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Greenovate for a Better Environment and Economy

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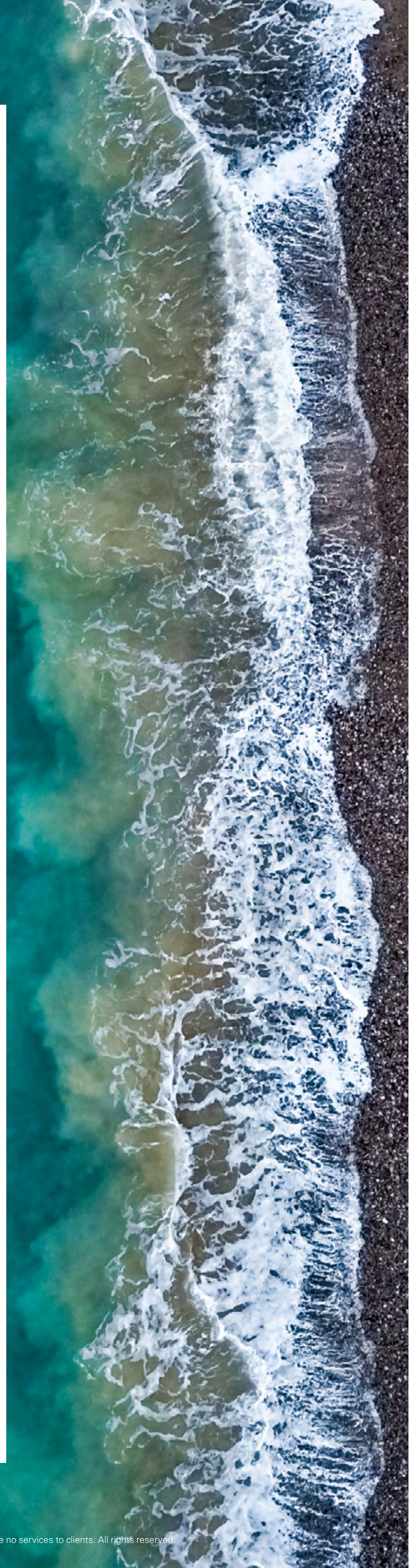


Foreword

The planet now stands at a historic crossroad as the profound and unmistakable impact of climate change continues to threaten humanity's very future.

Alarming evidence of this global crisis continues to emerge with growing ferocity by the day. And there is no denying that the business community and its leaders possess the ability – and share the responsibility – to act without delay.

The encouraging news is that so many of today's businesses are recognizing both the pressing need for dramatic change and the significant role they can play in the race to drive progress. KPMG International's 2021 CEO Outlook survey reveals three quarters of today's CEOs believe their organizations have the financial resources and skills needed to assist governments in delivering environmental solutions.

Further, many of those CEOs leading high-growth companies have also said that their business priorities now include plans to invest more than 10 percent of their revenues into sustainability initiatives that will help unlock breakthroughs for the planet's future while adding financial value to their organizations.

Why is this time different? Why are they pursuing decisive action now? In one word: opportunity. The business community knows that they have the means, responsibility and opportunity to make a real difference in their communities and across the world. In addition, they also know that the key to future success demands real transformative change.

I am proud to note that KPMG professionals continue to work shoulder-to-shoulder with today's forward-looking businesses through a dedicated network of climate-change and sustainability experts who understand the vast challenges ahead and the critical solutions that will drive change. At the same time, the KPMG global organization is also putting the Environmental, Social and Governance agenda at the heart of everything it does and is firmly committed to making a difference in the face of today's crisis.

It is for these reasons that KPMG International felt it necessary to be part of this important research – because no one area of society alone can solve the climate crisis. Ultimately, with the clock ticking on the well-being of the planet and humanity, it is now up to businesses, governments and society to pursue unprecedented levels of collaboration, solidarity, innovation and action to complete the historic journey ahead without further costly delay.

On behalf of KPMG International, let me offer sincere thanks for the critical insights and inspiration that the esteemed University of Cambridge authors have set out in this timely research which hopefully will help contribute to the dialogue and brain trust leading up to and beyond COP26.

Gary Reader
Global Head of Clients & Markets
KPMG International

Executive summary

Climate change is the most-severe threat facing the planet today and countries all over the world are gathering for COP26 with ambitious and extremely time-sensitive plans to reduce carbon emissions. In the race for progress, this report investigates whether increased innovation among green-related activities can combine environmental breakthroughs with future economic prosperity.

Drawing on patent data from the last three decades for 43 OECD and BRICS countries, we find that a doubling of green patent filings, if sustained, will lead to a significant increase of 4.8 percentage points in real GDP growth. This is particularly noteworthy when compared with a GDP gain of 3.4 percentage points if non-green patents alone are doubled yearly. We also show that the impact of green patent filings on growth is mostly channelled via the services sector.

Our report also documents the vital success stories we are witnessing among major innovating countries and renewable-energy businesses, and the instructive role that governments can play in driving progress for our planet's environmental and economic future.

Introduction

While COVID-19 has exerted a profound and devastating impact on the planet, perhaps one true benefit to emerge is the two-billion-gigatonne dip in carbon dioxide emissions witnessed in 2020 – the largest global drop since World War II (IEA, 2021). Unfortunately, this 6% decline translates into a mere 0.01°C reduction in global warming by 2050 (UN, 2020) – while a 2019 UN report warns that emissions must fall by 7.6% every year during this decade for the world to meet the 1.5°C target set by the Paris Agreement (UN, 2019).

Given the severity of today's unprecedented climate threats and extreme events – cold snaps and deadly heat waves, droughts, floods, raging fires, hurricanes and ever-rising sea levels (see IPCC 2021) – plus decades of costly procrastination, significant green innovation in all economic sectors has become absolutely crucial to our future. Countries all over the world now need to revisit their national contributions during COP26 if they hope to be consistent with the pressing Paris Agreement roadmap.

There are two main approaches to cutting emissions and achieving net-zero targets. One entails scaling down production and economic activity, a techno-pessimist approach. The other is adopting green-related investments and decarbonisation policies to maintain economic production and limit climate impacts, a techno-optimist approach. For more on this, see Pisani-Ferry (2021). This report focuses on the latter path and compares the impact of green and non-green innovation on economic growth.

The benefits of green innovation in reducing emissions are well documented – see for example Töbelmann & Wendler (2019) and Du, et al. (2019) – therefore this report focuses on green innovation's positive impact on economic activity.[1] Drawing on data covering all patent filings for 43 countries covering OECD and BRICS from 1990-2018, this report shows that green innovation can deliver economic growth that is equal to – or greater than – the impact of non-green innovation.

Doubling green patent applications every year leads to a 4.8 percentage point increase in real economic growth, compared to a 3.4 percentage point increase in real GDP growth by doubling non-green patents yearly. Our findings make clear that green investments can improve the environment and the economy at the same time.

The report also builds upon the latest trends in green-technology deployment, providing insights from the world's innovation-leading nations. The role of government in encouraging and funding green innovation is critical to progress, driving private-sector development and large-scale integration of green technologies.[2]

1. For more background information on the literature covering innovation and green innovation and their impacts on economic activity and emission reduction, please refer to Appendix A1. Related Literature.
2. It is important to emphasize that the purpose of this report is to provide a brief exposition of the effect of green innovation on economic growth, drawing on micro-data covering the universe of all patent filings from the past three decades. The report is not meant to provide a detailed explanation of all the channels through which patent filings affect economic growth. Additionally, small aggregate changes in long-horizons may well conceal transition costs (Agarwala, et al., 2021) and distributional effects (Cavalcanti, et al., 2021), which this report abstains from addressing or quantifying. As Pisani-Ferry (2021) puts it, optimistic long-run effects of decarbonisation does not justify overlooking transition costs that could be sizable and should be at the centre of policy making for the green transition.

Data and Findings

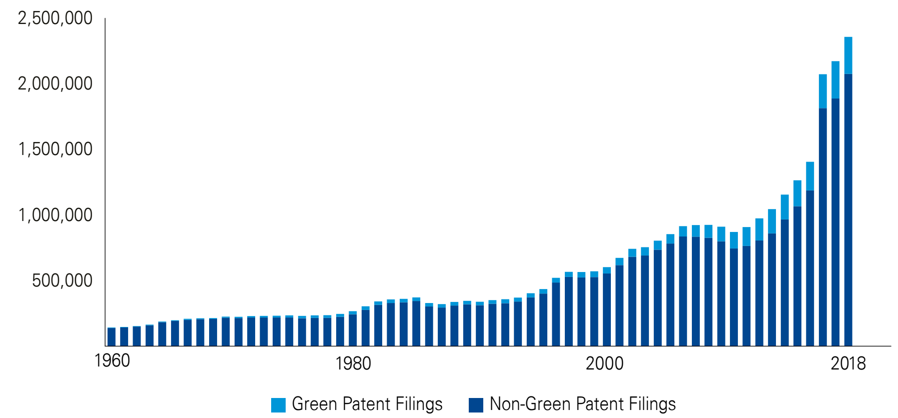
Green patents are as beneficial as non-green patents to economic growth – if not more so

We use data from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT) 2021 Spring edition, which covers the universe of all patent applications from 92 patent-application authorities worldwide, spanning almost six decades from 1960-2018.[3]

The patent nomenclature distinguishes between two main concepts: (i) inventions and (ii) patent filings. The former attributes the patent to the inventor's country of residence. The latter attributes the patent to the application authority in which the patent seeks legal protection. For the purpose of this study, we focus on the patent filings measure.[4,5,6]

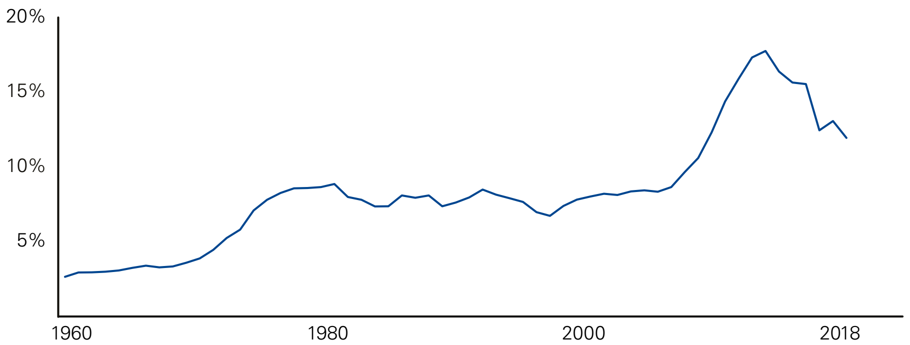
From the universe of all patent filings that we have, roughly 24 million observations, we separate filings into green versus non-green by referring to a patent's technical classification(s) from the Cooperative Patent Classification (CPC). Green patents are classified using the Y02-tag, a broad classification scheme that identifies patents related to climate change mitigation technologies (Angelucci, et al., 2018).

Figure 1 — Total and green patent filings on the rise



Source: PATSTAT 2021 and authors' calculations.

Figure 2 — Green patents increased as a share of total patent filings to reach 18% in 2012, but have been declining since



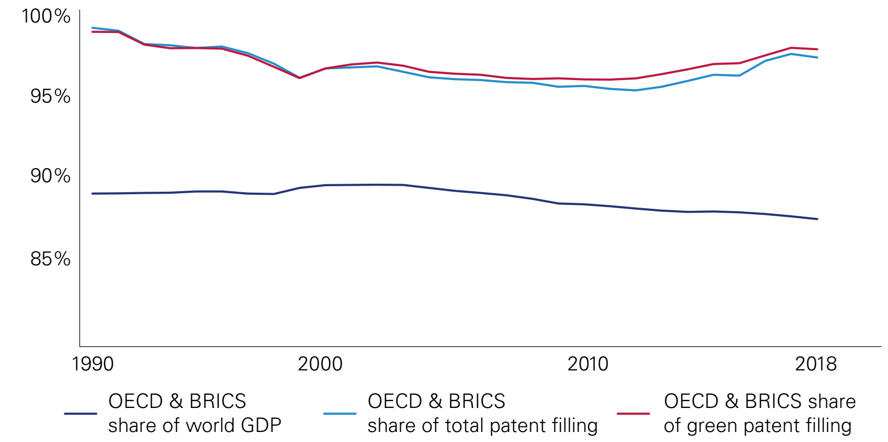
Source: PATSTAT 2021 and authors' calculations.

