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Corrigendum

An early version of this report from March 2023 was revised:

Page 20: changed Figure 12 (data updated for 2021 based on latest IEA Energy Technology RD&D Budgets database)

Page 21, second paragraph: text updated to reflect the latest update of OECD’s Effective Carbon Rates. Reference changed from OECD (2021) (“Effective Carbon Rates 2021: Pricing Carbon Emissions through Taxes and Emissions Trading”) to OECD (2022) (“Pricing Greenhouse Gas Emissions: Turning Climate Targets into Climate Action”)

Page 22, figures 14 and 15: updated to reflect the latest update of OECD’s Effective Carbon Rates.

Page 22, first paragraph: text updated to reflect the latest update of OECD’s Effective Carbon Rates.

Driving low-carbon innovations for climate neutrality

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The transition to climate neutrality requires cost reductions in existing clean technologies to enable rapid deployment on a large scale, as well as the development of emerging technologies such as green hydrogen. This policy paper argues that science, technology, innovation, and industrial (STI&I) policies focusing on developing and deploying low-carbon technologies are crucial to achieving carbon neutrality. It notes however that the current level of innovation is insufficient to meet the net-zero challenge due to a policy emphasis on deployment rather than research and development (R&D) support. The paper explores the rationale for more ambitious STI&I policies targeted at R&D for climate neutrality and provides policy recommendations for an effective innovation policy for net-zero, including its interaction with the broader climate policy package.

Keywords: climate change mitigation, low-carbon innovation, technological change, innovation policy, climate policy

JEL codes: O38, Q54, Q55, Q58

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Executive Summary

Countries representing more than 80% of world GDP have announced targets of climate neutrality by mid-century. Recent IEA analysis shows that these **climate targets cannot be achieved by only deploying existing technologies**, e.g. renewable energy. Almost half of the reductions in 2050 will have to come from technologies that are currently only at the demonstration or prototype phase, e.g. green hydrogen or low-carbon steel. Moreover, there is room for further innovation even in technologies that are considered mature, e.g. geothermal energy or concentrated solar power.

Despite the urgent need for low-carbon innovation, **the current pace of innovation is insufficient to meet carbon neutrality goals**. Climate-related innovation as measured by patent filings has decreased as a share of all patenting over the past decade, and the global share of Venture Capital funding going to climate-related start-ups has remained stable despite the urgent need for innovation. On the other hand, trademark filings for climate-related goods and services have grown, pointing to an emphasis on deployment of existing technologies rather than on R&D. The slowdown in low-carbon innovation coincides with a lack of concrete climate policy measures across OECD countries, including a stagnation in public spending for low-carbon R&D relative to GDP. The limited take-up of carbon pricing also contributes to the lack of policy incentives.

Given the significant reallocations implied by the low-carbon transition (between activities, sectors, firms, workers, and technologies), the focus of climate policy is gradually shifting to transition costs, and to how to mitigate them. **Driving innovation to reduce these costs and make carbon-free technologies competitive with their high-carbon alternatives should therefore be a primary objective of climate policy**. This would also help accelerate the diffusion of available technologies, which is critical to reach medium-term carbon emissions reductions.

This paper argues that innovation and industrial policies – with a focus on both the development and deployment of low-carbon technologies – should constitute a cornerstone of strategies to reach carbon neutrality. Given the large range of barriers and market failures discouraging low-carbon innovation, the economics justifications for these policies are sound and well established. **Industrial policies, and innovation policies in particular, as well as science and technology policies, can also complement – and partially substitute – carbon prices**, which are often difficult to implement politically. In fact, STI&I policies are more popular among voters and citizens than other climate change policies (including carbon pricing, bans or regulations), making them an attractive option from a public acceptability point of view. In addition, by reducing technology costs for incumbent firms and boosting the growth of new carbon-efficient firms and sectors, such policies will facilitate the adoption of more ambitious climate policies, including – through international technology diffusion – in emerging economies, where the bulk of future emission growth is projected to take place.

A number of policies are key. First, **governments should consider re-balancing their Science, Technology, Innovation and Industrial (STI&I) policies**, giving greater emphasis to the different stages of RD&D, particularly for technologies that are not mature yet. Support for early-stage deployment of clean technologies is necessary because of the existence of barriers and market failures at this stage (e.g., learning spillovers, second-mover advantages) and should continue, but additional efforts should primarily focus on RD&D. An increase in public R&D expenditures targeted at technologies that are still far from market, but necessary to reach carbon neutrality by 2050, is urgent. As the increase might need the research system to adapt and so might be gradual, a larger forward leap can only happen if low carbon RD&D becomes a clear priority in governments' budgets. Such commitments should provide a long-term and stable perspective, like other climate policies. Post-COVID recovery programmes can help increase public R&D budgets, but such increases will need to be sustained in the long run, rather than be one-off increases.

Second, governments should continue to invest in scientific research, to help drive low carbon innovation and support climate policies more broadly. Science provides the evidence to inform governments and citizens about the potential impacts from climate change. Science also has an important advisory role to play and can help dispel misinformation that can erode public trust in science. It can also enable the public acceptance of low carbon technologies, and foster the participation of citizens in climate research,

Third, support to RD&D undertaken by business should primarily be direct, rather than horizontal. Climate neutrality will require innovation in breakthrough technologies, which cannot be incentivised through horizontal support (or deployment subsidies). R&D tax credits are unlikely to help for technologies that are far from market and require long development timelines. Technology neutrality – even between various low-carbon technologies – tends to favour technologies that are closest to market and with the shortest payback time and is therefore not neutral in practice.

Fourth, barriers to external funding should be reduced to help high-risk companies raise funds. Favourable tax schemes, low-interest or subsidised loans for young firms, and a greater mobilisation of government venture capital toward the green transition can help.

Fifth, strengthen collaboration in low-carbon innovation, both nationally and internationally. There is ample room for improvement in collaborative R&D, between firms, between firms and public research institutions and between countries, to capitalise on complementary skills and resources at the domestic and international levels. Strengthening international co-operation and technology transfer will be particularly important to accelerate the development and diffusion of low carbon technologies,

Sixth, embed low-carbon innovation policies in a broader package. Although innovation and industrial policies should play a greater role in carbon neutrality strategies, they are insufficient on their own and need to be part of broader packages of climate policies. Removal of fossil fuel subsidies and carbon pricing, in particular, are necessary to encourage the adoption of clean technologies that are closer to market and thus "redirect" innovation toward low-carbon activities. At the same time, by reducing the costs of low-carbon technologies, innovation policies can increase the responsiveness of emissions to carbon prices, especially if combined with regulations and standards.

Finally, **the low-carbon transition will involve a massive structural transformation that will require the alignment of policy frameworks beyond innovation, industrial and climate policies**. Competition and entrepreneurship policies play a critical role to encourage business dynamism, the creation of new innovative firms and the reallocation of resources toward the most resource-efficient firms. Education, skills and science policy are necessary to make sure that the transformation can rely on the right set of skills and research. An efficient and cost-effective shift to a low-carbon economy thus requires the engagement of many parts of government beyond those traditionally mobilised in the development of climate change policies. Developing such a package requires the **development of mission-oriented strategies** in countries committed to carbon neutrality.

1 Introduction

Countries representing more than 80% of the world GDP have announced targets of climate neutrality by mid-century. Reaching this objective requires rapidly adopting zero-carbon energy sources and production processes across all economic sectors, as well as reducing emissions unrelated to energy consumption, for example from the agriculture sector, which largely depends on major (but uncertain) technological advances. Some of the carbon-free technologies necessary to reach net zero emissions already exist, but their cost needs to be reduced so that they can become fully competitive with carbon-based alternatives and can be deployed rapidly and at scale (IPCC, 2022[1]). Other technologies are still in their infancy and need to be further developed. According to the International Energy Agency's Net-Zero Emissions by 2050 Scenario, half of the global reductions in energy-related CO_2 emissions through 2050 will have to come from technologies that are currently at the demonstration or prototype stage (IEA, 2021[2]).

