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

Benedict Probst[1][2]*, Simon Touboul[3], Matthieu Glachant[3], Antoine Dechezleprêtre[4]

1) Group for Sustainability and Technology, ETH Zurich, Switzerland
2) Cambridge Centre for Environmental, Energy and Natural Resource Governance CEENRG, University of Cambridge, UK
3) Mines Paris - PSL, i3 CNRS, France
4) London School of Economics and Political Science, UK

*corresponding author (bprobst@ethz.ch, Weinbergstrasse 56/58, CH-8092 Zürich)

Abstract:

Increasing the development and diffusion of climate change mitigation technologies on a global scale is critical to reaching net-zero emissions. We analyse over a quarter million high-value inventions patented from 1995 to 2017 by inventors located in 170 countries in all major climate change mitigation technologies. Our analysis shows an annual growth rate of 10 percent from 1995 to 2012 in these high-value inventions. Yet, from 2013 to 2017, the growth rate of these inventions has fallen by around 6 percent annually, likely driven by declining fossil fuel prices, low carbon prices, and increasing technological maturity for some technologies, such as solar PV. Invention has remained highly concentrated geographically over the last decade, with inventors in Germany, Japan, and the US accounting for more than half of global inventions, and the top 10 countries for almost 90%. Except for inventors in China, most middle-income economies have not caught up and remain less specialised in low-carbon technologies than high-income economies. This underscores the need for more technology transfers to low- and middle-income economies, where most of the future CO_2 emissions increases are set to occur.

Increasing the development and diffusion of climate change mitigation technologies (CCMTs) on a global scale is critical to reaching net-zero emissions in the second half of this century, as envisaged by the Paris Agreement[1]. Yet, a range of modelling results indicates that existing technologies are insufficient to reach net-zero emissions[2,3]. For instance, the IEA's Sustainable Development Scenario estimates that three-quarters of technologies needed for net-zero are not mature yet, with 41% in the early adoption, 17% in the demonstration, and 17% in the prototype stage. [2]

Historically, most CCMTs have been developed and deployed in high-income countries [4,5,6]. Yet, fast-growing low- and middle-income economies urgently need to adopt these technologies to decarbonise their economies. While middle-income economies, such as China and India, are building domestic CCMT industries, other low- and middle-income countries are often reluctant to bear the additional cost of CCMT compared to "brown" alternatives [4,7]. Within the United Nations Framework Convention on Climate Change (UNFCCC), several instruments – such as the UN Technology Transfer Mechanism and the Clean Development Mechanism – have attempted to address this challenge and to encourage international CCMT transfer [8].

While existing research has provided a clear picture of CCMT invention and diffusion from 1978-2005 [5], there is a lack of a recent and comprehensive global overview. Using data from the Worldwide Patent Statistical Database (PATSTAT)[9] maintained by the European Patent Office (EPO), we examine high-value inventions in the seven climate-change mitigation technologies identified under the Y02 classification (Table 1), which provides the most comprehensive and standardised low-carbon patent classification and covers most technology fields (buildings, carbon capture and storage (CCS), energy, information and communication technology (ICT), manufacturing, transportation, and waste management).[10]

To provide a cross-country comparison of low-carbon inventions, we rely on international patent families. A patent family refers to all patents that cover a single invention in one or more countries. International patent families hence protect an invention in at least two jurisdictions. By using international patent families, instead of simple patent counts or domestic patent families, we address two 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, therefore, provides a common metric across countries (as each family is counted as one invention, irrespective of how many patents protect the invention in each country) and enables us to focus on 'high-value' inventions, thereby filtering out low-value inventions that are less likely to meaningfully contribute to climate change mitigation [13]. Overall, high-value inventions constitute around 25% of patented CCMT inventions globally.

Another feature of international patent families is that they can (and have widely been) used to measure the transfer of patented technologies between countries, by counting families 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. These patent protections sought for inventions outside of the country of first filing (the 'priority' country) permits us to analyse technology transfers between the inventor and all non-inventor countries where patent protection for the invention has been filed. While patents do not capture all inventions, they currently represent the best available proxy for cross-country inventive activity and international technology diffusion. We also show that the transfer of inventions via cross-country patent filings is highly correlated with other important transfer channels, such as foreign direct investments (FDI) and exports of capital goods (see Methods section for a detailed discussion).

We provide an up-to-date analysis of CCMT invention and diffusion trends in two steps. First, we document global invention trends in CCMT based on 286,997 (high-value) international patent families invented from 1995 to 2017 by inventors located in 170 countries (and 16 dependent territories, such as Hong Kong) in all major climate mitigation technologies (see Table 1). While our data extends to 2019, we exclude the last two years because it can take up to 30 months from an initial patent application to subsequent filings in other countries.[13] Hence, 2017 is the last reliable year in our patent database. Secondly, we use the same data on international patent families to investigate trends in international technology diffusion.

[Table 1 here]

We find an average increase of 10% in annual high-value CCMT invention rates from 1995 to 2012. Yet, from 2013 to 2017, high-value CCMT invention rates have fallen by around 6 percent annually, likely driven by declining fossil fuel prices and technology-specific drivers, such as maturity. CCMT invention is highly concentrated geographically: Germany, Japan, and the US account for more than half of global inventions and the top 10 countries for almost 90%, while the contribution of most middle-income economies remains negligible. The concentration in the top-10 countries has remained largely stable over the last two decades. While inventive activity in CCMTs has recently increased substantially in China, the country only accounts for only 5% of (high-value) inventions. These trends underscore the need for more transfers to low- and middle-income economies whose energy-related contribution to global CO_2 emissions have doubled over the last two decades and now account for around two-thirds of global energy-related emissions.[1617]

Decline in CCMT inventions

Figure 1 shows the annual high-value invention rates for both CCMTs and all technologies (indexed at 1 in 1995). The period 1995-2012 saw an almost fivefold increase in the number of yearly high-value inventions in CCMTs, and substantially higher growth of CCMTs compared to all high-value inventions from 2002 onward, potentially accelerated by the adoption and ratification of the Kyoto Protocol in the period from 1997-2005 [18]. Over the period 1995-2012, the average annual growth rate was 10.3 percent. Yet, during the period 2013-2017, there has been a general decline in CCMT inventions by 5.5 percent annually.

[Figure 1 here]

Disaggregating the data (Figure 2) shows the strongest decrease of annual invention rates in the period 2013-2017 in energy, buildings, ICT, and CCS. Particularly noteworthy is the sizeable decline in ICT and CCS inventions in the period 2013-2017, which saw the largest- and second-largest increase respectively in yearly invention rates from 1995-2012. In contrast, waste management, transportation, and manufacturing declined less than the average. Overall, waste management's and manufacturing's inventions growth rates appear to be most stable over time. Both sectors did not experience above-average growth rates for the period 1995-2012 and neither above-average declines between 2013-2017.