3. See Appendix A6. Application Authority Table for an exhaustive list of all application authorities included in PATSTAT 2021 Spring Edition.
4. For example, suppose there is a patent application that is filed at the United States Patent and Trademark Office (USPTO), but the country of residence of the inventor is Japan. In this example, the US would have a Patent Filing Count of 1, whereas Japan would have an Invention Count of 1. In the case that a patent application has multiple inventors, with multiple countries of residence, equal weighting is given to each country of residence.
5. We focus on the patent filings measure for three main reasons: 1) The data for patent filings is exhaustive to the best of our knowledge, while almost half of the patents have missing inventor country; 2) A patent filing made to an application authority shows an intention from the inventor to employ that particular invention in that market, hence we would expect that invention to impact economic activity through various channels in that particular market; 3) Invention Count is a closer measure of the inventive activity of a market and reflects the economic impact of the inventive process, as opposed to the economic impact of the innovation itself.
6. In order to use patent filings data for European Patent Office (EPO) member states (primarily constituting EU member states), we apportioned patent applications to the EPO into its constituent member states using shares of Post Fee Grant Payments, similar to Haščič, et al. (2015).

Green patent filings have been gradually increasing since the 1960s **(Figure 1)**. As climate change has gained momentum amid public discussion and government policy, green patent filings rose as a share of total filings from 2.7% in 1960 to peak at 17.8% in 2012. More recently, there has been a plateau in green patent filings that has been outpaced by growth in total patents, driving down the share of green patents among total patents to 12.0% in 2018 **(Figure 2)**.[7]

Within this data set, we focus on green patent filings for 43 countries covering OECD and BRICS from 1990-2018.[8] These 43 countries cover on average over the past three decades 89% of world real GDP and 97% of total and green patent filings **(Figure 3)**.

Figure 3 — OECD and BRICS countries constitute approximately 89% of world GDP and 97% of total and green patent filings



Source: PATSTAT 2021 and authors' calculations.

We follow the empirical strategy detailed in **Box 1** to explore the long-run effects of green and non-green patent filings on economic growth, employment and their sectoral breakdown. We focus on the long-run, as it is generally understood that innovation will have a delayed effect on economic activity, since it takes time to integrate into the country's production structure and provide a positive supply shock to economic activity.

Results show that in the long-run, green patent filings are at least as economically positive and significant as non-green filings. Indeed, doubling green patent filings yearly increases real economic growth by 4.8 percentage points, while doubling non-green patent filings yearly increases real economic growth by 3.4 percentage points.

7. For example, in 2018, green patent filings deteriorated by 0.7% from previous year, while total patent filings grew by 8.6%.
8. We start our analysis from 1990 to cover as many individual time series as possible. In fact, data for seven of the 43 countries started after 1990, and these are: Latvia (1992), Lithuania (1992), Czech Republic (1993), Estonia (1994), Colombia (1994), Costa Rica (1995) and Chile (2002).

Box 1. Technical Description of the Empirical Strategy

We build on Kahn et al. (2019) and estimate a panel Auto-regressive Distributed Lag (ARDL) Model to quantify the dynamic effects of green and non-green patent filings on economic activity by estimating their long-run effects on economic growth and other macroeconomic outcomes. The empirical specification is as follows:

$$\Delta y_{it} = a_i + \sum_{l=1}^{p} \varphi_l \, \Delta y_{i,t-l} + \sum_{l=0}^{p} \beta_l \, \Delta x_{i,t-l} + \varepsilon_{it},$$

where, $y_{i,t}$ is the natural logarithm of real output per capita (in our analysis later on, instead of growth rate of real GDP, we use the growth rates of sectoral output, such as agriculture, industry and services) in country *i* and year *t* and $x_{i,t}$ is the natural logarithm of patent filings count per capita.

The panel ARDL specification allows us to estimate the long-run effects of $\Delta x_{i,t}$ on $\Delta y_{i,t}$, in the following way:

$$\frac{\sum_{l=0}^{p} \beta_l}{1 - \sum_{l=1}^{p} \varphi_l}$$

In a series of papers, Pesaran and Smith (1995), Pesaran (1997), and Pesaran and Shin (1999) show that the traditional ARDL approach can be used for long-run analysis, and that the ARDL methodology is valid regardless of whether the regressors are exogenous or endogenous, and irrespective of whether the underlying variables are *I(0)* or *I(1)*. Moreover, the ARDL approach is robust to potential bidirectional feedback effects and omitted variables. However, sufficiently long lags are necessary for the consistency of the ARDL estimates, whereas specifying longer lags than necessary can lead to estimates with poor small-sample properties. We use the same lag orders for all countries/variables. Given that we are working with growth rates which are only moderately persistent, a maximum lag order of 3 (*p=3*) should be sufficient to fully account for the short-run dynamics (although we also test for other lag lengths for robustness). Furthermore, using the same lag order across all variables and countries helps reduce the possible adverse effects of data mining that could accompany the use of country and variable specific lag order selection procedures such as the Akaike or Schwarz criteria. Note that our primary focus here is on the long-run estimates, rather than the specific dynamics that might be relevant to a particular country.

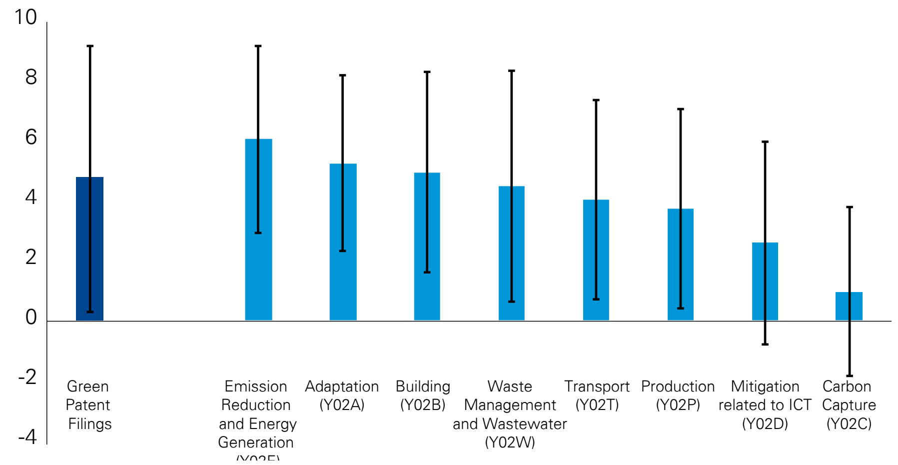
Finally, we use the half-panel jackknife fixed effects estimator proposed in Chudik, et al. (2018) to address any potential bias arising with the standard fixed effects estimator. The benefit of the half-panel jackknife estimator is that it corrects for possibly Nickell-type bias arising when the time dimension of panel is moderate relative to its cross-sectional dimension and regressors potentially weakly exogenous, which is the case in our application (Nickell, 1981).

To better understand the effect of green patent filings on economic activity, we investigate the impact of green and non-green patent filings on sectoral output (agriculture, industry and services). We find that the effect of green patent filings is mostly channelled via the services sector, versus an insignificant effect on agricultural and industrial output at the aggregate levels. Nevertheless, a more-refined sectoral breakdown of the services sector, as well as the other sectors, will help us understand these results better.

Using aggregate employment data, we also find that green patent filings have the strongest impact on employment in services, but more-granular data and further investigation is needed to understand the impact of green innovation on employment at the sectoral level.

The effects of green patent filings on economic activity could potentially mask heterogeneity within different types of green patent filings. We take our analysis a level deeper, decomposing green patents into its eight subcategories and some noteworthy sub-subcategories. Details on this breakdown can be found in **Appendix A3**. Results show that the impact of green patent filings on economic growth is driven significantly by green filings related to energy (specifically energy storage), adaptation, buildings, wastewater, transportation and production **(Figure 4)**. All of these subcategories have a significant positive effect on real economic growth, specifically within the services sector.

Figure 4 — Long-Run Effects of Doubling Green Filings on Economic Growth (in percentage points)



Source: PATSTAT 2021 and authors' calculations.

Notes: The bars depict the long-run impact as percent of GDP growth and the lines show the 10th and 90th percentile error bands.

However, green patent filings on energy and transport also have a strong effect on industry, albeit with varying smaller and larger magnitudes. It is also interesting that solar PV patent filings had a negative effect on agricultural output, explained perhaps by land use shifting from crops and agricultural production to solar panel deployment. However, innovation and deployment in agrivoltaics, a hybrid of agriculture and solar PV infrastructure, may see this negative effect dissipate in the very long-term as hybrid technologies enable solar PV benefits while mitigating negative agricultural impacts (Barron-Gafford, et al., 2019). **Table 4** and **Table 5** in **Appendix A3** provide further insights on these results.

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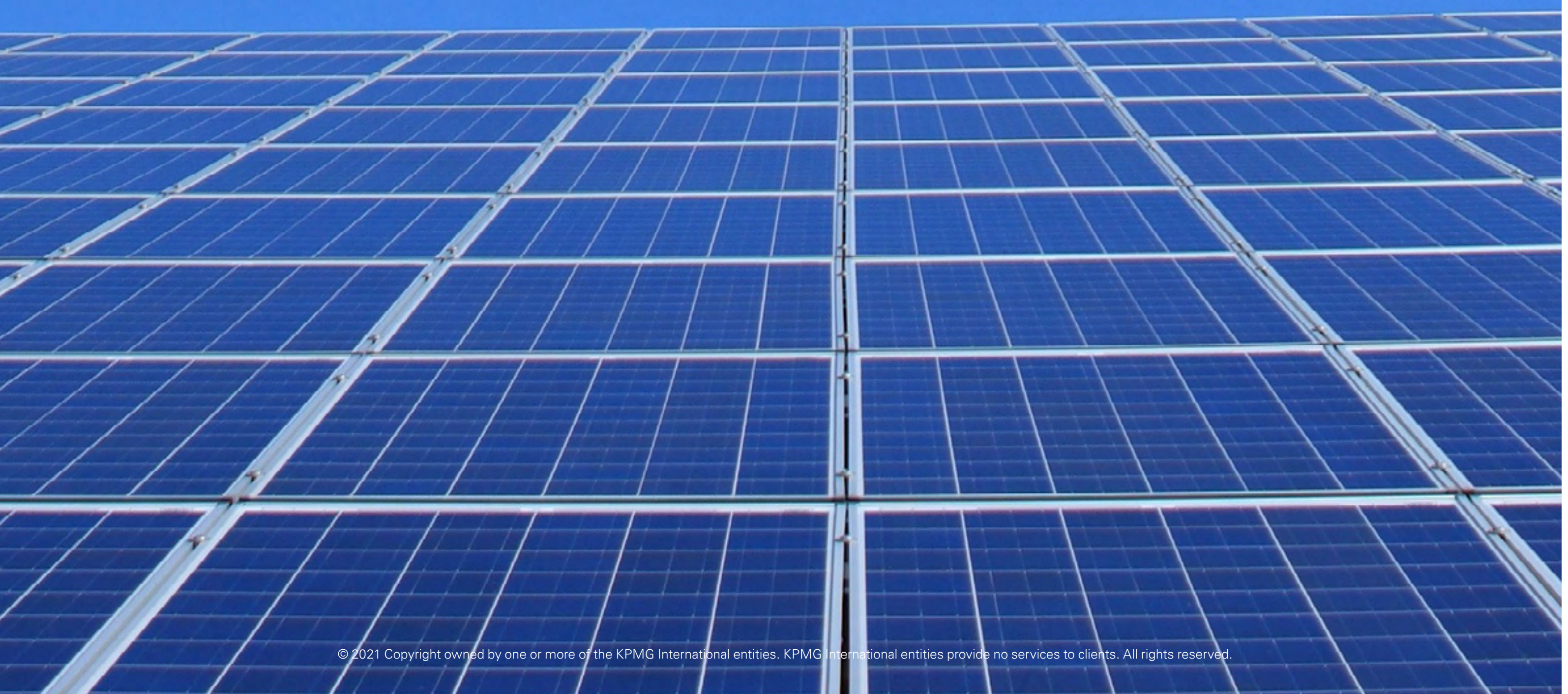
What next?