In the context of more ambitious greenhouse gas emissions reduction targets, science, technology, innovation and industrial policies should form a critical part of the comprehensive set of policy instruments within national strategies needed to trigger the transition to a zero-carbon world. Current policy debates on climate change across OECD Member countries and beyond increasingly emphasise the role of technological change and the need to strengthen innovation efforts to achieve carbon neutrality. This is reflected in the widespread integration of low-carbon innovation support in green recovery packages adopted as countries seek to recover from the economic recession brought about by the COVID-19 pandemic, as well as in the passing of recent climate-related policy packages such as the U.S. Inflation Reduction Act and the European Union's REPowerEU Plan funded through the Recovery and Resilience Facility (of which 37% is allocated to the climate transition). Indeed, as the main source of modern economic growth, innovation can enable a zero-carbon future that goes hand in hand with new growth opportunities, e.g. in low-carbon activities, and strengthened efficiency in the use of all production factors.

Against this background, the objective of this paper is to take stock of the current level of climate-related innovation and public support thereof, to explore the rationale for integrating ambitious science, technology and innovation (STI) policies for climate neutrality into coherent industrial strategies, and to offer practical policy recommendations on what should constitute an effective low-carbon innovation policy, including interactions with broader climate policy packages.

The paper is organised as follows. Section 2 illustrates the massive, system-wide technological shift required by the scale of the climate neutrality objective. It then offers descriptive evidence – from public R&D expenditures, patent and trademarks filings, venture capital investment and climate policy stringency – suggesting that the scale of the current innovation response is not in line with the goal of net zero by 2050. Section 3 reviews the rationale and justifications for ambitious climate-related their Science, Technology, Innovation and Industrial (STI&I) policies. Section 4 provides a systematic examination of the key policies that governments can implement to support low-carbon innovation, organised along the various stages of technological development, from science to deployment and diffusion. Section 5 discusses the interaction of STI climate policies with broader climate policy packages and green industrial strategies. Section 6 summarises the paper's main policy recommendations.

2 The case for climate neutral innovation policies

Climate neutrality requires massive technological change

The net-zero target implies a radical technological and systemic shift, and innovation and diffusion are both key

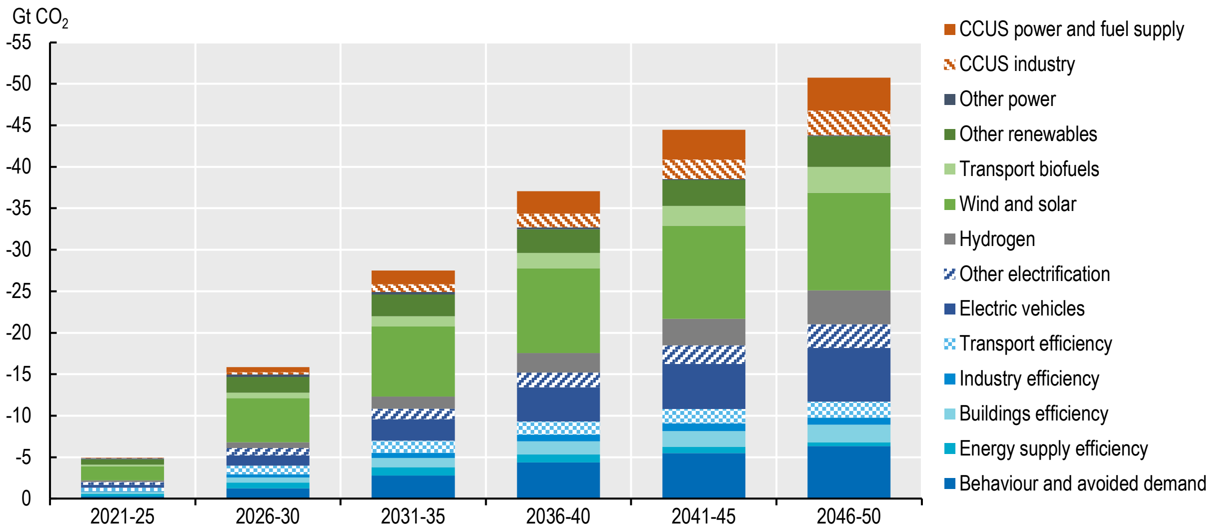
Global ambitions on climate change have risen dramatically during the Covid-19 crisis and in the run-up to the twenty-sixth session of the Conference of the Parties (COP26) of the UNFCCC in Glasgow in 2021, with countries representing more than 80% of the world GDP having announced targets of climate neutrality by mid-century.[1] Medium-term carbon emissions reductions targets have also been increased, with the European Union for example having adopted a 55% reduction target for 2030.

The climate neutrality objective requires a radical shift in the mix of technologies used for production and consumption across all sectors of the economy, and technological breakthroughs may be necessary in some sectors. Institutional and organisational changes, new services and business models, new ways of producing, consuming, living and moving are also needed to drive changes in production and consumption patterns, habits and behaviours.

In terms of energy-related technologies, the key pillars of climate neutrality include renewable energy deployment, increased energy efficiency in buildings and industry, electrification of the transportation and manufacturing sectors, carbon capture, utilisation and storage (CCUS), hydrogen and hydrogen-based fuels, and bioenergy use (Figure 1). Large-scale energy storage is critical for renewable deployment and electrification. Beyond energy, technological change is also needed to reduce emissions from global food systems (e.g. better cropping systems, fertilisation, and irrigation practices, advanced digital agriculture technologies, methane inhibitors for ruminant livestock), from waste generation and disposal, and to enhance carbon sinks in global ecosystems.

Figure 1. The net-zero economy requires system-wide technological change

Average annual CO2 reductions from 2020 in the IEA's Net Zero Emissions scenario, by source



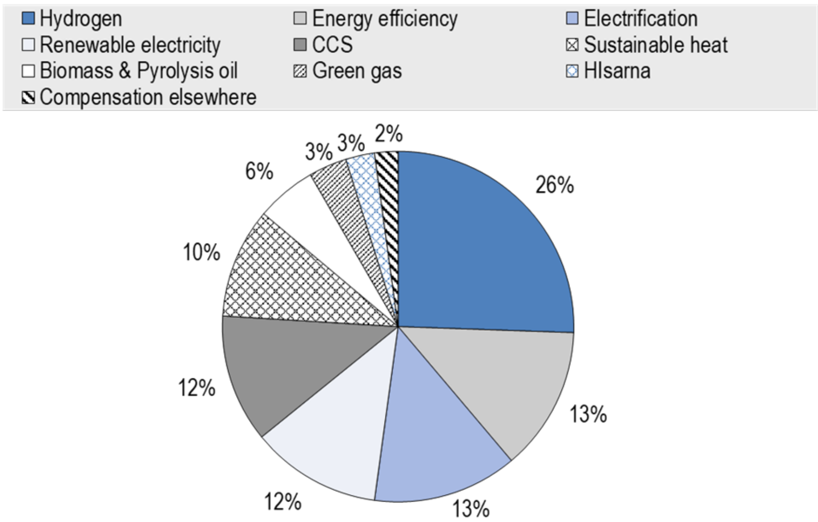
Note: Behaviour = change in energy service demand from user decisions, e.g. changing heating temperatures. Avoided demand = change in energy service demand from technology developments, e.g. digitalisation.
Source: (IEA, 2021[2]).

Achieving climate neutrality requires both the large-scale deployment of existing technologies, such as renewable energy, and the development and adoption of technologies that are far from mature today, such as green hydrogen. The "Net-Zero by 2050" IEA report (IEA, 2021[2]) makes it clear that the carbon neutrality objectives cannot be reached simply by deploying currently existing technologies at scale. While most of the global reductions in CO_2 emissions through 2030 in the net-zero scenario come from technologies readily available today, almost half the reductions in 2050 will have to come from technologies that are currently at the demonstration or prototype phase. In heavy industry and long-distance transport, the share of emissions reductions from technologies that are still under development today is even higher. Similarly, of the total emission mitigation potential achievable by the year 2030 calculated in the latest IPCC's Sixth Assessment Report (IPCC, 2022[1]), options with mitigation costs lower than USD 20/tCO_2 make up more than half of this potential. However, given currently available technologies, mitigation options beyond 2030 are still much more expensive.

A recent OECD report on the decarbonisation of the Dutch manufacturing industry illustrates this clearly (Figure 2). The 2050 zero-emission scenario for the Dutch industry combines a massive increase in renewable electricity generation, the adoption of technologies that are close to the market (e.g. CCUS, electrification of low temperature heat processes) but also the deployment of many technologies that are still far from maturity, notably bio-based products and green hydrogen (Anderson et al., 2021[3]).