[Figure 2 here]

Drivers of the decline in CCMT inventions

There are several potential reasons for the decline in high-value CCMT inventions since 2013. The first likely explanation is the massive fall in fossil fuel prices. Historically, the proportion of global inventions in CCMTs has closely followed oil prices as shown in Figure 3. 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 and taxes on fossil fuel consumption [19–21].

That patenting responds so quickly is plausible: First, 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). Second, the first-to-file rule provides a strong incentive for inventors to file patents early in the R&D process, which grants the patent to the first person to file the invention, regardless of the actual date of invention[13].

Carbon prices have not compensated for the decrease in fossil fuel prices in the period 2013-2017 likely because of insufficient coverage and low prices. Until 2020, only 15% of global CO_2 emissions were covered by carbon pricing instruments, such as carbon taxes or emissions trading schemes.[22] Overall, the effective carbon rate in 2018 – including the price of fuel excise taxes, carbon taxes, and emissions permit prices – across 44 OECD and G20 countries (accounting for 80% of global energy-related CO_2 emissions) was less than 30 EUR / tonne CO_2 for 75% of all emissions.[23] While China launched sub-national emissions trading scheme (ETS) ETS pilots in 2013, a national ETS was only introduced in February 2021. Allowances in the European Union ETS saw falling prices from a peak of almost 30 EUR/t CO_2 in 2008 to around 5 EUR/t CO_2 in 2017[24]. In the meantime, the price in the largest trading scheme in the US – California's Cap-and-Trade programme – has only moderately risen from around 10 USD in 2012 to 19 USD per tonne of CO_2 in 2021.[25]

Yet, recent increases in coverage and prices will likely strengthen incentives for CCMT inventions. The Chinese ETS covers around 12% of global CO_2 emissions, making it the largest in the world, substantially increasing the scope of carbon pricing. The recent surge in EU ETS prices to 55 EUR / t CO_2 in June 2021 partly driven by more stringent emissions goals under the European Green Deal will likely also contribute to increased incentives for CCMT inventions.[26,27] Econometric evidence shows that the introduction in 2005 of the European Union Emissions Trading System increased patenting in regulated firms vis-à-vis unregulated firms by up to 30% in the period 2005-2009 [20].

[Figure 3 here]

Another potential reason for the decline could be changes to clean-energy R&D funding. Several studies[28,29] and our analysis in Supplementary Table 1, Supplementary Figures 2 and 3 indicate a correlation between public clean-energy R&D funding and patented high-value inventions in CCMTs. Hence, if public clean-energy R&D was driving the observed trends, one would expect to have seen a fall in public clean-energy R&D. Yet, clean-energy public R&D expenditures actually doubled between 2000 and 2012 instead of declining and have remained relatively stable since (Supplementary Figure 3). In addition, a group of 24 governments, including the European Union, committed to doubling public clean energy RD&D public expenditures in the period 2015-2020. While these pledges made under Mission Innovation have fallen short of the initial goal of doubling RD&D spending, public investments in RD&D increased by 38% in these countries.[30]

Hence, clean public energy R&D does not appear to be driving the observed trends. More generally, establishing a direct causal relationship between public energy R&D and patented CCMT inventions is tricky for several reasons. First, patenting is not only influenced by public expenditures on energy R&D but also depends on private R&D (occurring within firms that do not commonly disclose R&D data) and other market factors. Second, the main goal of public R&D is to fund scientific research – which commonly leads to scientific studies – and not patents.[29] Third, the lag between public R&D and scientific publications is estimated to take up to 10 years, especially because public R&D often is further removed from the eventual commercialisation than private R&D.[29]

In addition to low oil and carbon prices, technology-specific drivers likely explain the recent decrease in CCMT inventions, such as technological maturity. The increasing maturity of CCMT could have led to a decrease in patented high-value inventions, as the marginal return to R&D investment decreases. Yet, while some technologies are becoming more mature – such as solar photovoltaics and wind power (Supplementary Figure 4) – others are constantly emerging such as CCS and green hydrogen, such that, on average CCMT inventions have not become less original over time, as indicated by Popp et al[31].

However, our data suggests that for certain technologies technological maturity likely played a role in the observed decrease, while for others it did not, which we explore by disaggregating the trends even more across the different sectors (Figure 4).

[Figure 4 here]

Inventions in energy (including renewable energy and storage) have seen the most sizeable decline from 2013-2017 (Figure 2 and 4a), although this trend may be reversing in more recent years as fossil fuel prices recover[32]. This particular decline in technologies that compete with fossil fuel-based energy is suggestive of the significant role that the decline in fossil fuel prices has likely played. Inventions related to hydrogen have not decreased and enabling technologies (such as storage) have decreased only slightly, in part because these technologies are early in their invention cycle, with high returns to R&D.

The invention trends in one of the central renewable technologies – solar PV – demonstrate substantial heterogeneity across solar PV types. Our data shows a decline in polycrystalline inventions (Figure 4b) likely driven by China's rise to dominance in polycrystalline solar PV manufacturing, which has led to a decline in solar PV inventions, R&D intensity, and start-up creation in the solar PV sector [33,34]. Yet, inventions in organic PV – which is still early in its invention cycle – have not decreased, likely because public clean energy R&D is a central driving force in organic PV (Figure 4b). For other PV technologies closer to market – such as Copper Indium Selenium (CuInSe2) used in thin-film technologies of intermediary maturity[35] – the rise to dominance of Chinese polycrystalline manufacturers appears to have led to a stark decrease in these inventions rather than the maturity of the technology itself (Figure 4b).[33] Hence, while for polycrystalline solar PV maturity likely played a role in the decline of inventions, for CuInSe2 market factors are more likely to have led to the decline in inventive activity.

For buildings, lighting inventions dominate inventions in heating and efficient home appliances. Lighting inventions have experienced a 10-fold increase in yearly inventions (Figure 4c) in the period from 1995-2012. The uptick in lighting inventions is dominated by the rise of light-emitting diodes (LEDs), which have fallen in price by 95% from 2002 to 2020 and have become the de-facto lighting standard.[36] Yet, similar to solar PV inventions, the dominance of LEDs has likely reduced the diversity of inventions and contributed to the drop in inventions since 2013.[33]

Manufacturing has only seen a modest increase in inventions over the last decades, except for final industrial and consumer goods (Figure 4d). Very energy-intensive metal and minerals processing plants often benefit from cheap energy as well as the free allocation of emission permits due to competitiveness concerns, lowering the pressure to innovate despite increasing energy prices.[37] For instance, energy-intensive industries have been exempted from certain surcharges in several countries such as Germany and the Netherlands[37] and have received free emissions allowances under the EU ETS. In contrast, final industrial and consumer goods may not benefit from these exemptions to the same extent, increasing the pressure to innovate.