Government regulation can encourage green innovation

With the established literature linking green innovation to reduced CO_2 emissions (see **Appendix A1**), and our analysis illustrating that green innovation can drive economic growth, the question is what can we do about it? This section argues that government regulation can play a significant role in encouraging green innovation. The argument hinges on two main points: firstly, we draw context from innovation-leading countries to highlight that patent activity is highly sensitive to government regulation. Secondly, we provide a brief overview of the role of investments in expanding green activity to date.

While studies have shown that green investment is sensitive to targeted investment incentives, such as Feed-in Tariffs (FiT) and long-term power purchase agreements (Ang, et al., 2017), this section investigates country-level narratives to demonstrate the influence of government regulation on patent activity. To do so, we move beyond the global stage and focus on seven countries that are the main drivers of total and green patent filings: the China, France, Germany, Japan, Republic of Korea, UK and the US. These seven economies capture, on average, nearly 80% of total and green inventions and approximately 70% of total and green patent filings. We provide a deep-dive into the two main global players, China and the US, and brief synopses of the other five key players.

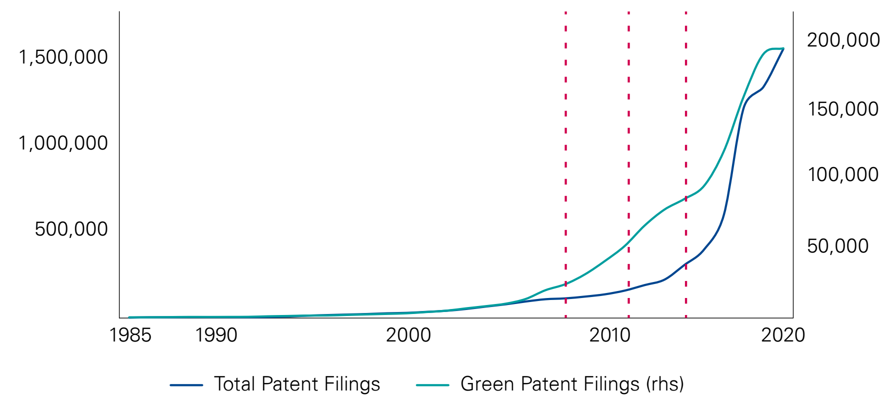


What can we learn from China?

National innovation is guided closely by China's social and economic-development initiatives, such as the Five-Year Plans (Campbell, 2011), and state-driven initiatives such as the Medium-to-Long-Term Plan for the Development of Science Technology (MLP) (The State Council of the People's Republic of China, 2006). These are supported by provincial and local governments who have integrated various patent-subsidy policies to meet and/or exceed patent targets set by the government (Lei, et al., 2012).

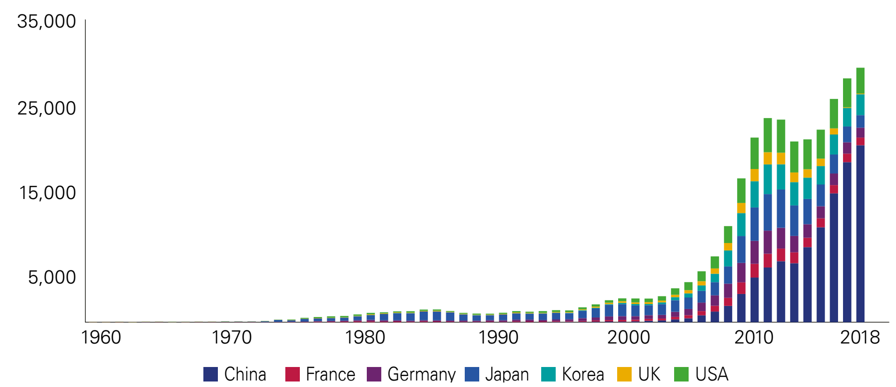
The announcement of the MLP in 2006 has kickstarted China's domestic innovation with an attempt to reduce China's dependence on imported technologies and instead position it as a global leader in patent filings. Indeed, since 2006, total annual patent filings growth soared – from 109,000 in 2006 to 1,565,000 by 2018. China is now a global leader in patent filings, with 53.3% of total patent filings and 57.2% of green patent filings worldwide as of 2018.

Figure 5 — Total and green patent filings in China have picked up since 2006



Source: PATSTAT 2021 and authors' calculations.

Figure 6 — China constitutes the lion's share of solar PV patent filings



Source: PATSTAT 2021 and authors' calculations.

Green innovation exhibits a similar reliance on state guidance, and the dynamics of green patent filings closely coincides with the degree of green policy in China's Five-Year Plans. In the 11th Five-Year Plan (2006-2010), China introduced control indicators for sulphur dioxide and chemical oxygen demand, indicating environmental protection as a common concern throughout China. The twelfth Five-Year Plan (2011-2016) saw a concerted effort into green innovation and was reinforced by aggressive green policies from Premier Li Keqiang, who declared war on pollution in 2014.[9] This was driven by significant public funding into clean-energy industries while bringing attention to environmental degradation. This was quantified by China aiming to reduce energy consumption per unit of GDP (a measure of energy inefficiency in the economy) by 16%. China's extensive green innovation achieved an 18.2% reduction by 2016.

Figure 5 plots the evolution of total and green patent filings in China, highlighting clearly the significant influence of China's national policies in 2006, 2011 and 2016.

Government regulation in China has also been influential at the sub-subcategory level, with China being a global leader in the solar PV industry, both in global production at 80% of total production in 2021,[10] and in terms of global innovation, constituting 73.1% of global solar PV patent filings in 2018.

Indeed, the Chinese surge in solar PV changed the landscape of solar PV manufacturing (Hart, 2020). In the mid-2000s, provincial Chinese authorities would offer subsidized land, financial support and tax relief to the emerging solar PV industry (Hart, 2020). Additionally, China has also aimed to integrate solar PV as a viable renewable-energy resource. For example, in China's thirteenth Five-Year Plan, the Chinese government aimed to have at least 105GW of energy from solar PV. To encourage domestic adoption of solar PV, the Chinese government in 2011 announced substantial incentives to encourage the development of solar PV, such as preferential FiT rates. China maintained competitive FiT rates in the thirteenth Five-Year Plan to allow for greater domestic solar PV uptake. This gave China almost 2.5 times the capacity of the second-largest market, the US (Solar Power Europe, 2021).

With China's aggressive state-led policies, Chinese firms were able to dominate every stage of global PV module manufacturing. They were also less likely to exit the solar PV market than their respective foreign counterparts, given favourable business environments domestically (Hart, 2020). This set in place a virtuous cycle in China, whereby increased solar PV innovation gave rise to a greater competitive edge for domestic deployment and global production, while foreign counterparts struggled to catch up.[11]

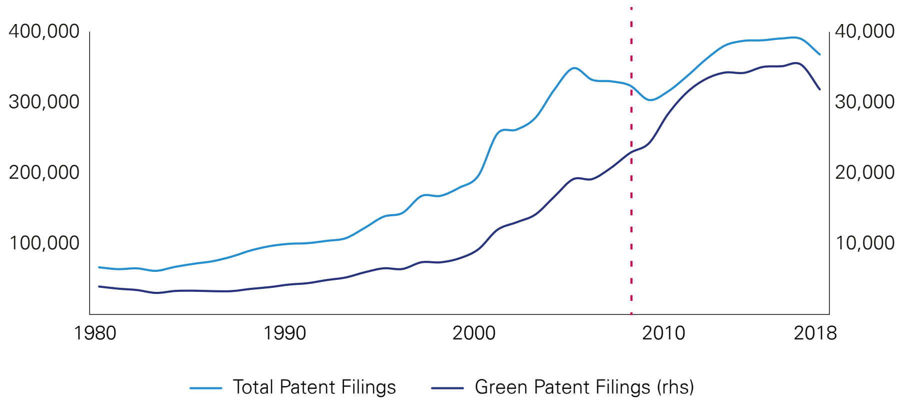
In **Appendix A4.1 China: Energy Storage and Hybrid and Electric Vehicles**, we elaborate on the influence of Chinese government regulation on energy storage and hybrid and electric vehicles.

9. See https://www.reuters.com/article/us-china-parliament-pollution-idUSBREA2405W20140305 for a deep-dive into Premier Li Keqiang's war on pollution.
10. For more on this, see https://www.forbes.com/sites/kenrapoza/2021/03/14/how-chinas-solar-industry-is-set-up-to-be-the-new-green-opec/?sh=340ff0481446
11. In turn, this simultaneously created a vicious circle for foreign PV firms – as their market share declines, their revenue declines, reducing their R&D and competitive edge - a prime example being the US, where solar PV market activity flourished from the early 1980s but has since declined, with only large players such as SunPower and First Solar surviving.

What can we learn from the United States?

The US has consistently been a leader in total innovation. The US is accredited with almost 28.8% of all inventions since the 1990s and 15.7% of all patent filings. National patent filings in both total and green exhibited consistent growth from the 1980s onward.[12]

Figure 7 — ARRA green lending has helped maintain growth in green patents in the US despite the economic slowdown brought by the crisis



Source: PATSTAT 2021 and authors' calculations.

Green patent filings maintained a positive growth rate through the great financial crisis of 2007-2008. This was likely due to green innovation being dependent on government intervention – already significant prior to the American Recovery and Reinvestment Act of 2009 (ARRA) – versus external financing/a firm's ability to borrow, thus sheltering green innovation from the negative impact of the crisis (Hardy & Sever, 2020).

The ARRA was introduced in an attempt to rescue the US economy and create long-run growth. The ARRA stimulus package exceeded US$787 billion, directing more than US$100 billion into programs for innovation and technology development, with US$30 billion in innovation funding directed to green innovation.[13] For non-green innovation, access to credit and funding from the ARRA likely kick-started the return to growth shown in total patents. As to green innovation, the additional green funding increased annual growth in green patent filings from 8% in 2008 to 15% in 2010.

Beyond encouraging green innovation at the aggregate level, government policy has also played a critical role in encouraging green innovation at the micro-level, which we explore in more detail for hydrogen technology and solar PV in **Appendix A4.2 United States: Hydrogen Technology and Solar PV.**

12. Following the great financial crisis, total patent filings declines, reflecting the well observed impact of the crisis on private firm innovation (Hardy & Sever, 2020).
13. See https://obamawhitehouse.archives.gov/recovery/innovations/intro for a breakdown of the American Recovery and Reinvestment Act.

Other lessons from key world players

Government regulation has had noticeable first-hand effects in other leading countries as well. In Germany, the Renewable Energy Act of 2000 established a guaranteed 20-year FiT for renewables, reinforcing the commercial viability of wind energy in Germany and resulting in wind energy patent filings tripling from 2000-2010. See **Appendix A4.3 Germany: Wind and Nuclear Energy** for more details.

Japan enacted an aggressive capital subsidy scheme in 1998 (Mizuno, 2014) that partially covered capital costs for both the private and non-profit sectors. The scheme remained in place until 2012, when it was rolled back. Wind energy patent filings increased from 130 in 1998 to 570 in 2011. See **Appendix A4.4 Japan: Wind Energy** for more details.

In Korea, the government placed a keen focus on the commercialisation of electric vehicles in 2009 with policies such as Entering the Four Great Green Car Powers by 2013, which marked the first year that innovation in hybrid and electric vehicles (HEVs) surpassed Internal Combustion Engine (ICE) innovation, given the encouraged substitution of innovation towards HEVs. With the Ministry of Environment offering substantial purchase subsidies from 2017-2018 alone, EV sales doubled, which kickstarted the virtuous cycle of making HEV innovation commercially viable (Hardman, et al., 2017). See **Appendix A4.5 South Korea: Hybrid and Electric Vehicles** for more details.

In France, solar PV uptake picked up in 2009 as the government offered attractive FiT rates following Germany's effective FiT policies (Fabra, et al., 2015). As a result, solar PV installed-capacity grew tenfold. See Appendix **A4.6 France: Solar Thermal and PV** for more details.