Figure 2. Decarbonising manufacturing requires existing technologies and breakthroughs

Contribution of different technologies in Scope 1 and 2 emission reduction between 2015 and 2050 in Dutch manufacturing



Note: The scenario covers four manufacturing sectors: chemical sector, metallurgy, refineries and food-processing. The contribution of "Renewable electricity" corresponds to the abatement of the 2015 scope 2 emissions, which would be overturned by completely shifting to renewable electricity sources by 2050. The contribution of "Electrification" corresponds to additional electricity needed to reach the carbon neutrality objective in 2050, assuming that this additional electricity is also renewable and carbon-neutral.
Source: (Anderson et al., 2021[3]); (OECD, 2021[4]).

The potential of green hydrogen for decarbonisation has been the subject of particular policy focus recently and may serve as an example of the need for further innovation. Production of hydrogen from water and renewable electricity through electrolysis (green hydrogen) can contribute to reducing emissions through four channels. First, hydrogen is already a feedstock for a number of chemical products and green hydrogen can make this production carbon-neutral. Second, hydrogen is a promising alternative to fossil fuels for high-temperature industrial processes in hard-to-abate sectors such as steel production. Third, hydrogen is necessary for the development of fuel-cell long-haul freight transport and can also, in specific circumstances, reduce emissions in the built environment by partly replacing natural gas. Finally, hydrogen can be used to store energy produced from intermittent sources, thereby supporting the supply of low-cost renewable electricity (Cammeraat, Dechezleprêtre and Lalanne, 2022[5]).

Most net-zero emission scenarios agree that hydrogen could play a pivotal role in decarbonisation at the 2050 horizon, particularly for agriculture and industrial applications, provided cheap and abundant renewable energy becomes available. However, in 2021, the production of green hydrogen is still about 3 times more expensive than grey hydrogen (made out of natural gas through steam reforming), even under the most favourable conditions. Major cost reductions – and the rapid deployment that they would induce – are realistic in the next 10-20 years, but will crucially depend on massive improvements in the cost of electrolysers (through R&D and large-scale demonstration projects) and the availability of large volumes of cheap renewable electricity.

Biotechnology is another enabling technology that could make important contributions to help countries meet their climate objectives. In the context of climate change, biotechnology could offer contributions in three key critical areas:

- Sustainable energy and enhanced carbon sequestration. Advances in biotechnology have enabled biofuel producers to achieve substantial efficiency improvements in recent decades. This has been combined with a greater focus on the need for sustainable biomass feedstock. In addition, biotechnology advances are enabling the development of CCU technologies that use engineered microorganisms to capture GHG emissions without requiring biomass.

- Food and agriculture: new synthetic fertilisers, new crop varieties, methane inhibitors for ruminant animals, manure recycling technologies, plant-based and cell-based meat and other biotechnologies can all substantially mitigate GHG emissions, while also helping agricultural systems adjust to climate change (Wang et al., 2021[6]).
- Industry and manufactured products: Biobased products can both partially eliminate the need for fossil fuel extraction and serve as sinks for carbon that would otherwise be emitted to the atmosphere. In the chemicals sector carbon is irreplaceable as it is the basis for products such as plastics, synthetic rubber, synthetic lubricants, fertilisers and pharmaceuticals. While normal consumption of chemical products derived from fossil fuels do not generate direct CO2 emission, their production and disposal generate large direct and indirect quantities of CO2 (Levi and Cullen, 2018[7]).

Even within technologies that are considered mature, such as renewable energy, there is room for breakthrough innovations in, for example, geothermal or concentrated solar power (IEA, 2017[8]; IRENA, 2018[9]). Technological progress in enabling technologies, in particular energy storage, is also critical for the large-scale deployment of renewable energy, as it eases the demand of peak loads and increases flexibility. High-energy-density storage (i.e. where a lot of energy can be stored in small spaces) has important potential for the future, especially thermochemical storage (IEA, 2014[10]).

Climate neutrality requires innovation beyond low-carbon technologies

Alongside low-carbon and sector-specific technologies, climate neutrality will rest on innovation in other domains, in particular digital technologies and recycling.

The digital transformation could be a key enabler for reaching climate goals, thanks to technologies such as smart meters, sensors, artificial intelligence (AI), the Internet of Things (IoT) and blockchain, and to digitally-induced changes in business models and consumption. In the energy sector, demand-side management can help balance the renewable-based electricity system. For example, AI can help forecast weather and electricity prices, thus mitigating intermittency problems in the system and increasing energy efficiency. Transmission and distribution system operators could use AI for real-time decision support (OECD, 2020[11]; OECD, 2019[12]). Similarly, IoT[2] devices could help buildings adapt in real time to weather conditions and prices, thus increasing energy efficiency (OECD, 2016[13]). Smart mobility will change transport demand and efficiency: ‘smart’ traffic lights can adapt to traffic flows, reducing air pollution and increasing energy efficiency of transport. Blockchain[3] could help managing the distributed grid as it facilitates decentralised consumer-to-consumer selling of electricity and balancing supply with demand without needing a third party. Industrial sectors will be reshaped through increased robotisation, smart manufacturing systems, additive manufacturing, internet of things, smart appliances, sensors and artificial intelligence, which can all improve energy and material efficiency. Digital solutions are equally important on the supply side, for example by accelerating low-carbon innovation with simulations and deep learning. Already, around 20% of patents protecting climate change mitigation technologies have a digital component (Amoroso et al., 2021[14]). The increased use of digital solutions can also change production patterns and trade, and bring production back to some countries (“reshoring”) with better environmental performance. However, digital technologies consume large amounts of energy, implying higher direct energy demand and related carbon emissions, which warrant further efficiency improvements.

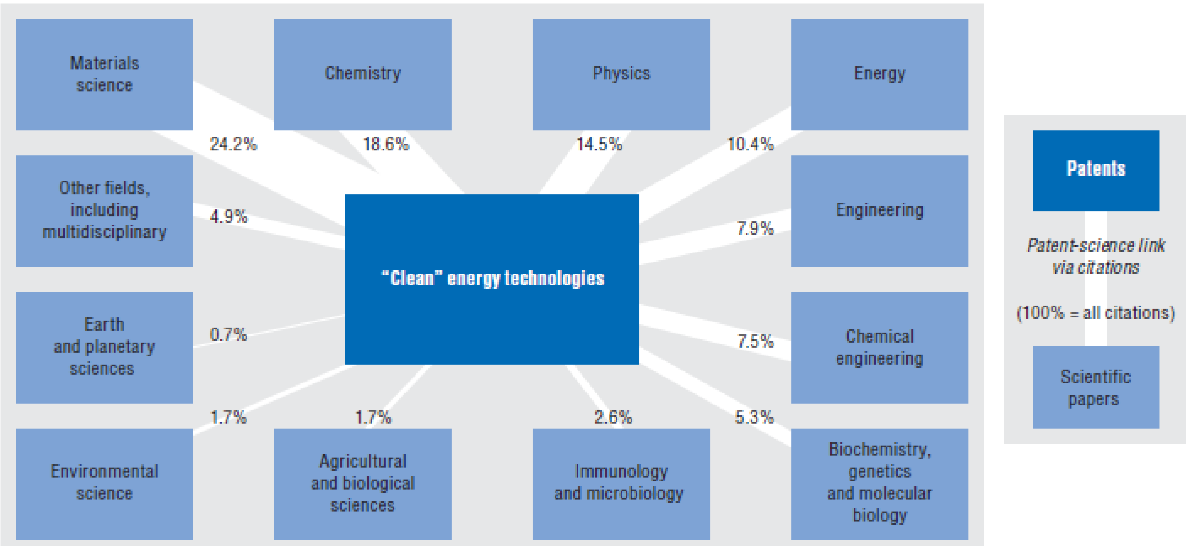
Improved recycling technologies can also contribute to decarbonisation by reducing the need of fossil-based feedstock in the chemical industry or of primary stell in the metal industry (de Sa and Korinek, 2021[15]). Mechanical or chemical recycling can transform existing products into new feedstock, thereby closing the materials chain. For plastics, the technological readiness level for mechanical recycling is high, but chemical recycling of plastics is still very much under development. For the recycling of major metals, the technological readiness level is high, but much more improvement is possible for the recycling of minor metals. In general, multiple options need further technological development and cost reductions to be deployed widely.