The substantial reversal in patented high-value inventions in carbon capture and storage (CCS) is also noteworthy (Figure 4e). 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 [24]. Besides, carbon utilisation has also struggled to demonstrate a viable business model over the last decade beyond its use in enhanced oil recovery.[38] The transport and storage of CO_2 in deep underground rock formations have also faced technical, economic, and societal setbacks.[39] Yet, at least in Europe, two new CO_2-storage sites off the coast of the Netherlands (Porthos[40]) and Norway (Northern Lights)[41] may contribute to the revitalisation of CCS invention dynamics over the next decade. It should also be noted that the capture of other greenhouse gases – such as nitrous oxide, methane, and perfluorocarbons – has not declined, likely because most inventions in that sector are not driven by market dynamics but rather fundamental research and emission standards.

Air, maritime and road transport (especially electric vehicles and improvements to the internal combustion engine) have seen a substantial rise in inventions, whereas rail only saw moderate increases (Figure 4f). A potential reason that explains the difference in trends is the exposure of air, maritime, and road transport to oil prices, whereas rail is mostly powered by electric trains, which are only partly exposed to oil and gas prices. For instance, in 2016 the share of electric trains was 54% in India, 75% in China, 76% in North America, 80% in Europe, 86% in Russia, and more than 90% in Korea and Japan.[42]

The areas of manufacturing and transport also underscore the importance of invention across different parts of CCMTs as the IEA[2] highlights. For instance, electric vehicles depend on inventions in battery technology (energy) and metal processing (manufacturing). Yet, the rate of inventions has grown much faster in battery technologies than in metal processing, even though global adoption of EVs hinges on the availability of lightweight vehicles.[2]

CCMT invention trends on a country level

We now investigate the invention trends in CCMT across countries (Figure 5). As the majority of carbon emissions increases in the next 30 years will come from low- and middle-income economies [43], understanding whether these countries are 'catching up' in CCMT inventions is critical. Yet, our analysis shows that CCMT inventive activity remains highly concentrated in few high-income countries: Inventors in Japan, the U.S.A, and Germany account for 58% of global CCMT inventions, whereas inventors in the top-10 countries account for 86%. The concentration of low-carbon invention in few countries has remained largely stable over the last decade compared to the 2000s (in the period 2000-2005, the top 10 accounted for around 88%). The major difference is that inventors in China and Taiwan have substantially increased in their ranking over the last decade, whereas inventors in Japan, the U.S.A., and Germany have lost a few percentage points of the global CCMT share. Yet, apart from inventors in China, no other middle-income economy has entered the top-10.

It is important to note that many middle-income economies perform better when analysing all patented inventions (in contrast to high-value inventions that we measure), which indicates that a sizable share of their patented inventions currently has a low value (as measured by domestic vs. international patent families), but this may change in the future.

[Figure 5 here]

Inventors in middle-income economies do not only develop fewer CCMT inventions, but they are also less specialized in CCMT – computed as the proportion of CCMT compared to all inventions in the country – than high-income countries (Figure 6). Apart from Mexico India, and Brazil, middle-income economies have only become slightly more specialised in CCMTs over the last two decades, while industrialized countries have substantially redirected their invention efforts towards CCMTs (in the mid-nineties, the share of CCMT in all patented inventions was roughly 4% everywhere).

Most high-income countries are now highly specialised in CCMT. For instance, in Denmark almost 20 percent of all inventions are CCMT. In contrast, Mexico, India, and South Africa are the only middle-income economies that have an above-average specialisation in CCMTs, whereas Russia, Brazil, Turkey, Malaysia, and China have a below-average specialisation compared to the global average.

[Figure 6 here]

Global diffusion trends

To adopt CCMT technologies, countries can invent them or import them from foreign countries. We measure the transfer of inventions by counting patent families filed outside of the inventor's country. If the patent family is filed in multiple countries, we divide the fractions evenly across all receiving countries.

To corroborate our metric of CCMT diffusion, we correlate our approach with the most important technology transfer channels[44], namely Foreign Direct Investment (FDI) and trade. Data on licensing – another important transfer channel – is limited. Yet, as licensing agreements are commonly based on locally filed or transferred patents, our indicator also captures that transfer channel.

Overall, our approach correlates well with FDI and moderately well with trade. In Supplementary Table 4, we show that CCMT invention transfers are highly correlated with

FDI. For instance, FDI deals from 2012-2016 in CCMTs between high- and high-income countries accounted for 68% (vs. 66% for the transfer of inventions) and 31% between high- and middle-income countries (vs. 27% for the transfer of inventions). Our analysis of trade in renewable energy products (Supplementary Table 5) shows that middle-income countries export more renewable energy goods to high- and middle-income countries than their invention transfer share indicates, which is primarily driven by China's exports of solar PV equipment to high- and middle-income countries. Yet, our indicator captures all CCMTs and not merely renewable energy products for which we have trade data.

Figure 7 shows the geographical distribution of cross-country invention transfers by income groups. 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 CO_2 emissions are expected to come from low- and middle-income countries. High-income economies invent around 93% of all CCMTs and around two-thirds of global transfers occur between high-income countries. In contrast, only one-third is transferred to middle-income countries. Yet, the majority of inventions transferred from high- to middle-income countries go to China, which received 72% of all transfers from high-to-middle income countries for the period 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.

In Supplementary Figure 8, we show that for many low- and middle-income countries the share of global CCMTs that are invented in these countries or transferred are below their share of global CO_2 emissions. While it is difficult to assign a definitive value on what would constitute 'sufficient technology transfer', this indicates that increased transfer to low- and middle-income economies outside of China is paramount to mitigate climate change.

This low rate of transfer to low- and middle-income economies alike suggests that political and economic factors appear insufficient to substantially accelerate the rate of transfer. The UN Technology Transfer Mechanism, which has been established under the UNFCCC in 2010, has likely not accelerated international technology transfer in a significant manner. 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 [45].

[Figure 7 here]

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 Supplementary Figure 9. 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 high-income countries 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 [46]. 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 CCMTs.

Discussion

After almost two decades (1995-2012) of increasing high-value inventions in low-carbon technologies, our analysis shows an overall decline in CCMT-invention trends from 2013-2017. Macro factors, such as low fossil-fuel and carbon prices, as well as technology-specific drivers, such as maturity, 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 [47].

Over the last decade, the concentration of CCMT invention in few (mostly high-income) countries has remained largely stable. Nonetheless, inventors in 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, except for Mexico, India, and South Africa, middle-income economies remain less specialised in CCMT technologies than the global average.

Our findings indicate two important lessons: First, there is a dangerous downward trend in low-carbon inventions, which is likely – at least in part – driven by a decline in fossil fuel prices. Carbon prices can play a key role in accelerating CCMT inventions. The introduction of the largest carbon pricing mechanism – the Chinese ETS – as well as the creation of the Market Stability Reserve and more stringent emissions reduction objectives in the EU ETS, may contribute to an acceleration of CCMT invention in the coming years. The recent surge in fossil fuel prices may also have already had a positive impact. Second, our findings underscore the need for more transfers to low- and middle-income economies where most CO_2 emissions increases are set to occur. While global transfers do not merely occur between high-income countries, most of the transfers from high-income to middle-income countries go to China. Hence, transferring more technologies to other middle-income economies – such as South Africa, Brazil, and Russia – is critical to mitigating climate change. Here, domestic policies to create demand for the transfer of key CCMTs – such as domestic carbon pricing, energy efficiency standards, and renewable energy support policies[48,49] – appears key.