It is clear then that patent filing activity, green or otherwise, is highly sensitive to government intervention and regulations. The commercial landscape for green innovation is in its infancy and still requires considerable government support via long-term financial support and a commercially viable market. Studies show that preferential FiT encourages investment and allows deployment of commercial-scale renewable energy, making targeted deployment incentives crucial to green innovation (Ang, et al., 2017).

The narratives explored above and in **Appendix A4** provide first-hand evidence that substantiates a virtuous cycle for green incentives and production. The right incentives drive greater green innovation – reducing renewable energy prices and providing a commercially viable landscape for private innovation, so the cycle persists. However, it is important to note that in countries such as Germany, where digression came in too early, or in Japan, where capital subsidies are cut, the cycle can easily be broken and deflate any benefits.

Overview of green investments to date

Progress on carbon-emission reduction to combat climate change will require a major shift to generating energy from renewable sources. Fossil fuels currently account for 87% of the world's CO_2 emissions[14] and have traditionally dominated energy generation because it was cheaper to produce energy from fossil fuels than from renewables (Roser, 2020). The world now faces a critical need to increase its reliance on renewables and this will only be achieved when prices of renewables are lower than those of fossil fuels. Roser (2020), Henbest (2020) and Krugman (2021), among others, draw on the exponential reduction in renewable prices in the past few decades and argue for increased policy support to subsidize green innovation.

Indeed, there has been an exponential reduction in renewable energy prices. For example, in terms of levelized costs of energy[15], the cost of producing electricity from utility-scale solar PV dropped by 89% between 2009 and 2019, from US$359/MWh to US$40/MWh, while that of onshore wind dropped by 70%, from US$135/MWh to US$41/MWh. Meanwhile, the price of coal only declined by 2% between 2009-2019, from US$111/MWh to US$109/MWh. This price decline in renewables has triggered rampant investment – wind and solar constituting 72% of all new capacity additions.[16]

It is important to leverage the price difference that is expected to keep growing between renewables and fossil fuels. It is difficult to expect fossil fuels to get cheaper in the long-run given the cost structure of fossil fuel energy production. There are two main costs underlying fossil fuels and nuclear power generation: the power plant's operating costs and the price of the fuel. On the first cost source, there is little room to improve the efficiency of coal plants. On the second cost source, fuel itself constitutes 40% of total costs with fossil energy production (McNerney, et al., 2011), therefore there is a lower bound below which the price of fossil fuel energy cannot fall.

Meanwhile for renewable energy plants, operating costs are low since there are no fuel costs – fuel is freely provided by nature, so the bulk of their cost is for the technology itself. This bodes well for renewables, since technology can only become cheaper with more production. According to the BloombergNEF (2021) analysis of future of energy, solar PV prices are expected to drop another 14%-22% by 2025-2030 (BloombergNEF, 2021). As such, learning-by-doing will spark a virtuous cycle of rising demand and falling prices, making technology cost effective in more applications and further increasing demand versus traditional sources of energy (Acemoglu, et al, 2012 and Aghion, et al, 2014).

Indeed, improvements in solar PV technology have made it the most cost-competitive source of energy (Solar Power Europe, 2021). Solar PV innovation is driven by an array of novel technology combinations and refinements, resulting in efficiency and price improvements (Roser, 2020). Solar PV innovation includes improved production of silicon wafers, increased economies of scale and improved manufacturing techniques, all serving to dramatically decrease solar PV module prices. Solar power is leading the way for renewable energy resource innovation and there are no signs of innovation slowing in the future. Solar innovation is being targeted at cutting costs and at greater integration with other green technologies such as hydrogen energy solutions (Solar Power Europe, 2021).[17]

Recent trends regarding the installed capacity and prices of renewable energy sources have shown that the renewable industry has a steep learning curve. This means that as cumulative installed capacity increases exponentially, the price drops exponentially.[18] Given the learning curve that exists for the renewable energy sector, even modest government incentives encouraging green technology can drive significant gains. Government subsidies will only be needed for a few years as knowledge builds up to sufficiently drive down costs (Krugman, 2021). This will reach a tipping point beyond which renewable sector growth will be self-sustaining and subsidies will no longer be needed.

14. For more on this, see: https://ourworldindata.org/grapher/global-co2-emissions-fossil-land?country=~OWID_WRL.
15. The levelized cost of energy (LCOE), or levelized cost of electricity, is a measure of the net present cost of electricity generation for a generating plant over its lifetime. It encompasses the cost of building the power plant itself as well as the ongoing costs for fuel and operating the power plant over its lifetime.
16. For more on this, see: https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.
17. In Appendix A5. Technology Improvements in Energy Storage and Electric Vehicles, we give two detailed examples on the improved deployment and cost of energy storage and electric vehicles as a result of improvements in innovation and technology.
18. At each doubling of installed solar capacity and onshore wind, the price of electricity declined by 36% and 23%, respectively.

Beyond lowering emissions, scaling up renewable energy production will also reduce the cost of energy more generally, which will have a positive effect on public welfare. Falling energy prices will increase real incomes, particularly for people in lower income brackets, where energy costs constitute a larger share of income than higher-income households (Büchs, et al., 2011). This will boost economic prosperity by increasing disposable incomes and reducing inequality.

Green innovation is also needed to unlock significant advantages beyond lowering prices. With renewable energy production ultimately dependent on natural resources such as wind and solar, sufficient funding should go into both ensuring the security of the world's energy supply and increasing its flexibility (Henbest, 2020). One example could be the use of lithium-ion batteries to support solar and wind energy sources. In addition, resources and technologies should target greenhouse gas removal, carbon capture, and storage, all of which are necessary to meet the Paris goals but still in need of research and development (Hepburn, et al., 2019).

In conclusion, government involvement – in terms of regulations and investment – is needed, at least in the short run, to spur green innovation. Stern & Zenghelis (2021) argue that given current favourable lending conditions, the time is ripe for governments to increase public investment in green-related activities that will in turn encourage private-sector investment. Moreover, Hepburn, et al. (2020) conducted a global survey of 231 economists, including finance ministry and central bank officials, and respondents claim that it is feasible for policy action directed at stimulating the economy from its current recession to also make progress towards curbing emissions. Indeed, many of the respondents believe that climate-positive policies are associated with superior economic benefits.

Key Takeaways

Given decades of procrastination and signs of falling short on ambitious Paris Agreement targets, the world needs to act fast on reducing emissions. With the role of green innovation in reducing climate change clear, this report argues that green innovation can also improve economic activity.

Drawing on micro-data covering the universe of all patent filings for OECD and BRICS over the past three decades, the report provides a brief exposition of the long-run effects of green and non-green patent filings on economic growth. Results show that green patent filings have been as beneficial to economic growth as non-green patent filings, if not more so. Indeed, doubling green patent filings yearly has led to a 4.8 percentage point increase in real economic growth, compared to a 3.4 percentage point increase by doubling non-green patent filings.

The report also documents success among major innovating countries and renewable energy businesses and highlights the role governments have played in those successes. Prospects for a sustainable recovery and achieving Paris targets hinge on government actively encouraging green innovation, facilitating regulations and increasing investments. This will drive real economic growth and reduce carbon emissions for generations to come.

References

Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. (2012), 'The environment and directed technical change', American Economic Review 102(1), 131–66.

Agarwala, M., Burke, M., Klusak, P., Mohaddes, K., Volz, U. and Zenghelis, D. (2021), 'Climate change and fiscal sustainability: Risks and opportunities', Cambridge Working Papers in Economics 2163.

Aghion, P., Hepburn, C., Teytelboym, A. and Zenghelis, D. (2019), Path dependence, innovation and the economics of climate change, in 'Handbook on Green Growth', Edward Elgar Publishing.

Akcigit, U., Kerr, W. R. and Nicholas, T. (2013), 'The mechanics of endogenous innovation and growth: evidence from historical us patents', Unpublished.

Ang, G., Röttgers, D. and Burli, P. (2017), 'The empirics of enabling investment and innovation in renewable energy', OECD Environment Working Papers 123.

Angelucci, S., Hurtado-Albir, F. J. and Volpe, A. (2018), 'Supporting global initiatives on climate change: The EPO's "Y02-Y04S" tagging scheme', World Patent Information 54, Supplement, S85–S92.

Asia-Pacific Economic Cooperation (2017), 'The Impact of Government Policy on Promoting New Energy Vehicles (NEVs)', APEC Project: CTI 26.

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P. et al. (2019), 'Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands', Nature Sustainability 2(9), 848–855.

BloombergNEF (2021), 'New Energy Outlook'.

Brown, P. T., Li, W., Jiang, J. H. and Su, H. (2016), 'Unforced surface air temperature variability and its contrasting relationship with the anomalous TOA energy flux at local and global spatial scales', Journal of Climate 29(3), 925–940.

Büchs, M., Bardsley, N. and Duwe, S. (2011), 'Who bears the brunt? Distributional effects of climate change mitigation policies', Critical Social Policy 31(2), 285–307.

Campbell, R. J. (2011), 'China and the United States—a comparison of green energy programs and policies', Federal Publications Paper 826.

Cavalcanti, T., Hasna, Z. and Santos, C. (2021), 'Climate Change Mitigation Policies: Aggregate and Distributional Effects', Cambridge Working Papers 2122.

Cherp, A., Vinichenko, V., Jewell, J., Suzuki, M. and Antal, M. (2017), 'Comparing electricity transitions: A historical analysis of nuclear, wind and solar power in Germany and Japan', Energy Policy 101, 612–628.

Chudik, A., Pesaran, M. H. and Yang, J.-C. (2018), 'Half-panel jackknife fixed-effects estimation of linear panels with weakly exogenous regressors', Journal of Applied Econometrics 33(6), 816–836.

Divya, K. and Østergaard, J. (2009), 'Battery energy storage technology for power systems—An overview', Electric Power Systems Research 79(4), 511–520.

Du, K., Li, P. and Yan, Z. (2019), 'Do green technology innovations contribute to carbon dioxide emission reduction? Empirical evidence from patent data', Technological Forecasting and Social Change 146, 297–303.

Emissions Gap Report 2019 (2019), UN.

Emissions Gap Report 2020 (2020), UN.

Feng, Y., Ning, M., Lei, Y., Sun, Y., Liu, W. and Wang, J. (2019), 'Defending blue sky in China: Effectiveness of the "Air Pollution Prevention and Control Action Plan" on air quality improvements from 2013 to 2017', Journal of Environmental Management 252, 109603.

References

Fernandes, C. I., Veiga, P. M., Ferreira, J. J. and Hughes, M. (2021), 'Green growth versus economic growth: Do sustainable technology transfer and innovations lead to an imperfect choice?', Business Strategy and the Environment 30(4), 2021–2037.

Fulton, M., Capalino, R. and Auer, J. (2012), 'The German feed-in tariff: recent policy changes', https://www.researchgate.net/publication/323665953_The_German_feed-in _tariff_Recent_policy_changes.

Global Energy Review: CO_2 Emissions in 2020 (2021), IEA.

Global EV Outlook 2021 (2021), IEA.

Global Market Outlook for Photovoltaics 2014–2018 (2014), European Photovoltaic Industry Association.

Global Market Outlook for Solar Power 2021–2025 (2021), Solar Power Europe.

Hardman, S., Chandan, A., Tal, G. and Turrentine, T. (2017), 'The effectiveness of financial purchase incentives for battery electric vehicles–A review of the evidence', Renewable and Sustainable Energy Reviews 80, 1100–1111.

Hardy, B. and Sever, C. (2021), 'Financial crises and innovation', European Economic Review 138, 103856.

Hart, D. M. (2020), 'The Impact of China's Production Surge on Innovation in the Global Solar Photovoltaics Industry', https://itif.org/sites/default/files/ 2020-china-solarindustry.pdf.

Haščič, I., Silva, J. and Johnstone, N. (2015), 'The use of patent statistics for international comparisons and analysis of narrow technological fields', OECD Science, Technology and Industry Working Papers 2015/05.

He, G. and Kammen, D. M. (2016), 'Where, when and how much solar is available? A provincial- scale solar resource assessment for China', Renewable Energy 85, 74–82.

Henbest, S. (2020), 'The first phase of the transition is about electricity, not primary energy', Energy News 38(1), 6–13.