Scientific research in multiple areas underpins progress in low-carbon technology

Low-carbon innovation relies on a wide range of scientific fields, including areas at the interface of different disciplines. For example, earlier analyses of the link between patents and the underlying scientific literature based on the "non-patent literature" (NPL) referenced in patent documents have shown that innovations in clean energy technologies draw on a broad base of scientific knowledge (Figure 3). The single largest field is materials science, followed by chemistry, physics and energy. Many other fields (including engineering, biochemistry, microbiology, molecular biology…) make up for a significant share of publications cited. The diversity of scientific sources highlights the impossibility of identifying a single major scientific contributor to innovation in this area. Therefore, basic research across all scientific fields is necessary – alongside applied research – to spur advances in low carbon technologies.

Figure 3. The innovation-science link in clean energy technologies

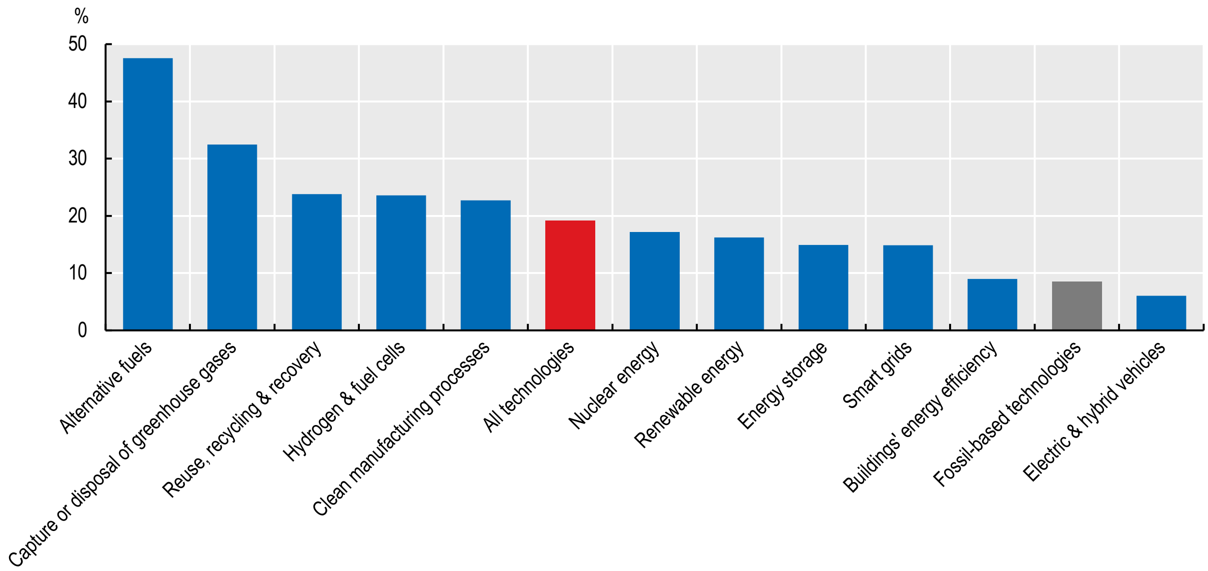
Share of scientific fields cited in non-patent literature referenced in clean energy patents filed 2000-2009



Note: OECD calculations, based on Scopus Custom Data, Elsevier, December 2010 and EPO, Worldwide Patent Statistical Database, April 2011.
Source: (OECD, 2011[16])

The importance of the role of science for innovation in low-carbon technologies is apparent from the proportion of patents referencing scientific literature, as shown in Figure 4. This is especially the case in technologies rooted in chemistry and biology, such as alternative fuels (biofuels and fuel from waste) and capture and disposal of greenhouse gases, as well as in breakthrough technologies such as hydrogen and fuel cells and recycling processes. In all these areas, the importance of scientific knowledge is greater than in the average patent filed across all technological fields (red bar). Interestingly, except for electric and hybrid vehicles, reliance on scientific knowledge is greater in all low-carbon technologies than in the high-carbon technologies they are replacing, a feature which could be associated with the greater novelty of these innovations compared to older, fossil-based innovations.

Figure 4. Share of patents applications in low-carbon technologies that cite scientific literature, 2015-2019



Note: Data refer to families of patents filed at the EPO and patent applications filed under the Patent Cooperation Treaty (PCT), by filing date. Citations to scientific literature include references to articles, chemical or biological abstracts made in patents. Classification of low-carbon technologies follows Cooperative Patent Classification "Y02" categories. "All technologies" cover all patents filed at EPO and PCT across all technology fields (not only low-carbon or high-carbon). Fossil-based technologies include petroleum, gas and coke industries (CPC/IPC classification group C10), steam engine plants (F01K), combustion engines (F02), steam generation (F22), combustion apparatus and processes (F23) and furnaces and kilns (F27).
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, October 2022.

The pace of low-carbon innovation is not in line with the climate neutrality challenge

Declining low-carbon innovation efforts; encouraging signs on the diffusion side

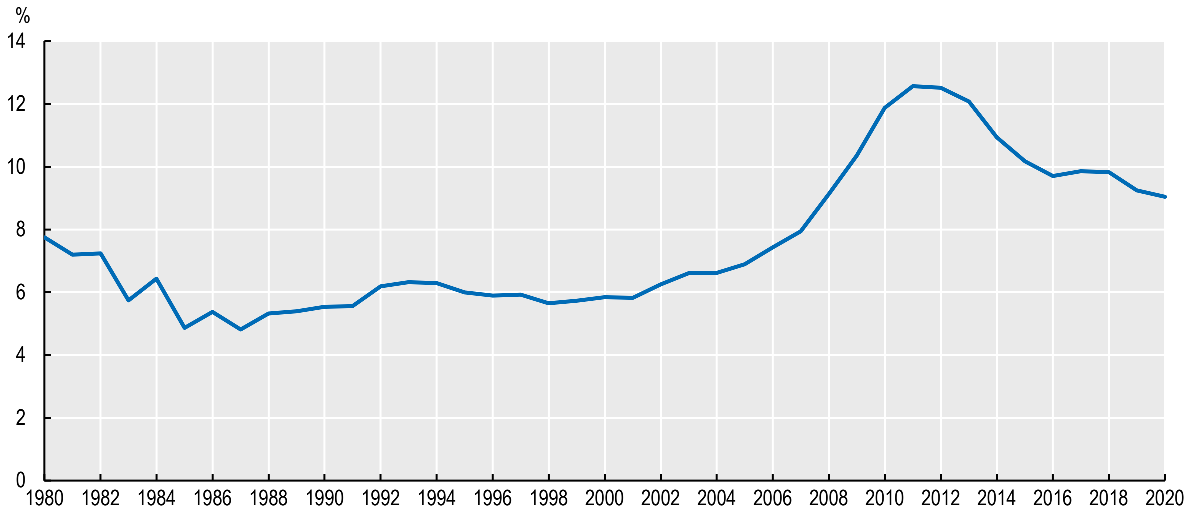
Global low-carbon patent filings

The pace and progress of climate-related innovation can be measured by looking at global patenting activity in this area. Figure 5 shows this activity between 1980 and 2020 (the last reliable year of data) for a range of climate-related technologies, including:

- Low-carbon electricity production, for example renewables, nuclear, biofuels, smart grids, energy storage and carbon capture and storage.
- Low-carbon transportation, for example fuel efficiency technologies, electric, hybrid and fuel cells vehicles, and lighter materials.
- Energy efficiency in the buildings sector, for example energy-efficient lighting and heating, and insulation.
- Energy efficiency in the manufacturing sector, for example energy-efficient industrial processes in the metal, chemicals, oil refining, mineral processing and agroalimentary industries, and material recycling.
- Waste management, for example solid waste collection, material recovery, recycling and re-use, fertilisers from waste, and energy recovery from waste incineration.

Because growth could reflect the general growth of patenting in all technologies (not just climate-related technologies), Figure 5 indicates climate-related inventions as a share of inventions in all technology areas. Following a period of strong growth between 2004 and 2011, innovation efforts in climate-related technologies have declined recently as a share of total patenting, from 12.6% of global patents in 2011 to 9.0% in 2020. Between 2005 and 2011, the number of new climate-related inventions patented globally grew at an average annual rate of 16.3%, while innovation in all technologies only grew at 6.2% per year on average. However, climate innovation efforts started to decline around 2012 despite the ambitious climate objectives and the signature of the 2015 Paris agreement. Since 2012, new climate-related inventions patented globally increased at an average rate of 0.3% per year (with over 5% decreases in 2014 and 2015) while overall innovation continued to grow at an average pace of 4.6% per year. Importantly, the decrease in low-carbon patenting affects nearly all technologies (see Figure A A.1 in Annex A): it affects renewable energy, alternative fuels, energy efficiency in buildings, energy efficiency in manufacturing processes, capture and disposal of greenhouse gases, electric and hybrid vehicles, nuclear energy, hydrogen and fuel cells, and smart grids alike. The only exception to this trend is energy storage (batteries).