Data & Methods

The following section sets out the data and methods employed in this study.

Data

Patent data

To measure the invention and transfer of technologies, we use patent data from the Worldwide Patent Statistical Database PATSTAT (2019, Autumn version)[9], a database maintained by the European Patent Office (EPO). The database includes more than 100 million patents. The relevant patent codes 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 mitigation technologies. Except for the Y02A class, dedicated to climate adaptation technologies, all categories within this Y02 classification refer to mitigation technologies.

The Y02 classification scheme was introduced in 2010 to standardise the tagging of technologies across different patent classification conventions. Typically, CCMTs are distributed across many different technological areas within the IPC and CPC classification scheme, but until the introduction of Y02, a single classification approach was missing. The complexity of CCMTs is mirrored in other emerging technological sectors (e.g., nano-technology) and is partly due to the increasing complexity of inventions (covering different sectors), interoperability between technologies, and the rise of digital technologies (e.g., peer-to-peer energy trading) [50].

Hence, merely relying on either the CPC or the IPC classification scheme (or both) for selecting CCMTs can lead to omissions or too many irrelevant inventions. For instance, to find inventions related to Carbon Sequestration and Storage a potentially relevant CPC code would be B01D 53/00 ("Separation of gases or vapours; Recovering vapours of volatile solvents from gases; Chemical or biological purification of waste gases, e.g. engine exhaust gases, smoke, fumes, flue gases, aerosols"). Yet, the CPC classification does not only refer to inventions aimed at removing CO_2 but also includes other gases, such as carbon monoxide (which is not a greenhouse gas). In addition, it only refers to biological or chemical removal but does not include other separation means. In addition, only considering CPC classification may lead to omissions – particularly for cross-country comparisons – since the CPC has poor coverage for countries like Japan.

The Y02 classification algorithm, therefore, uses a combination of CPC and IPC codes and combines it with expert input from the EPO, academia, the non-governmental sector, and industry. The resulting outputs are then perused by EPO experts to guarantee a high-quality standard across all Y02 codes. The EPO selects 150 random documents from the outputs and strives for an error rate below 7%. As the PATSTAT database contains more than 100 million documents, this approach enables the tagging of the entire database. In contrast to the above-mentioned example, the tag Y02C 10/00 only includes CO_2 capture or storage (and not irrelevant patents on carbon monoxide capture) and in addition to biological and chemical separation also includes capture by absorption, adsorption, membranes, or diffusion as well as rectification and condensation. The Y02 classification, therefore, contains fewer irrelevant patents and a greater variety of relevant patents.

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 call 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). We exclude patent families referring to design and utility models and use all patent applications – granted and not granted – for the analysis. We reran the analysis using only granted patent families, which produces qualitatively similar results.

Trade and FDI data

Foreign Direct Investments (FDI) deals data come from the Zephyr database provided by Brussels-based business publisher Bureau Van Dijk. Trade data was extracted from UN COMTRADE.

Methods

The following sections set out how we use patent data to track inventions in CCMTs and how we assess the transfer of inventions across countries.

Using patent data to track high-value inventions in CCMTs

Economists regularly use patents to measure invention [51–53]. 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 the invention. Inventors patent their inventions only at the end of the invention process when they plan to use or diffuse their invention. Patents as an indicator, therefore, reflect the output of the invention effort. Other indicators, such as R&D expenditures, or the average number of researchers per capita, can also be used as proxies for invention, but they reflect the inputs into the invention process (e.g., a country could have many researchers but fail to commercialise these findings). Patent documents contain detailed information on the inventor, including their country of residence, which we use to determine the inventor's 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. 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 invention, they are not a perfect proxy to investigate invention 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[54]. Yet, most widely-used technologies have been patented [55,56]. 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 high-income 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 high- and middle-income economies, which are responsible for the bulk of historical and future CO_2 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 invention, 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 inventions 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, which account for around 25% of CCMT inventions. High-value patent families provide a common measure of invention across countries while accounting for differences in the quality of inventions.

Assessing cross-country transfers of patents

An important feature of international patent families is that they can (and have widely been) used to measure the transfer of patented technologies between countries, by counting families 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. These patent protections sought for inventions outside of the ‘priority’ country, permit us to analyse technology transfers between the inventor and all non-inventor countries where the patent has been filed.

In our analysis, all high-value inventions constitute technology transfers excluding those that have inventors in multiple countries and those countries are the same as where the patents in that family are filed. For patent families with multiple inventors from multiple countries, we use fractional counts. For instance, a French inventor files various patents (a patent family) that protect a single invention in France, which is subsequently also filed in India, Brazil, and China. We allocate the entire invention to France (Figure 5) and then allocate one-third of the transfer from France to India, Brazil, and China, respectively (Figure 7).

To assess to what extent the transfer of inventions via the cross-country filings of patent families is correlated with other transfer channels – such as FDI and exports – we proceed as follows.

To assess whether a country is a high, middle, or low income, we use the official World Bank classification from 2020[57]. The thresholds are as follows: Below 1,036 GNI per capita in current USD a country is considered low-income. Between 1,036 and 12,535 GNI per capita in current USD, a country is considered middle-income and above 12,535 high income.

FDI

We select FDI deals linked with CCMT transfers for the period 1995-2015 replicating the two steps procedure from Dussaux, Dechezleprêtre, and Glachant[58] as follows. First, we keep deals for which the acquiring firms have invented and filed at least one climate change mitigation patent (patent classified with the CPC code Y02) in the country where the target firm is located. As we are only interested in technology transfers, we keep deals where the home countries of the acquiring and the target firms are different. Second, we restrict this selection to target firms whose main activity can be related to climate change mitigation. To do so, we use the standard EU industry-standard classification system NACE Rev.2 classification and select codes with a potential link to climate change mitigation (see Supplementary Table 3 for the list of NACE codes). The remaining FDI deals only represent firms that are active in one of the sectors displayed in Table 1.

Trade

To study another important transfer channel, we analyse traded products that are considered 'green' and therefore correspond to the Y02 classification. We use the classification employed in Mealy and Toytelboym[59] with slight modification. A complete list of trade codes can be found in Supplementary Table 4.

Acknowledgements

B.P. thanks Fabian Scheifele for support with trade data, Evan Petkov and Christof Knoeri for insights on innovation in the building sector.