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P. and Williams, C. K. (2019), 'The technological and economic prospects for CO_2 utilization and removal', Nature 575(7781), 87–97.

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. and Zenghelis, D. (2020), 'Will COVID- 19 fiscal recovery packages accelerate or retard progress on climate change?', Oxford Review of Economic Policy 36, S359–S381.

Hot and Bothered (2015), The Economist.

Hwang, S. K. (2015), 'Comparative study on electric vehicle policies between Korea and EU countries', World Electric Vehicle Journal 7(4), 692–702.

IPCC (2021), 'Climate Change 2021: The Physical Science Basis'.

Kacprzyk, A. and Dory , W. (2017), 'Innovation and economic growth in old and new member states of the European Union', Economic Research 30(1), 1724–1742.

Kahn, M. E., Mohaddes, K., Ng, R. N., Pesaran, M. H., Raissi, M. and Yang, J.-C. (2019), 'Long-term macroeconomic effects of climate change: A cross-country analysis', National Bureau of Economic Research Working Paper 26167.

Lei, Z., Sun, Z. and Wright, B. (2012), 'Patent subsidy and patent filing in China', Unpublished.

Maradana, R. P., Pradhan, R. P., Dash, S., Gaurav, K., Jayakumar, M. and Chatterjee, D. (2017), 'Does innovation promote economic growth? Evidence from European countries', Journal of Innovation and Entrepreneurship 6(1), 1–23.

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References

Matthes, F. C., Newbery, D., Colombier, M., Mathieu, M. and Ru¨dinger, A. (2015), 'The energy transition in Europe: initial lessons from Germany, the UK and France', https://cerre.eu/ wp-content/uploads/2020/07/151006_CERREStudy_EnergyTransition_Final.pdf.

McNerney, J., Farmer, J. D. and Trancik, J. E. (2011), 'Historical costs of coal-fired electricity and implications for the future', Energy Policy 39(6), 3042–3054.

Mizuno, E. (2014), 'Overview of wind energy policy and development in Japan', Renewable and Sustainable Energy Reviews 40, 999–1018.

Nickell, S. (1981), 'Biases in dynamic models with fixed effects', Econometrica 49, 1417–1426.

Pece, A. M., Simona, O. E. O. and Salisteanu, F. (2015), 'Innovation and economic growth: An empirical analysis for CEE countries', Procedia Economics and Finance 26, 461–467.

Pesaran, M. H. (1997), 'The role of economic theory in modelling the long run', The Economic Journal 107(440), 178–191.

Pesaran, M. H., Shin, Y. and Smith, R. P. (1999), 'Pooled mean group estimation of dynamic heterogeneous panels', Journal of the American Statistical Association 94(446), 621–634.

Pesaran, M. H. and Smith, R. (1995), 'Estimating long-run relationships from dynamic heterogeneous panels', Journal of Econometrics 68(1), 79–113.

Pisani-Ferry, J. (2021), 'Climate policy is macroeconomic policy, and the implications will be significant', https://www.piie.com/system/files/documents/pb21-20.pdf.

Ritchie, H. and Roser, M. (2020), 'CO_2 and Greenhouse Gas Emissions', Our World in Data.

Romer, P. M. (1990), 'Endogenous technological change', Journal of Political Economy 98(5, Part 2), S71–S102.

Roser, M. (2020), 'Why did renewables become so cheap so fast? And what can we do to use this global opportunity for green growth?', Our World in Data.

State Council of the People's Republic of China (2006), 'The National Medium-and Long-Term Program for Science and Technology Development (2006–2020)'.

State Council of the People's Republic of China (2013), 'Air pollution prevention and control action plan'.

Stern, N. and Zenghelis, D. (2021), 'Fiscal responsibility in advanced economies through investment for economic recovery from the COVID-19 pandemic', Grantham Research Institute on Climate Change and the Environment.

Töbelmann, D. and Wendler, T. (2020), 'The impact of environmental innovation on carbon dioxide emissions', Journal of Cleaner Production 244, 118787.

Ulku, H. (2007), 'R&D, innovation and output: evidence from OECD and non-OECD countries', Applied Economics 39(3), 291–307.

Ziegler, M. S., Mueller, J. M., Pereira, G. D., Song, J., Ferrara, M., Chiang, Y.-M. and Trancik, J. E. (2019), 'Storage requirements and costs of shaping renewable energy toward grid decarbonization', Joule 3(9), 2134–2153.

Appendix

A1. Related Literature

The empirical literature covering the relationship between general innovation and economic activity is well established. Studies such as Maradana, et al. (2017) demonstrate the long-run relationship between total patent filings and economic growth, reinforcing the notion that innovation is an engine of economic growth (Romer, 1990). Notably, papers such as Ulku (2007) explore the nuance in innovation and economic growth between countries, concluding that increases in *inventions* increase per-capita GDP for high-income OECD countries and in middle and high-income non-OECD countries. However, the literature covering the relationship between green innovation and economic activity is scant.

A recent paper by Fernandes, et al. (2020) explores the impact of sustainable *inventions* on economic growth using green invention data to proxy for green innovation. They conclude that an increase in green *inventions* per capita results in an increase in environmentally adjusted productivity.[19] Their study then shows that increases in productivity growth results in a statistically significant increase in economic growth. Fernandes, et al. (2020) indirect methodolgy suggests that green innovation drives economic growth via the productivity channel, indicating that green innovation can be an engine of economic growth.

19. Fernandes, et al. (2020) also note how an increase in the level of green patent filings leads to an increase in productivity growth.

Nevertheless, the green innovation literature is established, much of it investigating the direct impact of green innovation on Greenhouse Gas (GHG) emissions. With strong evidence suggesting GHG emissions are the main cause of contemporary global warming (Brown, et al., 2016), and climate change being shown to adversely impact economic growth (Kahn, et al., 2019), literature on green innovation lowering GHGs can indirectly indicate the benefits of green innovation on economic growth.

A recent study by Töbelmann & Wendler (2019) on green innovation in the EU-27 concludes that a 1% increase in green *inventions* is associated with an approximately 0.01% annual decrease in CO_2 emissions, whereas non-green *inventions* do not contribute to a reduction in CO_2. Similar studies, such as Du, et al. (2019), investigate the heterogenous impact of green *inventions* between high-income and middle-income countries. Du, et al. (2019) employ an extensive panel covering 71 countries and conclude that in high-income countries, a 1% increase in green *inventions* results in a 0.071% decrease in CO_2 emissions, whereas there is no statistically significant impact for middle-income countries.

With the benefits of green innovation on emission reduction well-established, and impact on growth indirectly established, this report provides a brief exposition of the long-run effects of green and non-green patent filings on economic growth using micro-data covering the universe of all patent filings.

A2. Detailed Results for Green and Non-Green Patent Filings

Table 1 Long-Run Effects of Patent Filings on Economic Growth

	Real Output per capita Growth				Employment per capita Growth			
	Total	**Agriculture**	**Industry**	**Services**	**Total**	**Agriculture**	**Industry**	**Services**
Green Patent Filings	0.0478* (0.0770)	-0.0272 (0.340)	0.0242 (0.474)	0.0471* (0.0728)	-0.00759 (0.854)	0.0230 (0.438)	0.0652 (0.280)	0.0502** (0.0129)
Non-Green Patent Filings	0.0339** (0.0351)	-0.00778 (0.637)	0.00932 (0.687)	0.0253 (0.184)	-0.0162 (0.568)	0.0349 (0.508)	0.0391 (0.321)	0.0349* (0.0703)

Notes: P-values are reported in the parentheses below the estimates. ***,**, * indicate significance at the 1, 5 and 10 percent levels respectively.

A3. Green Patents: Subcategories and Sub-subcategories

Green patents filings, or Y02 tag, can be decomposed into 8 main categories detailed in **Table 2**.

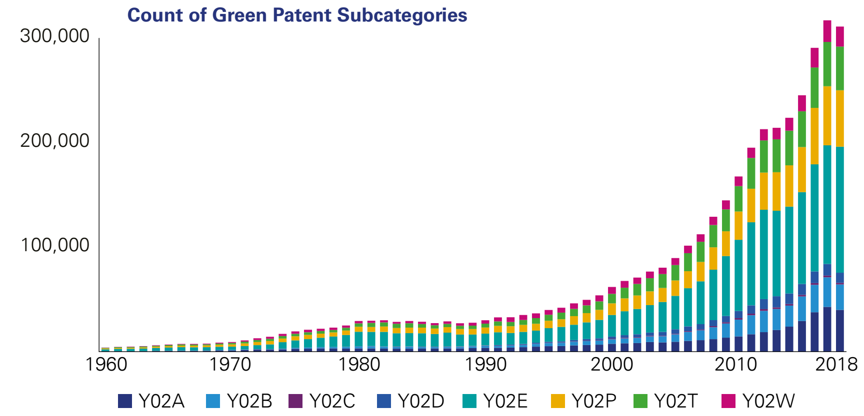
The distribution of the Y02 classification's subcategories is diverse; certain sectors of climate change mitigation technologies constitute the bulk of green innovation. By considering the proportion of green innovation, the top three subcategories are: Y02E - Energy (40%), Y02P - Production (20%), Y02T - Transportation (17%). Notably, the composition of Y02 classification's subcategories has remained relatively stable since the 1960s, with renewable energy patent filings (Y02E) consistently being the primary driver of green innovation, followed by production and transportation **(Figure 9)**.

As such, it is important to note that the dynamics of green innovation may be driven by further sub-subcategories of the Y02 classifications. We therefore break down Energy and Transport into their respective components to better investigate any underlying dynamics **(Table 3 Sub-subcategories of Green Filings on Energy and Transport)**. It is important to note that the aforementioned sub-subcategories capture 52% of total green innovation activity, hence we are able to investigate the underlying key drivers of global innovation from a bottom-up perspective.

Table 2 Subcategories of Green Filings

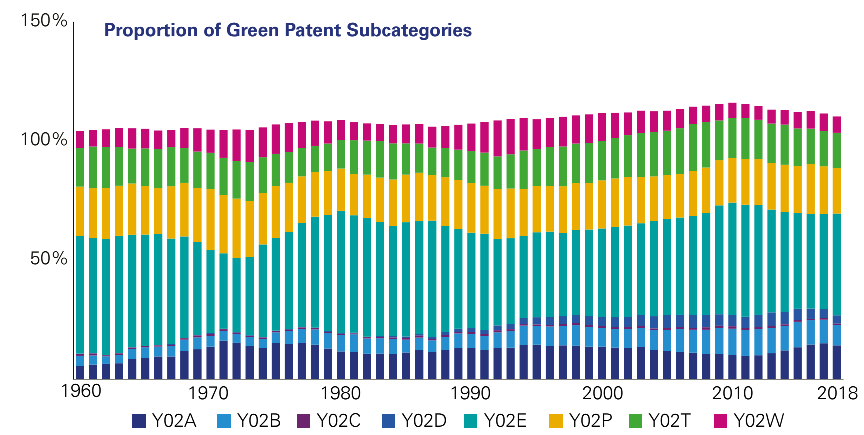
Green Subcategory	CPC Code	Avg. share of total green filings 1990-2018[20]
Adaptation to climate change	Y02A	12.7%
Climate mitigation related to buildings	Y02B	8.8%
Carbon capture	Y02C	0.8%
Climate mitigation related to ICT	Y02D	4.0%
Emission reduction and energy generation	Y02E	39.9%
Climate mitigation related to production	Y02P	19.6%
Climate mitigation related to transport	Y02T	16.5%
Climate mitigation related to waste management and wastewater	Y02W	9.5%

Figure 8 — Energy, Production and Transportation-focused green innovation is dominating green patent filings



Source: PATSTAT 2021 and authors' calculations.

Figure 9 — ...constituting a relatively stable share of around 79% of total green filings



Source: PATSTAT 2021 and authors' calculations.

