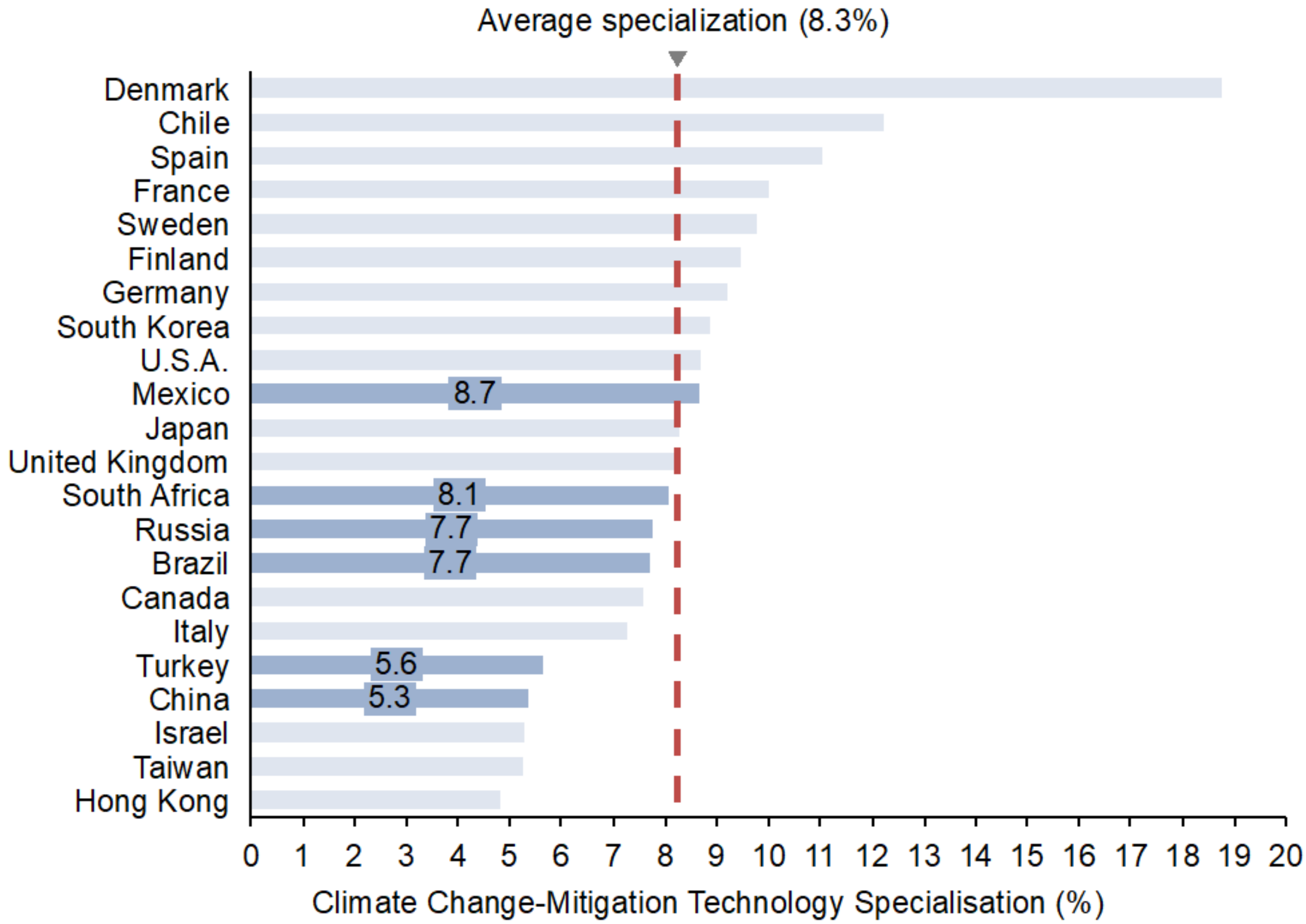

Figure 5

Climate change mitigation technology specialisation from 2013-2017. Specialisation is computed as the proportion of CCMT technologies compared to all inventions in the country. Only countries with at least 0.1% of global patenting in CCMT are shown. Source: PATSTAT (2019).