Figure 5. Global low-carbon patenting efforts have declined recently



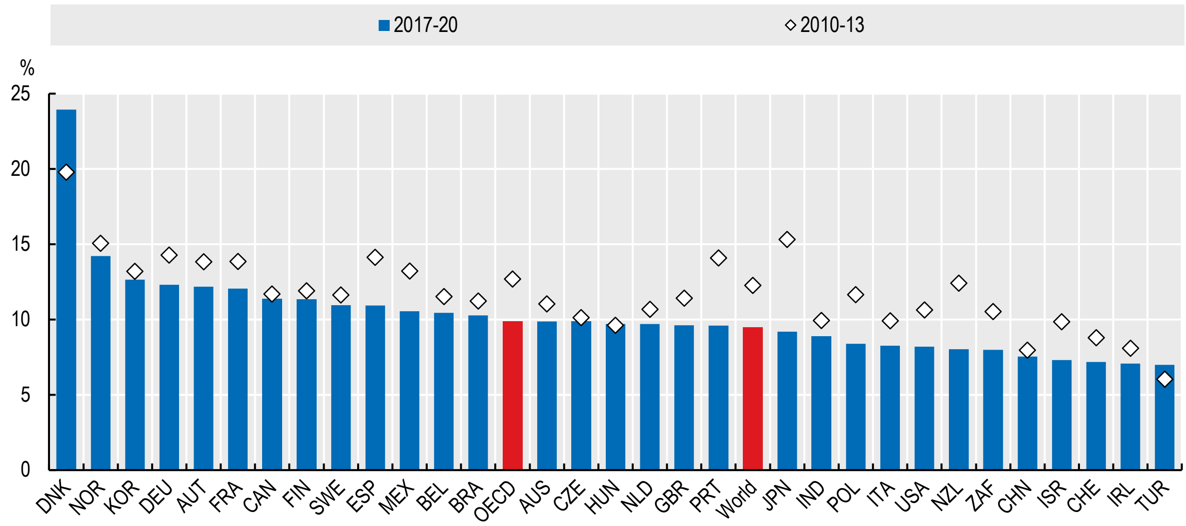
Note: Data refer to families of patent applications filed under the Patent Cooperation Treaty (PCT), by earliest filing date. Low-carbon patents are identified using the “Y02” classification code developed by the European Patent Office and applied to all patents filed globally. The categories included are climate change mitigation technologies related to buildings (Y02B), in information and communication technologies (Y02D), in the production or processing of goods (Y02P), in transportation (Y02T) and in wastewater treatment or waste management (Y02W); reduction of greenhouse gas emissions related to energy generation, transmission or distribution (Y02E); and capture, storage, sequestration or disposal of greenhouse gases (Y02C).
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, November 2022.

Country trends in low carbon patenting

The global decline in low-carbon patenting can be observed across nearly all major innovating countries around the world (Figure 6). Across OECD countries, between the peak period (2010-2013) and recent years (2017-2020), low-carbon patents have decreased from 12.7% of total innovation to 9.9%. The fall has been particularly severe in Japan (-6.1 percentage points), Portugal (-4.5 pp), New Zealand (-4.4 pp), Poland (-3.3 pp) and Spain (-3.2 pp). Only in Hungary (+0.1 pp), Türkiye (+0.9 pp) and Denmark (+4.2 pp) has this share increased, while innovation efforts towards low-carbon technologies have remained close to constant in Canada, the People's Republic of China (hereafter, 'China'), Czech Republic, Finland, Korea and Sweden.

Figure 6. Climate-related technologies in the patent portfolio of countries, 2010-13 and 2017-20

Share of climate related patents in total PCT patent applications



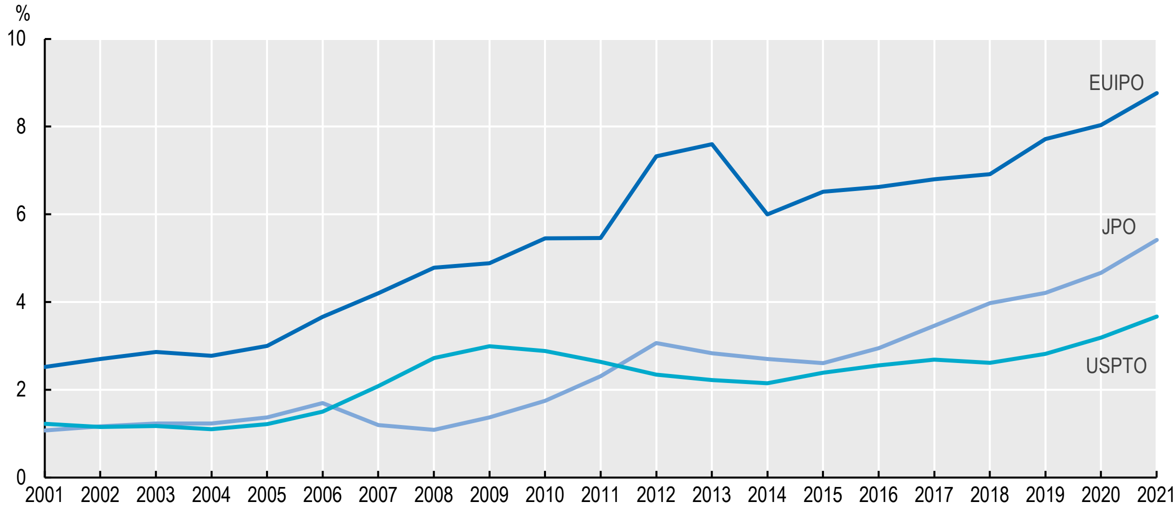
Note: Data refer to patent applications filed under the Patent Cooperation Treaty (PCT), by filing date, according to the inventor's residence using fractional counts. Only countries with more than 500 patents in the periods considered are included.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, November 2022.

Trademark filings in climate-related goods and services

While patent data are informative about the production of innovations, they do not indicate whether the technology protected by the patent is actually used by the owner. Data on trademark filings can usefully complement patent data by focusing on the commercialisation phase of innovations.[4]

Trademark application data from the European Union Intellectual Property Office (EU IPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO) show that the proportion of trademarks covering climate-related goods and services has grown markedly over the last two decades (Figure 7). As in Figure 5, the lines indicate climate-related trademarks *as a share of total trademarks filed*. The proportion has tripled in the United States and in Japan (from 1% to 3%) and has nearly quadrupled in Europe (from 2% to 8%). Like patents, a decrease was observed around 2012-2014, but the trend has picked up again in the most recent available years. This suggests that, while firms have reduced R&D efforts toward climate-related technologies, diffusion and commercialisation efforts have kept increasing.

Figure 7. Trademark filings in climate-related goods and services, 2001-2021



Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, February 2023.