Data availability

The data (PATSTAT, Autumn 2019)[9] used in this research was purchased from the European Patent Office (EPO). The contractual agreement restricts public posting of data sets containing information on individual patents. However, the aggregate data can be found on GitHub (https://github.com/SimonTouboul/ClimateMitig_Innov_NatureEnergy).

Code availability

The code used in this analysis can be found on the GitHub link above.

Contributions

All authors developed the research idea. S.T. conducted the empirical analysis with support from B.P., B.P. analysed and visualised the data and wrote the manuscript with support from S.T., while M.G. and A.D. edited the final draft.

Competing interests

The authors declare no competing interests.

Corresponding author

Correspondence to Benedict Probst

Tables

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,	33,633

		elevators and scalators, constructional or architectural elements, ICT, power management	
Carbon capture and storage (CCS)	Y02C	CO_2 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**

Table 1: Technology field, EPO classification, definition, and number of high-value 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)

Figure Legends / Captions

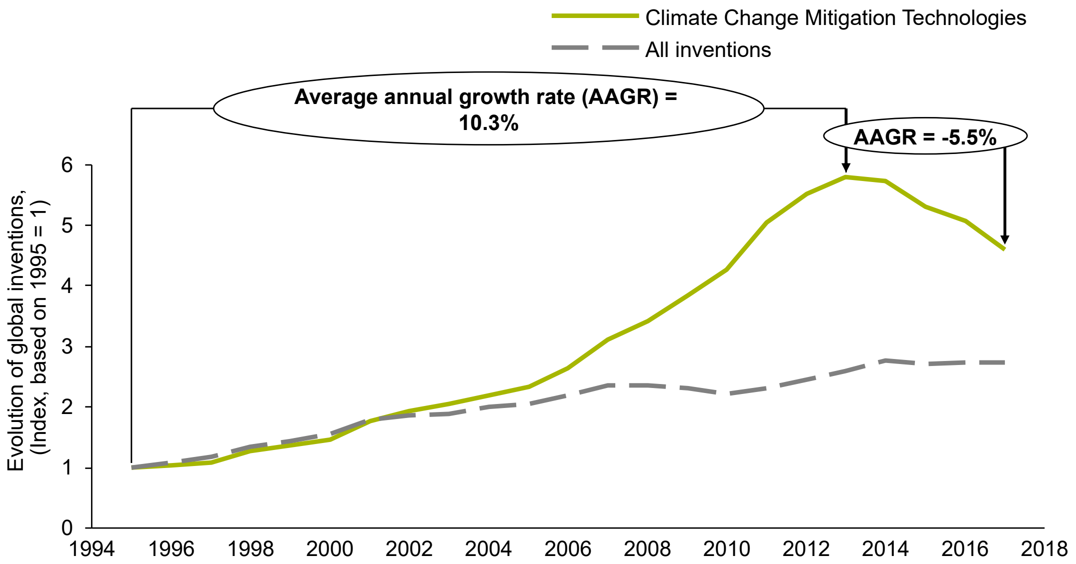

Figure 1: Evolution of global high-value climate change mitigation technology inventions from 1995-2017*. Climate change mitigation technologies include all technologies identified by the European Patent Office under the Y02 classification. These include energy, buildings, carbon capture and storage (CCS), transportation, waste management, manufacturing, and information and communications technology (ICT). Invention counts are based on international patent families filed 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 2018-2019 excluded as the patenting process takes around 2 years, potentially truncating the most recent data. Based on PATSTAT (Fall 2019) data.*

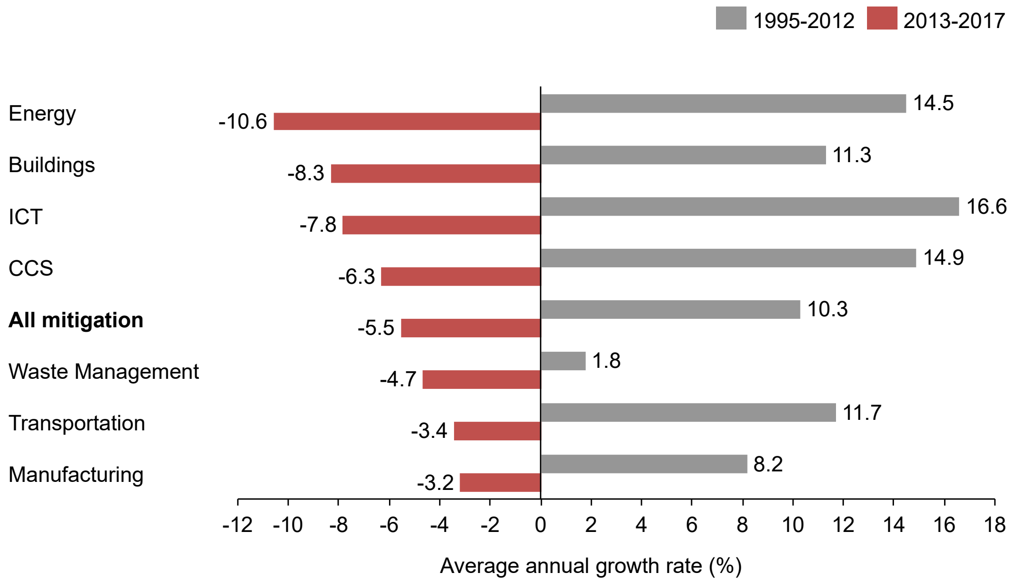

***Figure 2: Average annual growth of climate change mitigation technologies.** Average growth rate is weighted by number of high value inventions in each category and therefore differs from average of all displayed categories. Patent data based on PATSTAT Autumn (2019). Yearly trends can be found in Supplementary Figure 1.*

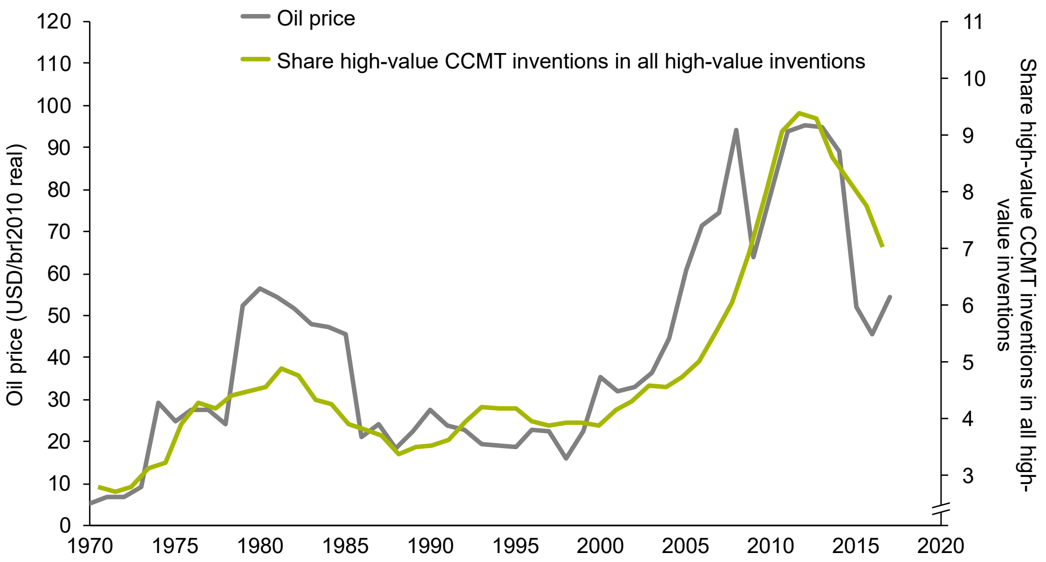

Figure 3: Correlation of oil prices with the share of high-value inventions in climate change mitigation technologies in all high-value inventions. *Based on PATSTAT (2019) and oil price based on World Bank* [61]