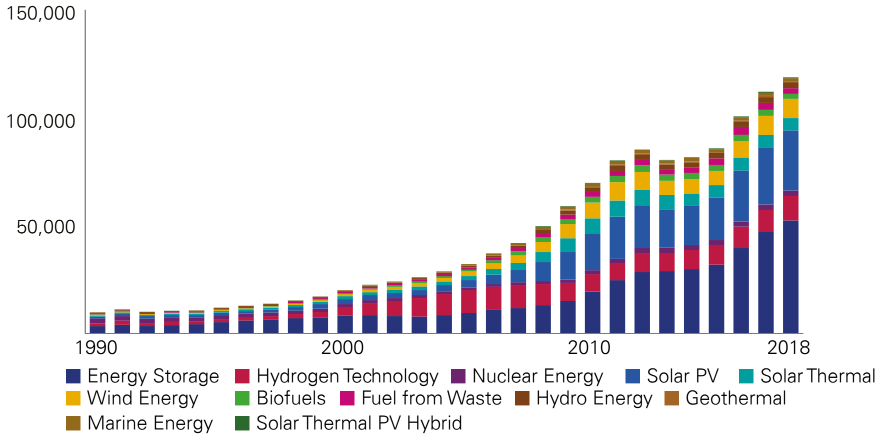
20. Note that the average share sums to more than 100% due to some patent applications lending their classification to multiple subcategories.

Table 3 Sub-subcategories of Green Filings on Energy and Transport

Green Subcategory	Green Sub-subcategory	CPC Code	Avg. share of total green filings 1990-2018
Energy (Y02E)	Wind Energy	Y02E 10/70	2.6%
	Solar Thermal Energy	Y02E 10/4	2.8%
	Solar PV Energy	Y02E 10/5	6.1%
	Solar Thermal-PV hybrids	Y02E 10/60	0.1%
	Geothermal Energy	Y02E 10/10	0.2%
	Marine Energy	Y02E 10/30	0.6%
	Hydro Energy	Y02E 10/20	1.2%
	Biofuels	Y02E 50/10	1.1%
	Fuel from Waste	Y02E 50/30	1.2%
	Nuclear Energy	Y02E 30	2.8%
	Hydrogen technology	Y02E 60/3	6.6%
	Energy Storage	Y02E 60/1	13.7%
Transport (Y02T)	Internal Combustion Engine	Y02T 10/1	8.2%
	Hybrid and Electric Vehicles	Y02T 10/6 Y02T 10/7	5.2%

While green filings in energy (Y02E) and transport (Y02T) have been maintaining equal shares in total green filings at 40% and 17%, their compositions are changing. Looking at the sub-subcategory level shows that energy filings are mostly driven by two main sub-subcategories: Energy storage and solar PV **(Figure 10)**; while transportation filings are being mostly driven by recent surges in HEVs as patent activity in Internal Combustion Engines stagnates **(Figure 11)**.

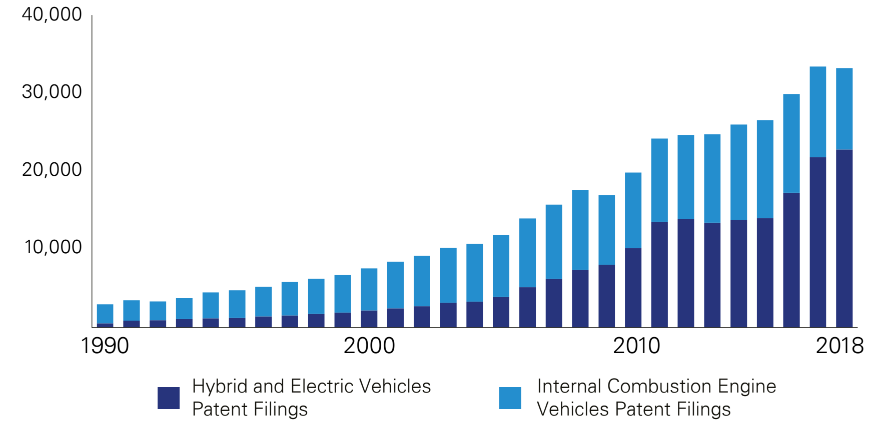
Figure 10 — Energy Storage and Solar PV dominate the green filings in energy



Source: PATSTAT 2021 and authors' calculations.

To contextualise why these sub-subcategories of green innovation are paving the way for green innovation, we explore some global narratives that highlight why green innovation has been so heavily influenced by certain sectors and the direct impact of these sub-subcategories on climate change mitigation technologies.

Figure 11 — Patent filings in Hybrid and Electric Vehicles surge while those in Internal Combustion Engines stagnate



Source: PATSTAT 2021 and authors' calculations.

Table 4 Long-Run Effects of Green Patent Filings on Economic Growth by Subcategory

	Real Output per capita Growth				Employment per capita Growth			
	Total	Agriculture	Industry	Services	Total	Agriculture	Industry	Services
Green Patent Filings on Adaptation (Y02A)	0.0523***	-0.010	0.004	0.0427*	-0.015	0.043	0.040	0.0309*
	(0.003)	(0.695)	(0.879)	(0.066)	(0.656)	(0.321)	(0.408)	(0.094)
Green Patent Filings on Buildings (Y02B)	0.0494**	-0.039	0.054	0.0560**	0.028	-0.015	0.038	0.012
	(0.015)	(0.282)	(0.149)	(0.022)	(0.138)	(0.593)	(0.284)	(0.526)
Green Patent Filings on Carbon Capture (Y02C)	0.010	-0.018	0.018	0.0522**	0.017	-0.035	0.037	0.011
	(0.575)	(0.532)	(0.562)	(0.011)	(0.230)	(0.121)	(0.111)	(0.447)
Green Patent Filings on Mitigation related to ICT (Y02D)	0.026	0.040	0.052	0.0485**	0.019	0.026	-0.010	-0.012
	(0.208)	(0.147)	(0.137)	(0.022)	(0.371)	(0.291)	(0.686)	(0.628)
Green Patent Filings on Emission Reduction and Energy Generation (Y02E)	0.0604***	-0.005	0.0454*	0.0623***	0.004	-0.011	0.044	0.0335*
	(0.001)	(0.840)	(0.098)	(0.006)	(0.849)	(0.693)	(0.209)	(0.070)
Green Patent Filings on Production (Y02P)	0.0373*	0.015	0.046	0.0639***	-0.027	0.014	0.005	0.0329*
	(0.065)	(0.617)	(0.135)	(0.001)	(0.566)	(0.665)	(0.933)	(0.074)
Green Patent Filings on Transport (Y02T)	0.0402**	0.013	0.0632*	0.0652***	-0.029	-0.035	0.016	-0.002
	(0.046)	(0.686)	(0.099)	(0.004)	(0.261)	(0.198)	(0.635)	(0.912)
Green Patent Filings on Waste Management and Wastewater (Y02W)	0.0449*	-0.002	0.044	0.023	-0.050	-0.003	-0.008	0.018
	(0.055)	(0.963)	(0.212)	(0.384)	(0.327)	(0.926)	(0.889)	(0.303)

Notes: P-values are reported in the parentheses below the estimates. ***,**, * indicate significance at the 1, 5 and 10 percent levels respectively.

Table 5 Long-Run Effects of Green Patent Filings on Economic Growth by Sub-subcategories

	Real Output per capita Growth				Employment per capita Growth			
	Total	Agriculture	Industry	Services	Total	Agriculture	Industry	Services
Panel A. Sub-subcategories of Green Patent Filings on Emission Reduction and Energy Generation (Y02E)								
Green Patent Filings on Energy Storage	0.0372*	0.034	0.0917**	0.0837***	-0.033	0.002	0.030	0.016
	(0.079)	(0.273)	(0.016)	(0.001)	(0.505)	(0.894)	(0.507)	(0.319)
Green Patent Filings on Solar PV	0.025	-0.0805**	0.052	0.0649**	0.005	-0.0495**	0.013	0.016
	(0.139)	(0.013)	(0.212)	(0.013)	(0.740)	(0.032)	(0.608)	(0.300)
Panel B. Sub-subcategories of Green Patent Filings on Transport (Y02T)								
Green Patent Filings on Internal Combustion Engines	0.019	-0.028	0.018	0.031	0.008	-0.006	0.018	0.003
	(0.342)	(0.375)	(0.581)	(0.106)	(0.541)	(0.775)	(0.497)	(0.865)
Green Patent Filings on Hybrid and Electric Vehicles	0.026	0.011	0.059	0.0623***	0.0262**	0.015	0.0404*	0.019
	(0.156)	(0.734)	(0.117)	(0.006)	(0.047)	(0.420)	(0.088)	(0.227)

Notes: P-values are reported in the parentheses below the estimates. ***,**, * indicate significance at the 1, 5 and 10 percent levels respectively.

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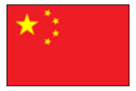
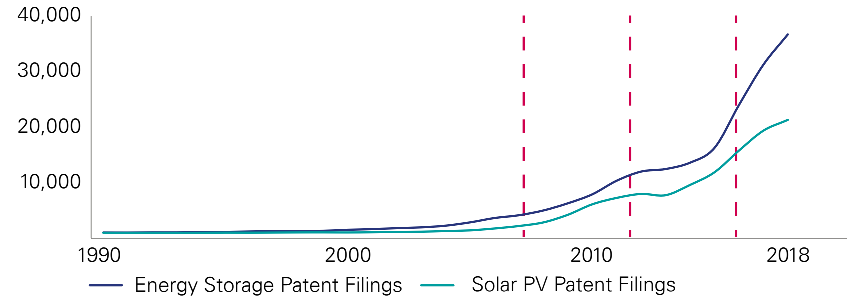
A4. National Narratives



A4.1 China: Energy Storage and Hybrid and Electric Vehicles

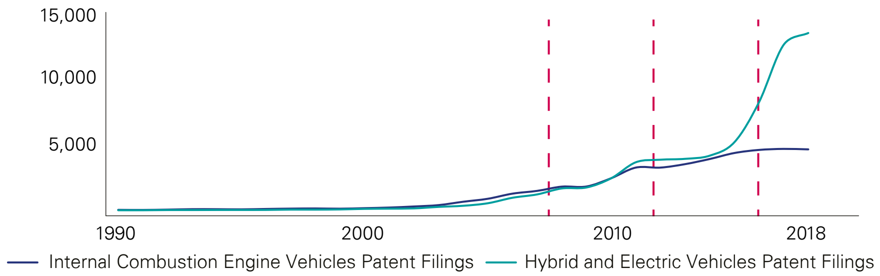
Deployment of solar cells is occurring in Western China, however, 94% of China's population lives in the east – creating large energy-transmissions problems.[21] China has an unusually low 'capacity factor' for solar at 20% (He & Kammen, 2016). The capacity factor indicates how much of the total capacity of an energy source is actually employed. Renewables in general have a low capacity factor due to dependence upon weather. However, China's need to transport electricity over long distances keeps the proportion of solar capacity use very low compared to other renewables and solar farms internationally. Therefore, we see that energy storage development has maintained pace with solar PV to make solar PV (and other renewable energy resources) both commercially viable and implementable in China's power grid network. With China's aggressive renewable energy growth necessitating aggressive energy-storage innovation, the fact that 68.3% of global energy storage patent applications are filed in China is understandable.

Figure 12 — Solar PV innovation tries to maintain pace with Energy Storage innovation in China



Source: PATSTAT 2021 and authors' calculations.

Figure 13 — Chinese ICE innovation plateaus, while HEV innovation experiences unprecedented growth



Source: PATSTAT 2021 and authors' calculations.

When Beijing announced a state of emergency in 2013 amid severe pollution, China's Environmental Ministry announced the national *Air Pollution Prevention Action Plan* as China's national strategy for improving air quality, particularly targeting $PM_{2.5}$ and PM_{10} particulates (Feng, et al., 2019) (The State Council of the People's Republic of China, 2013). The action plan limited the ICE vehicle population in China by encouraging green transport and accelerating the elimination of older vehicles (The State Council of the People's Republic of China, 2013). China's thirteenth Five-Year Plan reinforced this with a target to remove four million high-emissions vehicles from the road and encourage HEV uptake. By 2020, China's Ministry of Public Security recorded 4.92 million HEV on the road and the world's largest electric car market (IEA, 2021). China's HEV market is dominated by domestic manufacturers who make up 80% of China's HEV market share. China's HEV manufacturers are rapidly innovating and accounted for 57.3% of global HEV patent filings in 2018. Interestingly, we note that after 2014, HEV innovation experiences substantial growth, whereas ICE innovation plateaus in China. This likely reflects a redeployment by Chinese manufacturers, switching from ICE innovation to HEV innovation to capture the growing Chinese market, and succumbing to increasing government pressure for a low-emission vehicle fleet.