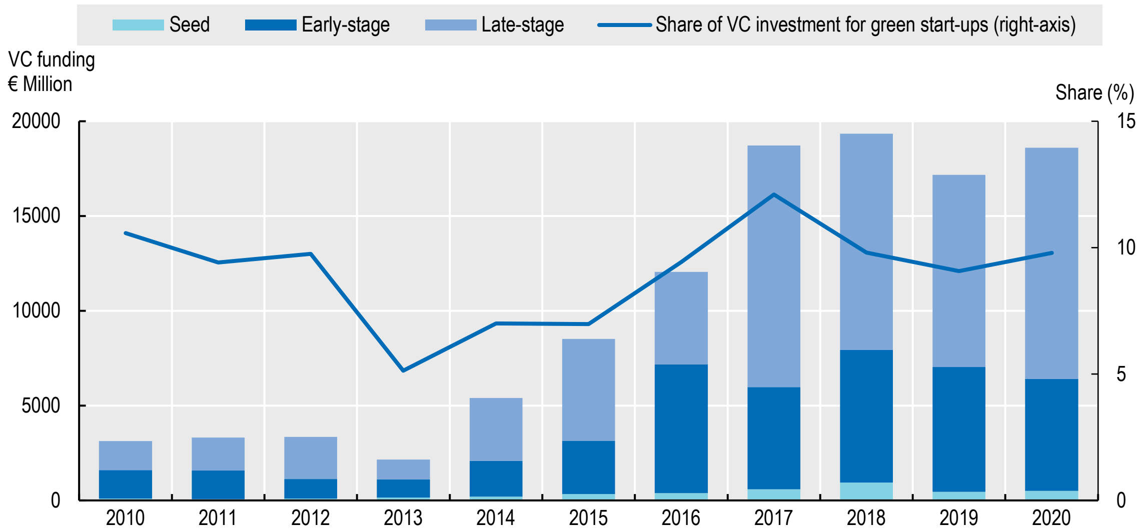
Venture capital funding for clean tech start-ups

Another way to look at innovation in climate-related technologies is to analyse investment in start-ups operating in the area. The shift towards a low-carbon economy requires radical new innovations on top of incremental improvements in existing technologies, and young firms tend to be major drivers of such radical innovation (Andrews, Criscuolo and Menon, 2014[17]; Calvino, Criscuolo and Menon, 2016[18]). A new database of clean-tech start-ups developed by the OECD shows that there has been a large increase in global venture capital (VC) investment in climate-related start-ups in the last decade, from USD 3.1 billion in 2010 to USD 18.6 billion in 2020.[5] However, after a peak in 2018, global VC investment in green start-ups has decreased in the last two years (Figure 8).

This growth in VC funding for start-ups in clean technology partly reflects the global growth in VC funding across all sectors of the economy. To account for this trend, Figure 8 also shows the share of global VC funding directed at climate-related start-ups (blue line). Between 2010 and 2020, the share of total VC funding going to climate-related start-ups has remained fairly stable (at 10% in both 2010 and 2020). After a peak at 12% in 2017, which followed four years of continued growth, this proportion has gone down to around 10% of total VC funding.

Importantly, data on green VC point to a focus of investors on the deployment of relatively mature technologies, as opposed to the development of more exploratory solutions. Indeed, the sharp increase in green VC observed since 2017 is to a large extent driven by large and late-stage funding rounds of more than USD 250 million, which account for more than 50% of total funding between 2016 and 2019. The share of VC directed at seed funding (representing very early-stage investment) amounts to only 3.5% of total VC for green start-ups across the 2010-2020 period, against 7.8% for non-green start-ups, and this finding is robust to measuring the difference in terms of the number of deals, rather than funding amounts. This suggests that green start-ups may be perceived as riskier than start-ups operating in other areas, inducing investors to get involved later in the technology development stage.

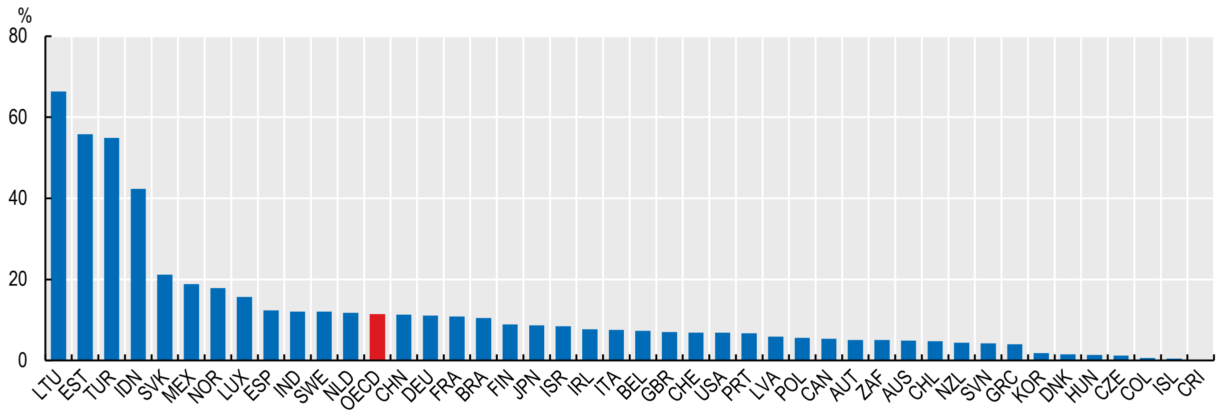
Figure 8. Global Venture Capital investment in green start-ups, 2010-2020



Note: Clean-tech start-ups are identified using information on their sector of operation (e.g. renewable energy) and on the textual description of their activity using natural language processing (NLP) methods, based on a climate change related vocabulary.
Source: Bioret, Dechezleprêtre and Sarapatkova, forthcoming.

There is considerable heterogeneity across economies, in the share of VC investment in green start-ups over total VC investment for the period 2016-2020, as shown in Figure 9. Smaller economies such as Lithuania and Estonia appear on top of this ranking with close to 70% of total VC investment going into green start-ups. In the two largest countries in terms of total VC investment, the United States and China, green start-ups received respectively 7% and 12% of total VC investment.

Figure 9. Share of Venture Capital funding flowing to green start-ups, 2010-2020, by country



Source: Bioret, Dechezleprêtre and Sarapatkova, forthcoming.

Concrete climate policy action is falling short of growing ambition

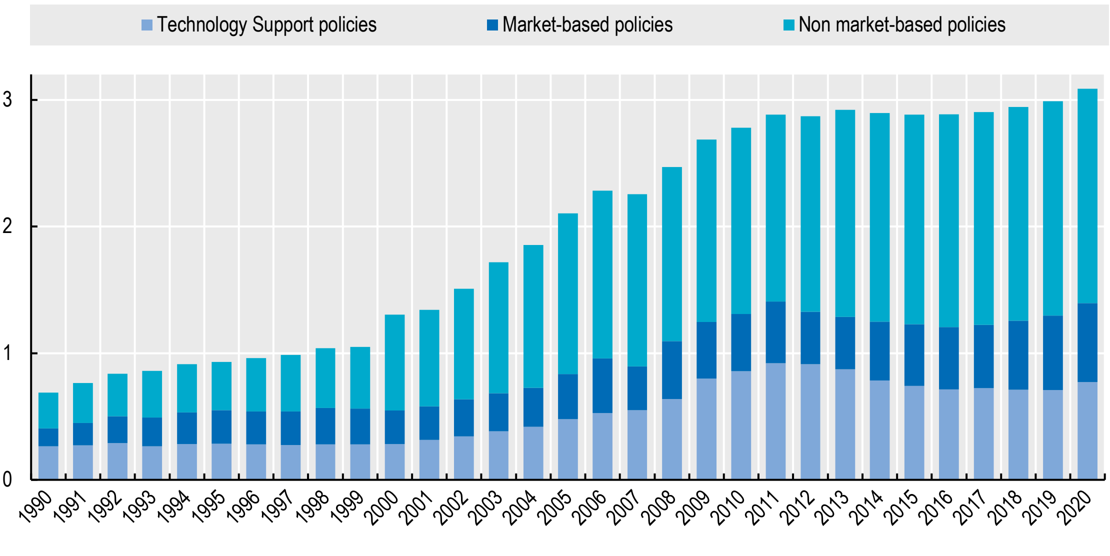
The apparent slowdown or stagnation in low-carbon innovation corresponds to a recent levelling- off of concrete climate policy measures across OECD countries, and particularly so for innovation-related policies (Kruse et al., 2022[19]). Figure 10 shows the evolution of the OECD's Environmental Policy

Stringency (EPS) indicator (which covers mostly climate-related policies) between 1990 and 2020 on average across OECD countries. After two decades of continuous growth characterised by the introduction of more stringent emissions standards, the creation of carbon markets and increased public support to low-carbon technologies, the stringency of climate policy has stabilised since 2011. This trend is explained by a reduction in the level of support for technology and innovation (-10%), which has happened in parallel with a small rise in the stringency of market-based instruments (e.g. carbon markets and carbon taxes) and another small increase in the stringency of non-market based regulations (e.g. emissions and performance standards).

The recent decrease in the level of technology support policies follows a strong increase from 2000 to 2011 and is driven by a drop in the level of the two main components of the technology support sub-indicator of the EPS index: public R&D expenditures for low-carbon technologies and subsidies for renewable energy adoption (via feed-in tariffs and auctions). The declining trend in technology support policies may be related to fiscal consolidation in the aftermath of the Global Financial Crisis when governments reduced fiscal expenditures, including public R&D spending and subsidies to renewable energy.