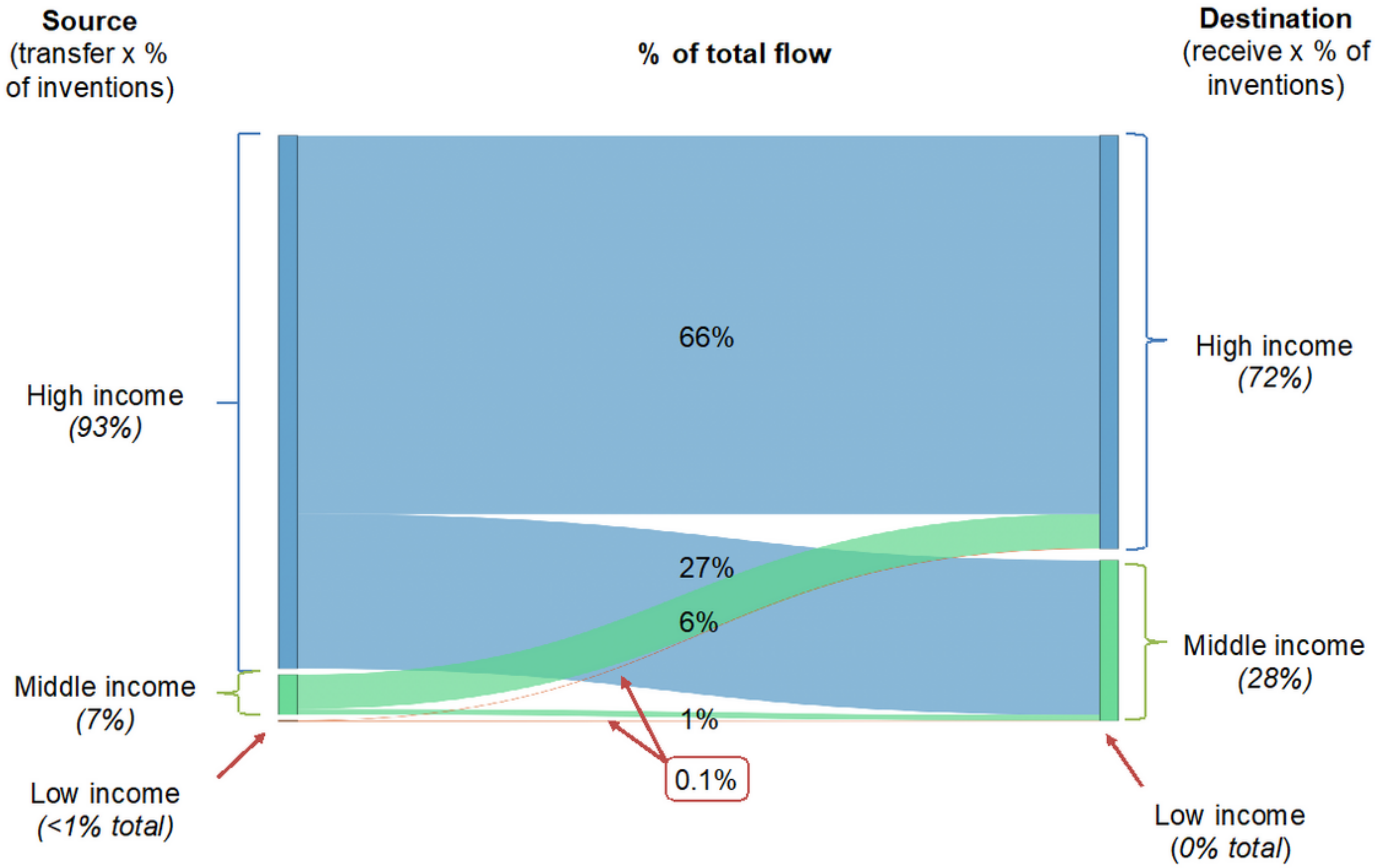

Figure 6

Source and destination of transferred climate change mitigation technologies from 2013-2017. We consider a transfer if the country where the patent is filed is different from the inventor's country or inventors' countries. Numbers may not add to 100% due to rounding. Source: PATSTAT (2019).