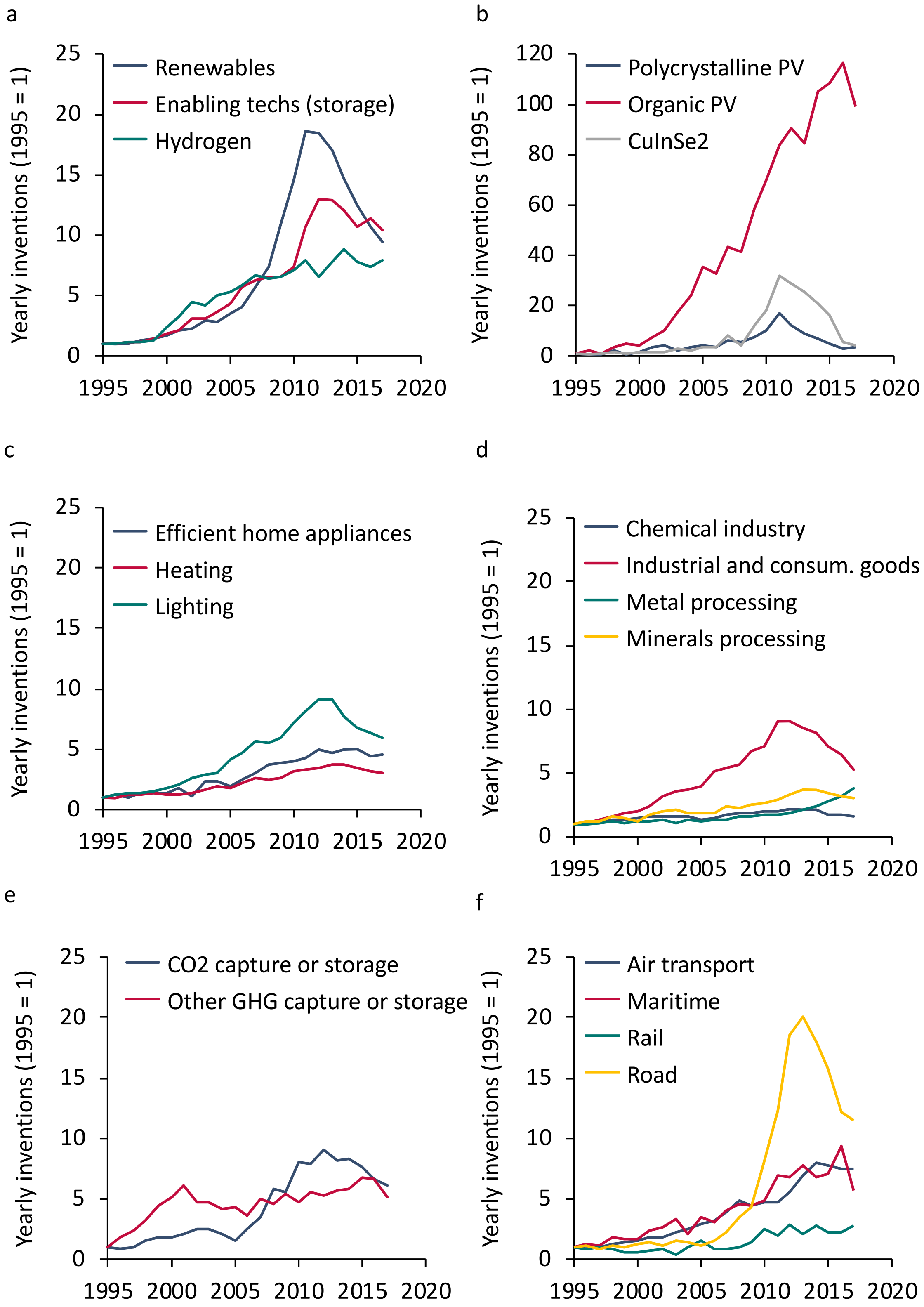

Figure 4: Yearly high-value inventions across sub-sectors. *Sub-sectors include a, energy, b, energy sub-category solar, c, buildings, d, manufacturing, e, carbon capture and storage (CCS), f, transport. Trends for wind energy, waste management and information and*

communication technology (ICT) can be found in Supplementary Figures 4, 5 and 6. The CPC codes employed for the technological trends are listed in the following: a, renewables (Y02E10/00), enabling technologies (Y02E60/00), and hydrogen (Y02E60/30). For b, polycrystalline PV (Y02E10/546), organic PV (Y02E10/549), CuInSe2 (Y02E10/541). For c, efficient home appliances (Y02B40/00), heating (Y02B30/00), and lighting (Y02B20/00). For d, chemical industry (Y02P20/00), industrial and consumer goods (Y02P70/00), metal processing (Y02P10/00), and minerals processing (Y02P40/00). For e, CO2 capture and storage (Y02C20/40) and other GHG capture and storage (Y02C20/10, Y02C20/20, Y02C20/30). For f, air transport (Y02T50/00), maritime (Y02T70/00), rail (Y02T30/00), and road (Y02T10/00). Based on PATSTAT (2019).