The timing of the decrease in the level of technology support policies strikingly corresponds to the slowdown in global low-carbon patenting activity shown in Figure 5. In principle, market-based and non-market based instruments could also support innovation, but the comparison of Figure 5 and Figure 10 suggests an important role for technology-support policies.

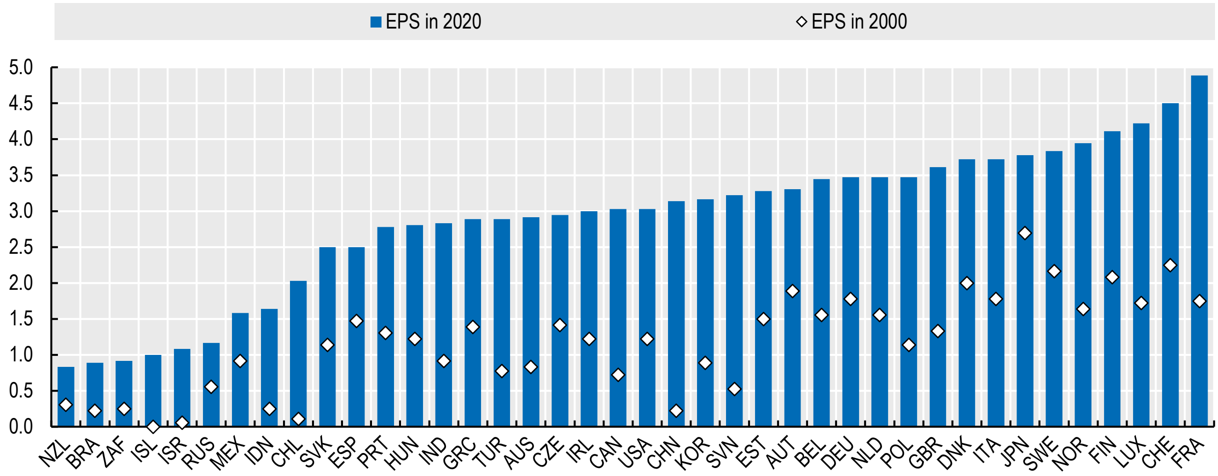
Figure 10. Average climate policy stringency across OECD countries, 1990-2020



Source: (Kruse et al., 2022[19]).

There is significant heterogeneity across countries in the stringency of climate policy. Figure 11 shows countries according to their EPS in 2020 (blue bars), together with their scores in 2000 (diamonds). All countries increased their environmental policy stringency between 2000 and 2020, albeit to significantly different extent. In 2020, the countries with the most stringent environmental policies (e.g. France, Switzerland, Luxembourg and Finland) have EPS scores four times greater than countries with the lowest indices.

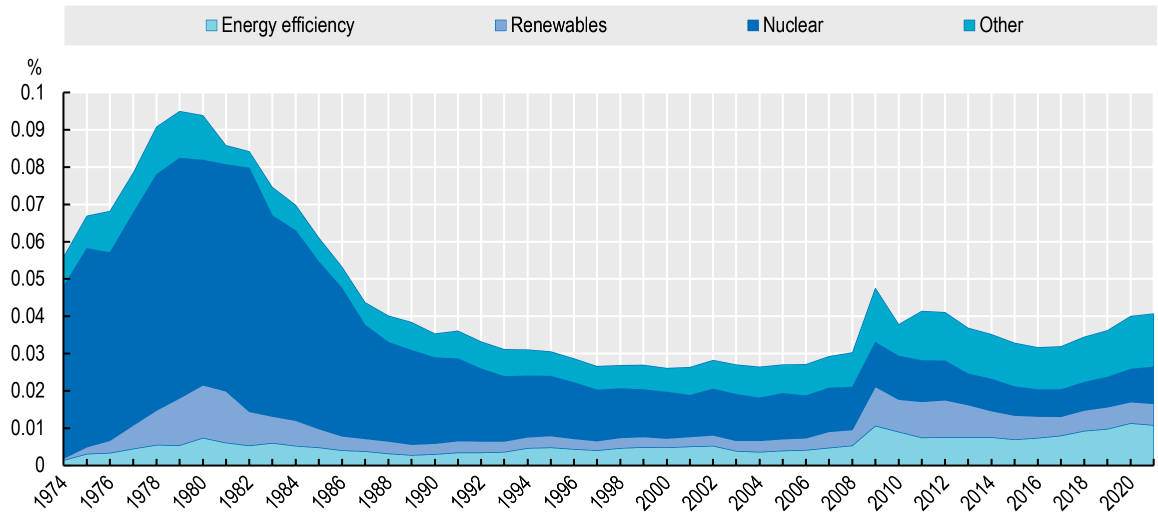
Figure 11. Climate policy stringency in 2020, by country



Source: (Kruse et al., 2022[19]).

Figure 12 zooms in on the main component of the EPS technology support indicator: public expenditures on research, development and demonstration for low-carbon technologies, as reported by the IEA Energy Technology RD&D database. These have remained broadly flat as a percentage of GDP over the last 30 years, at 0.04% of GDP, down from over 0.1% of GDP in 1980. This is despite pledges by the Mission Innovation partners – a global initiative of 22 countries and the European Commission – to double clean energy research and development funding between 2016 and 2021. However, between 2016 and 2020, the 22 Mission Innovation member states (which include emerging economies) increased RD&D spending by a mere 38%, and IEA Member countries increased total public expenditures on energy RD&D by only around 20% to EUR 20 billion.

Figure 12. Low-carbon public RD&D expenditures in GDP across IEA countries, 1974-2020

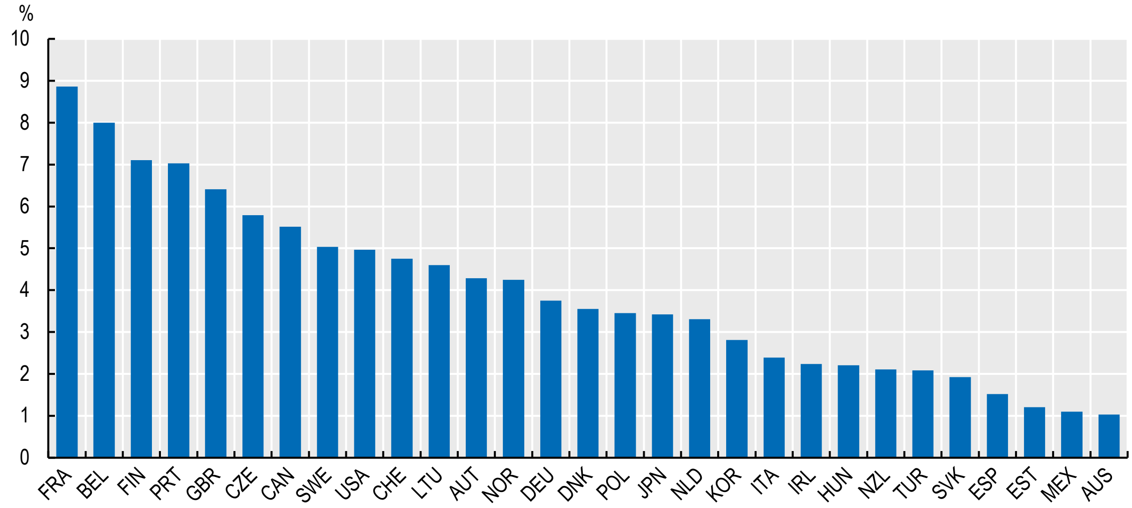


Note: The “Others” category includes Carbon capture and storage, Hydrogen and fuel cells, Other power and storage technologies, and Other cross-cutting technologies and research. See https://www.iea.org/data-and-statistics/data-product/energy-technology-rd-and-d-budget-database-2

Source: IEA Energy Technology RD&D Budgets database, December 2022.

There is, here also, heterogeneity across countries in terms of the share of public R&D budgets devoted to low carbon innovation, as shown on Figure 13. 18 OECD countries devoted more than 3% of their national R&D budgets to R&D in low-carbon technologies in 2021 (or in the latest available year), the maximum being 8.9% in France (due to large nuclear R&D), 8.0% in Belgium and 7.1% in Finland. This proportion is 6.4% in the United Kingdom, 5.8 % in the Czech Republic, 5.5% in Canada, 5.0% in the United States, 3.8% in Germany, 3.4% in Japan, and 3.3% in the Netherlands.