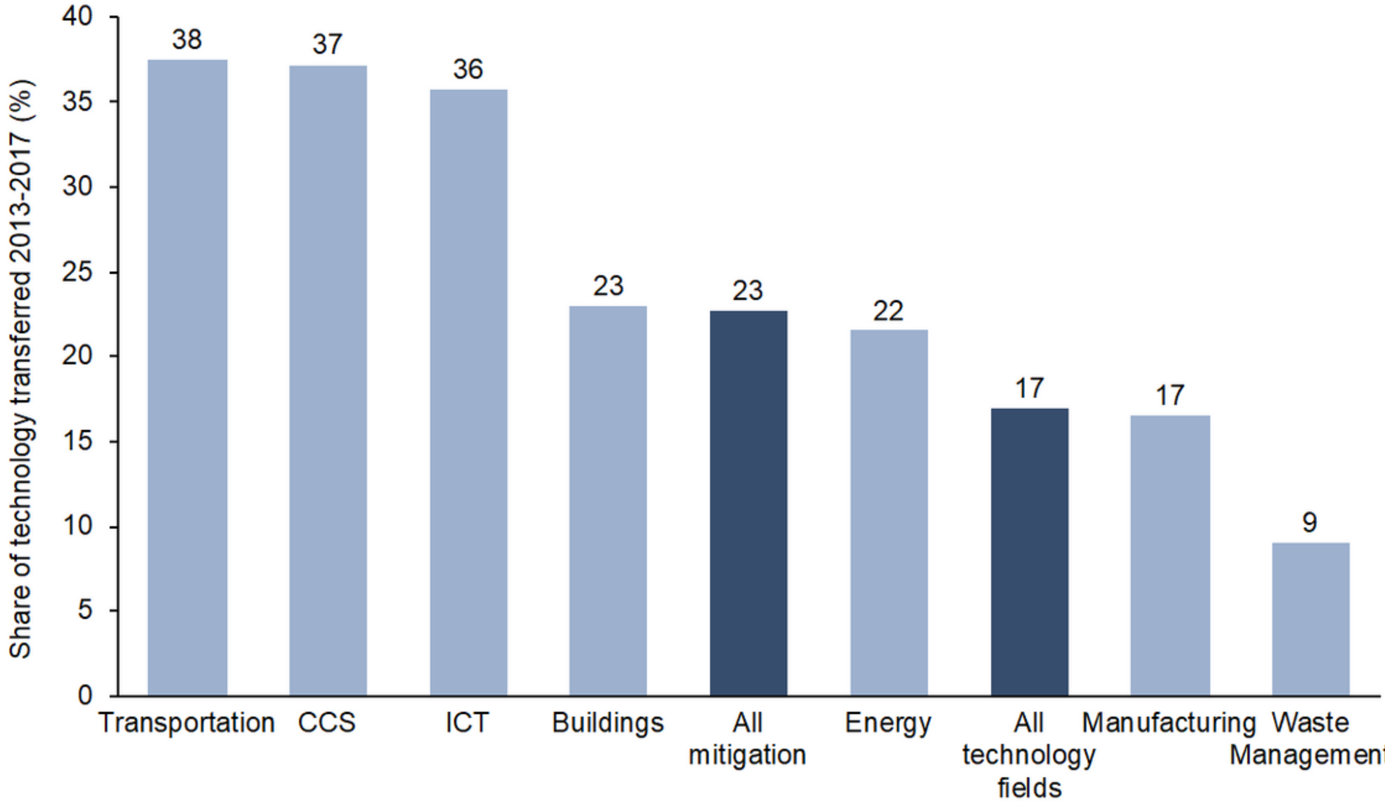

Figure 7

Share of technology transferred 2013-2017 (%). Source: PATSTAT (2019)