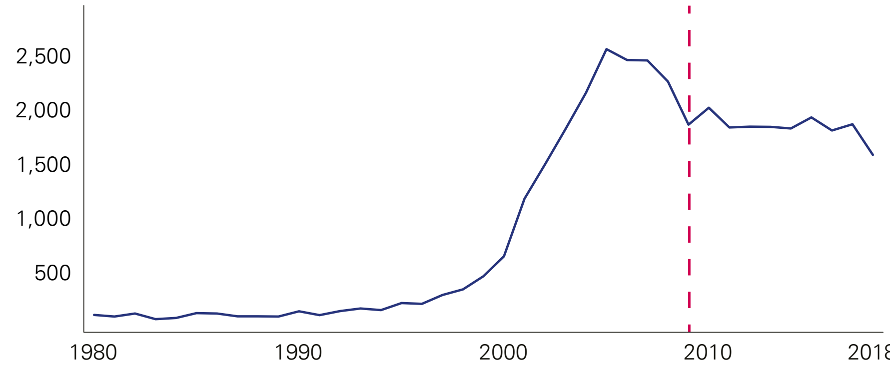
21. See https://www.bbc.com/future/article/20180822-why-china-is-transforming-the-worlds-solar-energy) for further information regarding China's giant solar PV farms.
22. See https://assets.kpmg/content/dam/kpmg/cn/pdf/en/2021/01/2020-china-leading-autotech-50.pdf for an in-depth analysis of China's HEV market.

A4.2 United States: Hydrogen Technology and Solar PV

In the US, the proportion of green patent filings attributed to hydrogen technology has experienced turbulent dynamics, increasing from 5.2% to 13.6% of green patents from 1985-2005, but declining to 5.1% by 2018. The dynamics of hydrogen technology innovation is closely linked to the expansion and subsequent cessation of hydrogen cell funding, reinforcing the reality that renewable energy tech requires significant and consistent government intervention while renewable energies remain in their infancy.

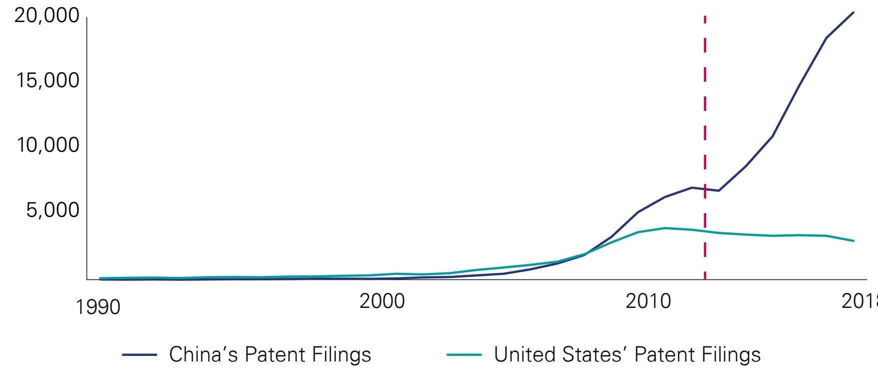
Hydrogen technology was kickstarted by the Hydrogen Future Act of 1996, enacted with the goal of "enabling the private sector to demonstrate the technical feasibility of using hydrogen for industrial, residential, transportation, and utility applications." The legislation offered US$50 million in research funding from 1997-1999. It was a first-step for US intervention in the hydrogen technology market, with then-President George W. Bush later announcing US$1.2 billion in research funding for hydrogen technology in 2003 via the Hydrogen Fuel Initiative. Hydrogen technology patent filings quadrupled by 2007 as a result.

Figure 14 — Hydrogen technology loses power as funding is dramatically cut



Source: PATSTAT 2021 and authors' calculations.

Figure 15 — Once a global leader in Solar PV, the US now has less than a fifth of China's annual Solar PV patent filings



Source: PATSTAT 2021 and authors' calculations.

Hydrogen technology declined following the great financial crisis. But while other renewables bounced back following government stimulus spending, hydrogen technology innovation plateaued. In 2009, the US reduced hydrogen cell research funding and redirected investment into renewable energies and energy storage, seeking better and earlier returns. In 2011, the US reduced hydrogen technology funding by more than 41%. We note how the sustained growth of hydrogen technology innovation – and its subsequent stagnation – are closely correlated with US government policy on hydrogen.

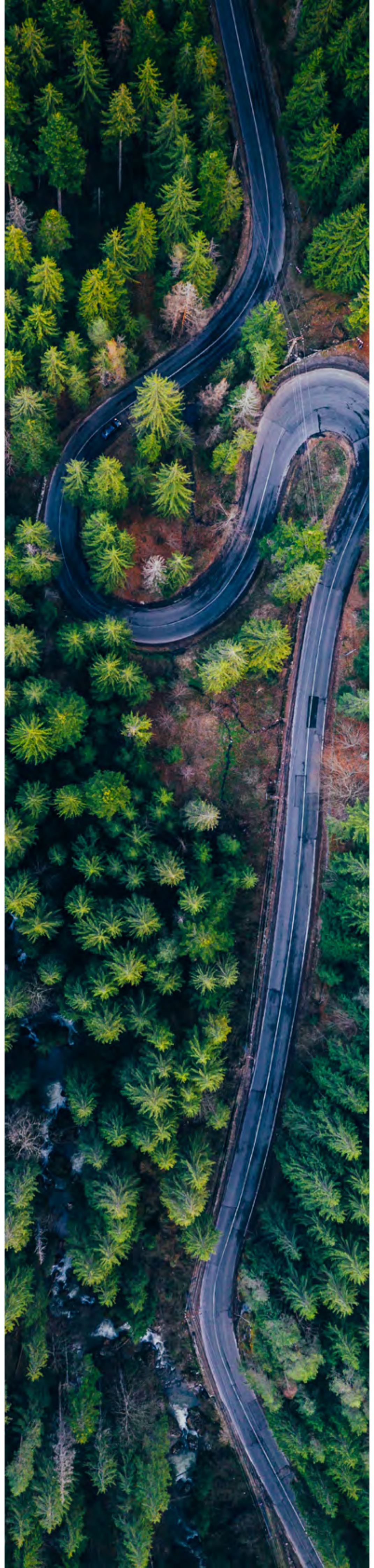
23. See https://www.technologyreview.com/2009/05/14/213138/q-a-steven-chu/ for a Q&A with Steven Chu regarding the Hydrogen power and technology.

In solar PV energy's infancy, the US was a global leader in 1978 with 40% of solar PV inventions. In terms of patent filing, the US has always had a much lower proportion of solar PV inventions due to most manufacturing occurring abroad. There have been many solar PV initiatives and incentives from the US government, including: the Department of Energy (DoE) introducing the Solar Energy Research Institute in 1977; the Solar America Initiative in 2008, investing US$17.6 million in early-stage solar PV projects; and the SunShot Initiative, aiming to support domestic solar energy adoption by reducing the cost of solar power by 75% from 2010-2020.[24]

However, given solar PV's global landscape, the US initiatives struggled to compete with China's aggressive solar PV policies. In 2012, the US Department of Commerce declared China to be dumping solar PV panels onto the global market at below cost. Studies suggested that China's government subsidies helped drive down the price of solar PV by 80% from 2007-12.[25] When the US Department of Commerce made this announcement, China did not possess an inherent cost advantage over the US, with the National Renewable Energy Laboratory (NREL) concluding that Chinese producers only had a 1% cost advantage relative to the US.[26]

Even with retaliatory measures such as subsidies and tariffs, China's dumping of solar PV incited a vicious cycle in US solar PV innovation. Existing solar firms such as Solyndra were driven out of business. US solar innovation declined, while China's flourished as Chinese firms grew their international market share. US solar PV became even less competitive and the cycle persisted. Consequently, the US has struggled to maintain its place in global solar PV production, falling from 22% to 1% of global solar PV supply, while China now has 75% of global solar PV production.

24. See https://www.nrel.gov/docs/fy07osti/40936.pdf for insight into the Solar America Initiative.
25. See https://www.theguardian.com/world/2012/may/17/us-tariffs-chinese-solar-panels for insight into retaliatory tariffs placed by the US Department of Commerce on Solar PV cells.
26. See https://renewablesnow.com/news/nrel-analysis-exposes-illegal-subsidies-for-solar-manufacturers-in-china-179063/ for information regarding China's solar PV manufacturing cost advantage in 2012.

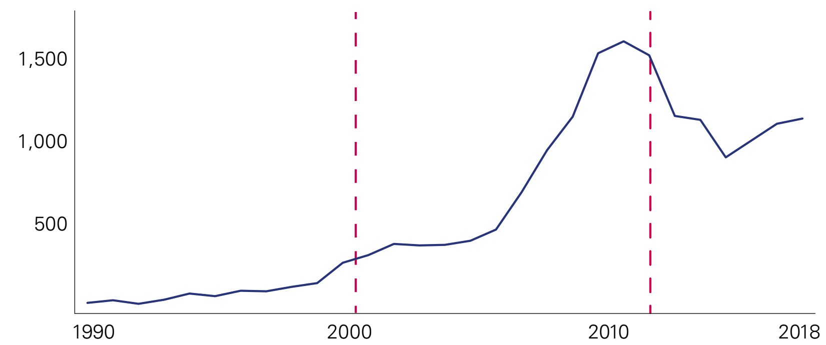


A4.3 Germany: Wind and Nuclear Energy

German wind-energy research gained political momentum in the 1980s as the German government pursued support for wind-energy deployment. However the government failed to provide an adequate commercial framework, leading to the project being abandoned (Cherp, et al., 2017). In 1991, this changed as the Electricity Feed in Tariff Act was announced, ensuring grid access for renewable energy sources by legally obliging grid companies to connect all renewable power plants. This sparked wind energy's rapid uptake, with wind initiatives accounting for 1% of energy generation in 1999 and providing commercial grounds for increased innovation. Firms such as Siemens entered the wind-turbine industry to become the second-largest producer in the world (Cherp, et al., 2017).

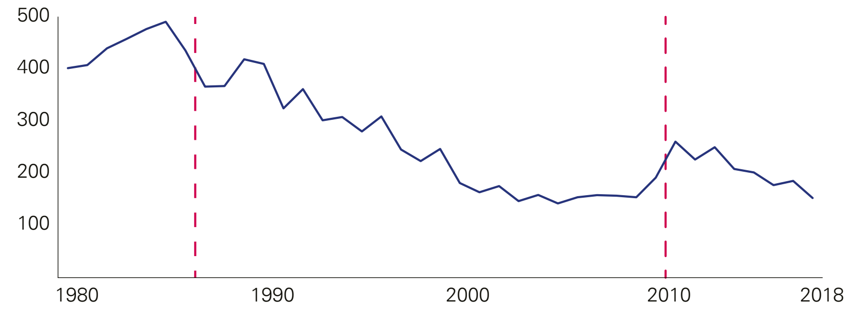
The Renewable Energy Act of 2000 established a guaranteed 20-year FiT for renewables, reinforcing the commercial viability of wind energy in Germany and resulting in wind-energy patent filings growing fivefold from 2000-2010. However, while government intervention and support is a powerful engine for green innovation growth, its premature removal can put any virtuous cycle on hold.

Figure 16 — German wind energy's substantial patent filings growth since the millennium is accompanied by generous FiT rates



Source: PATSTAT 2021 and authors' calculations.

Figure 17 — Nuclear energy innovation declines as Energiewende in Germany grows



Source: PATSTAT 2021 and authors' calculations.