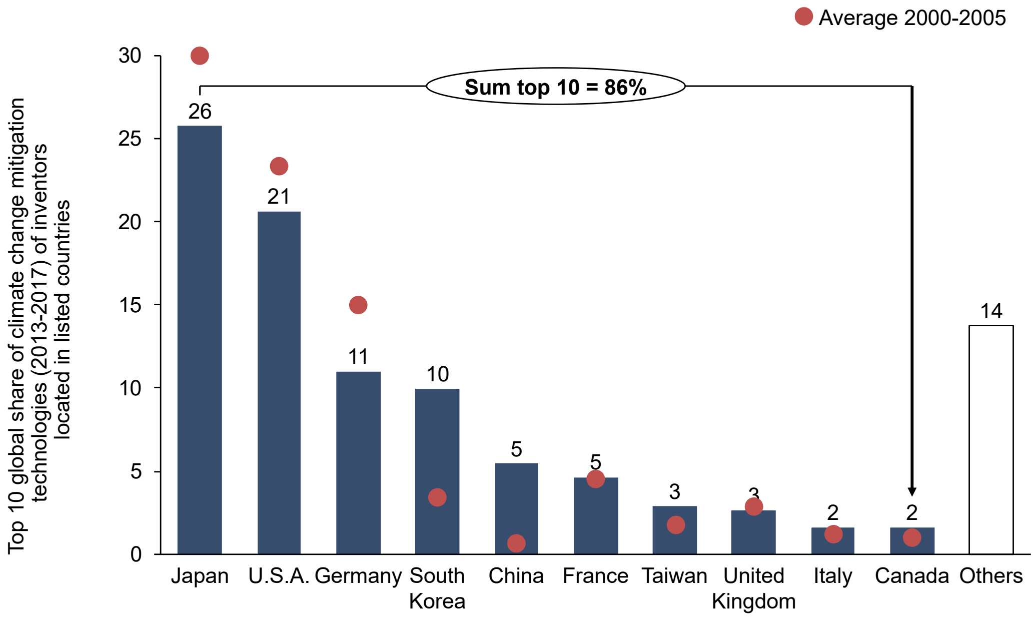

Figure 5: Top-10 inventor countries in CCMT. *Patent data based on PATSTAT (2019).*

608

609 ***Figure 6: Climate change mitigation technology specialisation in the period 2005-2005 and***
610 ***2013-2017.*** Specialisation is computed as the proportion of high-value CCMT inventions

compared to all high-value inventions in the country. Displayed average for selected countries. Source: PATSTAT (2019).

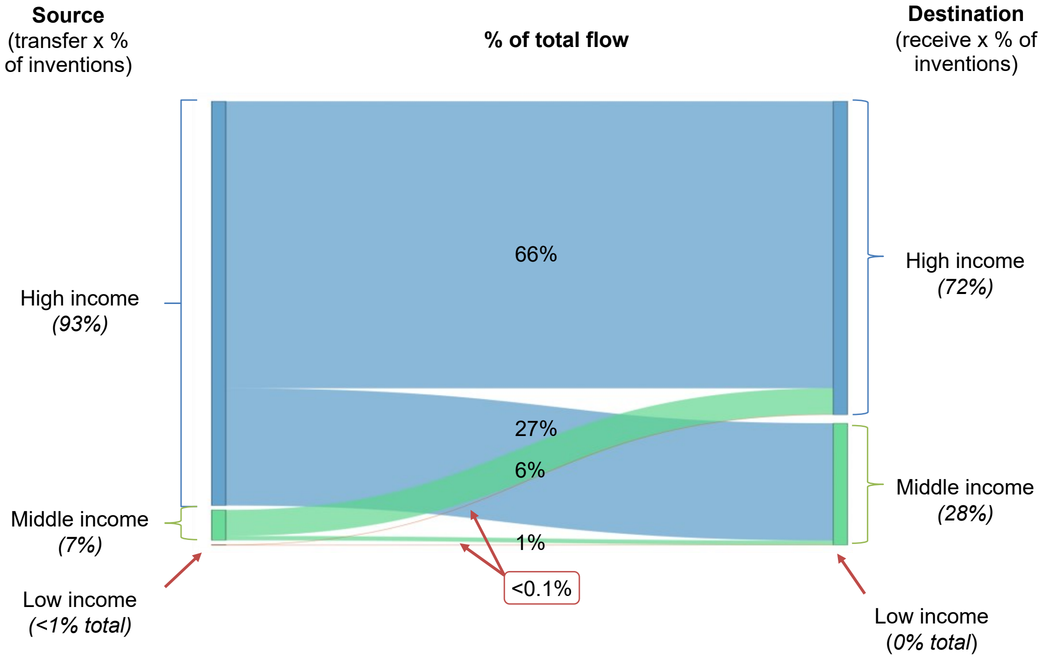

Figure 7: Source and destination of transferred climate change mitigation technologies from 2013-2017. We consider a transfer if the country where patent protection for the invention is sought is different from the inventor's country or inventors' countries. Numbers may not add to 100% due to rounding. Supplementary Tables 8-11 show detailed transfers between countries. Source: PATSTAT (2019).

References

1. Viñuales, J. E. The Paris Climate Agreement: an initial examination. *C-EENRG Work. Pap.* **9**, 1–16 (2015).
2. IEA. Energy Technology Perspectives. *Energy Technol. Perspect.* (2020). doi:10.1787/9789264109834-en
3. International Renewable Energy Agency. *Accelerating the Energy Transition through Innovation*. (2017).
4. Probst, B., Anatolitis, V., Kontoleon, A. & Anadón, L. D. The short-term costs of local content requirements in the Indian solar auctions. *Nat. Energy* **5**, 842–850 (2020).
5. Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N. & Ménière, Y. Invention and transfer of climate change-mitigation technologies: A global analysis. *Rev. Environ. Econ. Policy* **5**, 109–130 (2011).
6. REN21. *Renewables 2020 Global Status Report*. *REN21 Secretariat* (2020).
7. Huenteler, J. International support for feed-in tariffs in developing countries - A review and analysis of proposed mechanisms. *Renew. Sustain. Energy Rev.* **39**, 857–873 (2014).
8. Cames, M. *et al. How additional is the Clean Development Mechanism?* (2016). doi:CLlMA.B.3/SERl2013/0026r
9. EPO. PATSTAT 2019 Autumn Edition. (2019). Available at: https://www.epo.org/searching-for-patents/business/patstat.html.
10. EPO. Finding Sustainable Technologies in Patents. 10 (2013).
11. De Rassenfosse, G., Dernis, H., Guellec, D., Picci, L. & Van Pottelsberghe De La Potterie, B. The worldwide count of priority patents: A new indicator of inventive activity. *Res. Policy* **42**, 720–737 (2013).
12. Harhoff, D., Narin, F., Scherer, F. M. & Vopel, K. Citation Frequency and the Value of Patented Inventions. *Rev. Econ. Stat.* **81**, 511–515 (1999).
13. Dechezleprêtre, A., Ménière, Y. & Mohnen, M. International patent families: from application strategies to statistical indicators. *Scientometrics* **111**, 793–828 (2017).
14. Lanjouw, J. O. & Mody, A. Innovation and the international diffusion of environmentally responisve technology. *Res. Policy* **25**, 549–571 (1996).
15. Park, W. G. On Patenting Costs. *WIPO J. Anal. Intellect. Prop. Issues* **2**, 33–48 (2010).
16. IEA. Global CO2 emissions in 2019. (2019). Available at: https://www.iea.org/articles/global-co2-emissions-in-2019.
17. IEA. *Global Energy Review*. (2021).