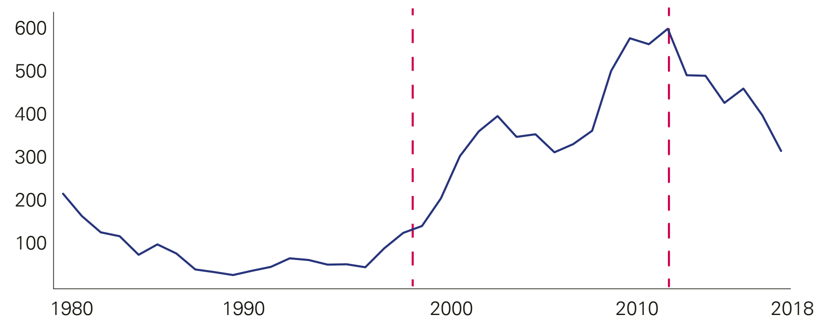
In 2012, the German government announced digression, whereby preferential FiT rates were gradually reduced as wind energy became more cost competitive (Fulton & Capalino, 2012). This coincided with Germany's decline in wind-energy innovation, suggesting reduced innovation in response to reduced commercial viability. Paired with political turbulence among various local authorities – making construction permits for wind farms arduous and uncertain (Cherp, et al., 2017) – renewable innovation's sensitivity to the political climate and investment activity is clear.

Nuclear energy experienced extremely quick abolishment in Germany in 2011, after a drawn out roll back since 1989 (The Economist, 2015). Following the Chernobyl disaster in 1986, Germany had rolled back nuclear deployment, its last nuclear power station being built in 1989, and nuclear energy innovation declined until 2010. In 2010, plans were announced to extend the lifespan of all 17 nuclear power plants in Germany, prompting a renewal of innovation in Germany's nuclear energy sector – but renewed innovation was quickly dampened in 2011 following the Fukushima disaster. Germany swiftly announced a rapid phase out of nuclear energy by 2022. We note a rapid reduction in Germany's nuclear innovation, in particular as Siemens announced in 2011 they would no longer produce nuclear energy systems.

A4.4 Japan: Wind Energy

Japan did not provide support for wind-energy deployment throughout the 1970s and 1980s (Cherp, et al., 2017). This changed in 1998, when Japan enacted an aggressive capital-subsidy scheme (Mizuno, 2014) that partially covered capital costs for both the private and non-profit sectors. The scheme remained in place until 2012, when it was rolled back, coinciding with a revamped FiT scheme. However, the FiT benefits were offset by the removal of the capital subsidies. In anticipation, wind-energy installation fell 20% between 2010 and 2011 (Mizuno, 2014). Since 2010, there has been a gradual decline in wind energy patent filings. Japan's Wind Power Association suggests that declining innovation is due to Japan having low economies of scale and poor social acceptance of wind turbines, resulting in bureaucratic bottlenecks (Mizuno, 2014).

Figure 18 — Japan's wind energy patent filings tripled under its aggressive capital subsidy scheme



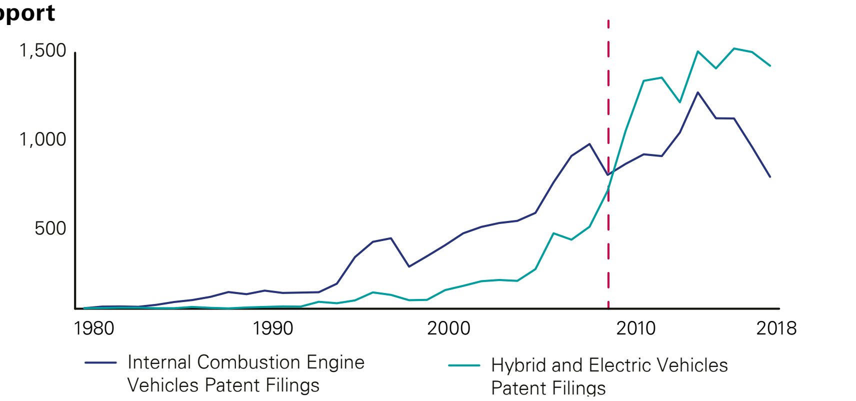
Source: PATSTAT 2021 and authors' calculations.

A4.5 South Korea: Hybrid and Electric Vehicles

Korea's government has taken a forward-looking stance on HEV technology, supporting HEV development since 1992 when the sector was in its infancy (APEC, 2017). The government placed a keen focus on the commercialisation of electric vehicles with policies such as 2009's Entering the Four Great Green Car Powers by 2013, and the Green Car Roadmap in 2010. The Green Car Roadmap reinforced the government's expansionary HEV stance, outlining that by 2015, 21% of domestic vehicles sales would be HEVs, with the government investing the equivalent of US$2.9 billion into the domestic auto industry to help achieve objectives.[27] With private-sector participants like Hyundai Motor taking part, the scope of the government's intervention was well placed both publicly and privately.

Patent filings in the HEV sector in Korea overtook that of ICE, representing a substitution in innovation towards HEVs. HEV market growth fell short of the Green Car Roadmap objectives (Hwang, 2015), but with the Ministry of Environment offering substantial purchase subsidies, EV sales from 2017-2018 alone doubled, kickstarting the virtuous cycle of making HEV innovation commercially viable (Hardman, et al., 2017), and resulting in persistent domestic growth. Korea's Ministry of Trade, Industry and Energy recently announced that Green Car sales constituted 24.7% of total domestic car sales in 2021.[28]

Figure 19 — ICE innovation runs out of fuel as HEV innovation gains political support



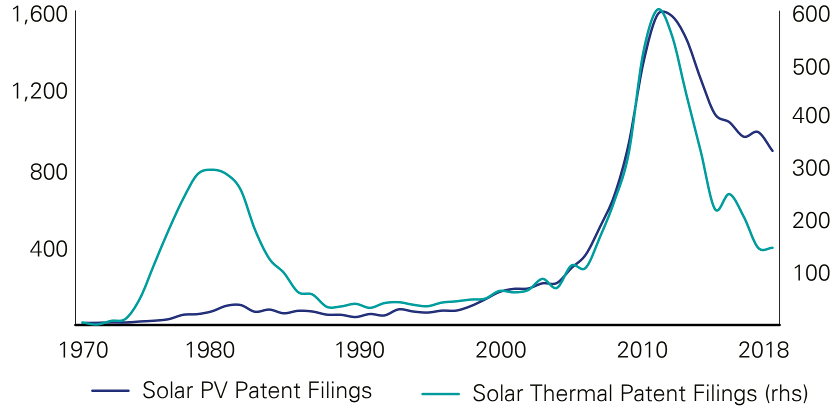
Source: PATSTAT 2021 and authors' calculations.

27. See https://www.iea.org/policies/3007-green-car-roadmap for further information regarding Korea's Green Car Roadmap.
28. See https://english.motie.go.kr/en/tp/alltopics/bbs/bbsView.do?bbs_seq_n=872&bbs_cd_n=2&view_type_v=TOPIC&&currentPage=1&search_key_n=&search_val_v=&cate_n= for the latest information regarding the Korean HEV market.

A4.6 France: Solar Thermal and PV

In 1979, France's state-owned enterprise EDF commissioned Project THEMIS. Project THEMIS was a solar power tower that was operational between 1983 and 1986 and likely the primary driver for solar thermal innovation in France in the 1980s. Following the project, solar-thermal innovation quickly declined. In 2009, solar PV uptake in France picked up as the government offered attractive FiT rates that outpaced Germany's, and solar PV capacity soared tenfold from 2009-11. In 2014, France began to freeze solar PV subsidies, causing large political uncertainty and making commercial deployment of solar cells less reliable. As Solar Power Europe (formerly EPIA) notes, solar PV uptake is heavily reliant on policy and political uncertainty dampens future growth (European Photovoltaic Industry Association, 2014). With consumers perceiving solar PV to be more profitable than solar thermal,[29] we note that following the FiT reduction, solar-thermal innovation faced a much more significant relative decline.

Figure 20 — Solar innovation wilts as FiT rates digress



Source: PATSTAT 2021 and authors' calculations.

29. See https://www.renewableenergymagazine.com/thermal/solar-thermal-output-driven-by-csp-in for insight into French public perception of solar thermal energy.

A5. Technology Improvements in Energy Storage and Electric Vehicles

Energy-storage innovation is crucial for the penetration of renewable energy into grid power systems (Divya & Østergaard, 2009). The integration of any energy resource into the grid power system requires consistency in terms of power quality and power reliability. Historically, fossil fuel energy sources have exhibited both quality and reliability. However, with most renewables dependent upon weather, sophisticated energy-storage solutions are required to make renewable energy sources competitive (Ziegler, et al., 2019).

Innovation in energy storage takes the form of improved battery densities, more robust battery technologies and improved manufacturing techniques. With the incredible pace of energy storage innovation, it is unsurprising that, over the last three decades, global battery prices have plummeted 97%.[30] Projects such as the Huanghe Hydropower Hainan Storage,[31] for example, are only feasible amid the significant global strides exhibited in energy storage innovation. Future leaps in renewable-energy innovation will require greater integration of renewable-energy sources with robust energy-storage solutions (Solar Power Europe, 2021), while continually reducing energy-storage costs (Ziegler, et al., 2019).

With road transport constituting 11.9% of global GHG emissions, a concerted effort for innovation in both passenger and commercial transport is a crucial step for a decarbonised society (Ritchie & Roser, 2020). Integrating hybrid and electric vehicles (HEVs) into the public and commercial landscape faces two key hurdles. HEVs face a significant cost disadvantage and they suffer from limited driving range – both of which can be alleviated with technical innovation and government intervention (APEC, 2017). Innovation in HEVs has seen a large increase in Y02T innovation following the 2008 financial crisis, with HEV patent filings constituting 8% of green patents.

The fast pace of innovation has directly translated into HEV improvements in cost and range and this has made the market penetration of HEVs more feasible. In terms of cost, we note that in 2020, the total annualised cost of EV ownership was lower than ICE equivalents by 2% to 13%.[32] Moreover, in terms of range, the average range of electric vehicles has increased by 60% over the last five years.[33]

In 2017, the British government, among other governments, announced the banning of ICE vehicle sales by 2030. The future of HEV innovation is driven by further improving pricing and range, with strides being required by the government to consolidate and coordinate electric vehicle charging infrastructure.

30. For more on this, see: https://ourworldindata.org/battery-price-decline.
31. Huanghe Hydropower Hainan Storage is the world's largest solar power plant. It is a 2.2GW solar plan connected to a 202.8MW battery.
32. For more on this, see: https://www.irena.org/costs/Charts/Electric-vehicles.
33. For more on this, see: https://www.iea.org/reports/global-ev-outlook-2021/trends-and-developments-in-electric-vehicle-markets.

A6. Application Authority Table

Application Authorities

African Intellectual Property Organization
African Regional Industrial Property Organization
Albania
Algeria
Argentina
Australia†
Austria†
Belgium†
Bosnia and Herzegovina
Brazil†
Bulgaria
Canada†
Chile†
China†
Chinese Taipei
Colombia†
Costa Rica†
Croatia
Cuba
Cyprus
Czech Republic†
Czechoslovakia
Denmark†
Ecuador
Egypt
El Salvador
Estonia†
Eurasian Patent Organisation
European Patent Office*
Finland†
France†
Georgia
Germany†
Gulf Cooperation Council
Greece†
Guatemala
Hong Kong (China)
Hungary†
Iceland†
India†
Indonesia
Ireland†
Israel†
Italy†
Japan†
Kenya
Latvia†
Liechtenstein
Lithuania†
Luxembourg†
Malawi
Malaysia
Malta
Mexico†
Monaco
Mongolia
Morocco
Netherlands†
New Caledonia
New Zealand†
Nicaragua
Norway†
Panama
Peru
Philippines
Poland†
Portugal†
Republic of Korea†
Republic of Moldova
Republic of North Macedonia
Romania
Russian Federation†
Singapore
Slovakia†
Slovenia†
South Africa†
Spain†
Sweden†
Switzerland†
Tajikistan
Trinidad and Tobago
Turkey†
Ukraine
Union of Soviet Socialist Republics (USSR)*
United Kingdom†
United States of America†
Uruguay
Vietnam
World Intellectual Property Organization (WIPO)
Yugoslavia (Serbia and Montenegro)
Yugoslavia (Serbia and Montenegro)
Zambia
Zimbabwe

† OECD & BRICS considered in analysis. * These application authorities were apportioned into their constituent member states a la Haščič, et al. (2015).

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