18. UNFCCC. What is the Kyoto Protocol? (2021). Available at: https://unfccc.int/kyoto_protocol. (Accessed: 7th July 2021)
19. Popp, D. Induced Innovation and Energy Prices. *Am. Econ. Rev.* **92**, 160–180 (2002).
20. Calel, R. & Dechezleprêtre, A. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Rev. Econ. Stat.* **98**, 173–191 (2016).
21. Acemoglu, D., Aghion, P., Barrage, L. & Hemous, D. Climate Change, Directed Innovation, and Energy Transition: The Long-Run Consequences of the Shale Gas Revolution. (2019).
22. World Bank. *State and Trends of Carbon Pricing 2021. State and Trends of Carbon Pricing 2021* (The World Bank, 2021). doi:10.1596/978-1-4648-1728-1
23. OECD. *Effective Carbon Rates 2021*. (2021).
24. Bayer, P. & Aklin, M. The European Union Emissions Trading System reduced CO2 emissions despite low prices. *Proc. Natl. Acad. Sci. U. S. A.* **117**, 8804–8812 (2020).
25. California Air Resources Board. *Summary of Auction Settlement Prices and Results May 2021*. (2021).
26. EMBER. Daily EU ETS Carbon Prices. (2021). Available at: https://ember-climate.org/data/carbon-price-viewer/. (Accessed: 1st July 2021)
27. European Commission. 2030 climate & energy framework. (2021). Available at: https://ec.europa.eu/clima/policies/strategies/2030_en. (Accessed: 8th July 2021)
28. Margolis, R. M. & Kammen, D. M. Evidence of under-investment in energy R&D in the United States and the impact of Federal policy. *Energy Policy* **27**, 575–584 (1999).
29. Popp, D. Economic analysis of scientific publications and implications for energy research and development. *Nat. Energy* **1**, 16020 (2016).
30. Myslikova, Z. & Gallagher, K. S. Mission Innovation is mission critical. *Nat. Energy* **5**, 732–734 (2020).
31. Popp, D., Pless, J., Hascic, I. & Johnstone, N. Innovation and entrepreneurship in the energy sector. *NBER Work. Pap. Ser.* (2020).
32. EPO, I. Patents and the energy transition: Global trends in clean energy technology innovation. (2021).
33. Hart, D. M. The Impact of China's Production Surge on Innovation in the Global Solar Photovoltaics Industry. *Inf. Technol. Innov. Found. Rep.* (2020).
34. Carvalho, M. D., Dechezleprêtre, A. & Glachant, M. Understanding the dynamics of global value chains for solar photovoltaic technologies. 1–31 (2017).

35. Sinke, W. C. Development of photovoltaic technologies for global impact. *Renew. Energy* **138**, 911–914 (2019).

36. Weinold, M., Kolesnikov, S. & Anadon, L. D. Quantifying the impact of performance improvements and cost reductions from 20 years of light-emitting diode manufacturing. in *Light-Emitting Devices, Materials, and Applications XXV* (eds. Strassburg, M., Kim, J. K. & Krames, M. R.) 34 (SPIE, 2021). doi:10.1117/12.2577591

37. OECD. Policies for a climate-neutral industry. Lessons from the Netherlands. 47 (2021).

38. IEA. *20 Years of Carbon Capture and Storage*. (OECD, 2016). doi:10.1787/9789264267800-en

39. Reiner, D. M. Learning through a portfolio of carbon capture and storage demonstration projects. *Nat. Energy* **1**, 15011 (2016).

40. Porthos. Porthos. (2020). Available at: https://www.porthosco2.nl/en/.

41. Lights, N. Northern Lights. (2020). Available at: https://northernlightsccs.com/en/about.

42. IEA. Share of activity on electric trains for selected countries and regions, 1995-2016. (2019). Available at: https://www.iea.org/data-and-statistics/charts/share-of-activity-on-electric-trains-for-selected-countries-and-regions-1995-2016. (Accessed: 7th July 2021)

43. Glachant, M., Dussaux, D., Paristech, M. & Dechezleprêtre, A. Promoting the International Transfer of Low- Carbon Technologies : Evidence and Policy Challenges. (2013).

44. Keller, W. International Technology Diffusion. *J. Econ. Lit.* **42**, 752–782 (2004).

45. Glachant, M. & Dechezleprêtre, A. What role for climate negotiations on technology transfer? *Clim. Policy* **17**, 962–981 (2017).

46. ACEA. Fact sheet: EU-China automobile trade. (2019). Available at: https://www.acea.be/news/article/fact-sheet-eu-china-automobile-trade.

47. Luderer, G. *et al.* The economics of decarbonizing the energy system-results and insights from the RECIPE model intercomparison. *Clim. Change* **114**, 9–37 (2012).

48. European Environment Agency. *The sustainability transition in Europe in an age of demographic and technological change*. (2019).

49. UNIDO. *The role of technology and innovation in inclusive and sustainable industrial development*. (2016). doi:10.18356/1b194e1c-en

50. Angelucci, S., Hurtado-Albir, F. J. & Volpe, A. Supporting global initiatives on climate change: The EPO's "Y02-Y04S" tagging scheme. *World Pat. Inf.* **54**, S85–S92 (2018).

51. Fleming, L., Greene, H., Li, G., Marx, M. & Yao, D. Government-funded research increasingly fuels innovation. *Science (80-.).* **364**, 1139–1141 (2019).

52. Popp, D. THEY DON'T INVENT THEM LIKE THEY USED TO: AN EXAMINATION OF ENERGY PATENT CITATIONS OVER TIME. *Econ. Innov. New Technol.* **15**, 753–776 (2006).

53. Dechezleprêtre, A., Martin, R. & Mohnen, M. Knowledge spillovers from clean and dirty technologies : a patent citation analysis Centre for Climate Change Economics and Policy. *Grantham Res. Inst. Environ. Work. Pap. No 151* (2013). doi:10.1016/S0890-8508(03)00045-8

54. Cohen, W., Nelson, R. & Walsh, J. *Protecting Their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or Not)*. (2000). doi:10.3386/w7552

55. Griliches, Z. *Patent Statistics as Economic Indicators: A Survey*. (1990). doi:10.3386/w3301

56. Svensson, R. Commercialization, renewal, and quality of patents. *Econ. Innov. New Technol.* **21**, 175–201 (2012).

57. World Bank. New World Bank country classifications by income level: 2020-2021. (2020). Available at: https://blogs.worldbank.org/opendata/new-world-bank-country-classifications-income-level-2020-2021.

58. Dussaux, D., Dechezleprêtre, A. & Glachant, M. Intellectual property rights protection and the international transfer of low-carbon technologies. *Grantham Res. Inst. Clim. Chang. Environ.* (2018).

59. Mealy, P. & Teytelboym, A. Economic complexity and the green economy. *Res. Policy* 103948 (2020). doi:10.1016/j.respol.2020.103948

60. EPO. Updates on Y02 and Y04S. (2019).

61. World Bank. Annual Commodity Prices. (2021). Available at: https://thedocs.worldbank.org/en/doc/5d903e848db1d1b83e0ec8f744e55570-0350012021/related/CMO-Historical-Data-Annual.xlsx.