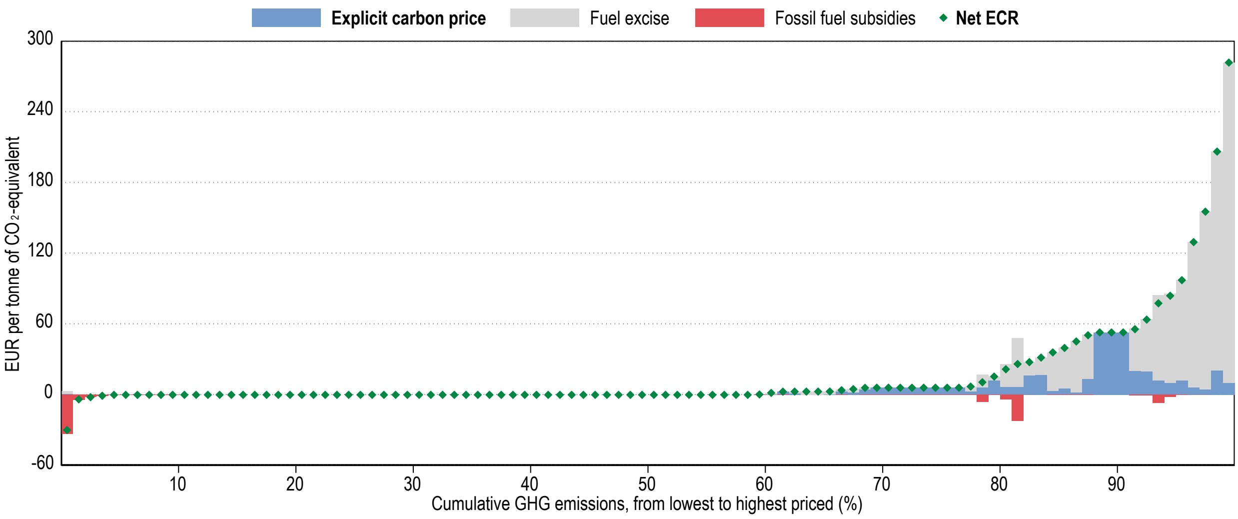
Figure 13. Share of government R&D budget devoted to low-carbon technologies, 2021



Note: The data refer to 2021 for low-carbon RD&D budgets and to 2021 or the latest available year for total government R&D budget (GBARD).
Source: IEA Energy Technology RD&D Statistics 2022 for low-carbon R&D budgets; OECD.stat for total government R&D budget (GBARD)

While Figure 10 shows a slight increase in the use of market-based instruments in the OECD, carbon remains largely unpriced at the global level (OECD, 2022[20]). In 2021, in 71 countries which together account for approximately 80% of global GHG emissions (including all OECD member countries and all G20 countries except Saudi Arabia), nearly 60% of carbon emissions were not priced at all and less than 9 percent of GHG emissions have a net effective carbon rate above EUR 60 per tonne of CO_2-equivalent, a mid-range estimate of current carbon costs (Figure 14). The average effective carbon rate (net of fossil fuel subsidies) across these 71 countries is only 16.7 EUR/ton CO_2-equivalent. This low average carbon price reduces the incentives to develop and adopt new low-carbon technologies.

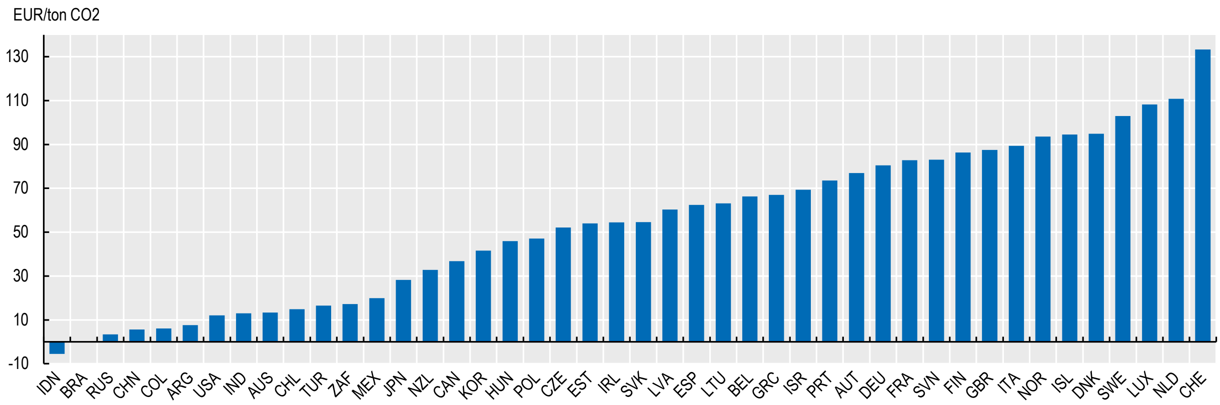
Figure 14. Carbon remains largely unpriced



Note: The figure shows the explicit carbon price, fuel excise, fossil fuel subsidies and net effective carbon rate at each percentile of the cumulative GHG emissions distribution.
Source: (OECD, 2022[20])

Here again, substantial variation in the carbon price (net effective carbon rate) is observed across countries, as shown in Figure 15. In 2021, Switzerland, the Netherlands, Luxembourg and Sweden reached an average effective carbon price of more than EUR 100 per tonne of CO_2. 21 of the analysed countries (out of 71) had an effective carbon price above EUR 60 per tonne of CO_2, while the average carbon price is much lower in many emerging economies as well as some large developed economies such as Australia, USA and Japan.

Figure 15. Average effective carbon prices in EUR/tCO2e, by country, 2021



Note: Effective carbon prices are averaged across all GHG emissions, excl. LUCF, of the 71 countries, including those emissions that are not covered by any carbon pricing instrument. 2021 Fossil fuel subsidy estimates (component of Net ECR) are based on data for 2020. All rates are expressed in real 2021 EUR using the latest available OECD exchange rate and inflation data.
Source: (OECD, 2022[20])

3 The macro- and micro-economic rationale for climate-neutral STI policies

A range of barriers and market failures impede innovation in low-carbon technologies

It is well established that a large range of factors and constraints limit the returns to investment in innovation and provide a rationale for public policy (OECD, 2015[21]). Some of these factors are common to all areas of innovation, others are specific to climate-friendly technologies. The existence of these multiple barriers and market failures, detailed below, justifies comprehensive policy action.

Market failures: knowledge, information and environmental externalities

The first set of market failures pertaining to climate R&D are knowledge market failures. It is well established in the economic literature that R&D activities provide returns to society that are not fully captured by inventors (Geroski, 1995[22]). In most cases, new technologies must be made available to the public for the inventor to reap the rewards of invention. However, by making new inventions public, some (if not all) of the knowledge embodied in the invention becomes public knowledge. These knowledge spillovers provide benefits to the public as a whole, but not to the innovator, and result in a large wedge between private and social rates of return to R&D: marginal social rates of return to R&D investments are typically estimated between 30 and 50 percent annually, while private marginal rates of return range from 7 to 15 percent annually (Popp, 2010[23]). Evidence suggest that – compared to their private returns – the social returns to R&D are “enormous” (Jones and Summers, 2020[24]): $1 of R&D investment today produces, on average, a $13 benefit in today’s dollars. This leads to underinvestment in innovation.

Empirical evidence suggests that knowledge market failures are particularly high for low-carbon technologies: for example, knowledge spillovers are 60% larger for low-carbon than for high-carbon technologies (Dechezleprêtre, Martin and Mohnen, 2014[25]). The intensity of knowledge spillovers from low-carbon technologies is comparable to that of other emerging technologies such as IT and biotechnologies. Thus, there is evidence that – compared to innovation in high-carbon technologies – innovation in clean technologies require higher R&D support because of their relative novelty. Similarly, Myers and Lanahan (2022[26]) quantify the magnitude of R&D spillovers created by grants to small firms provided by the US Department of Energy branch of the Small Business Innovation Research (SBIR) program. Their results show that, for every patent produced by grant recipients, three additional patents are produced by others who did not receive a grant but benefited from knowledge spillovers.

Knowledge externalities may also result from learning-by-doing (LBD). Learning-by-doing occurs when the costs to manufacturers or users fall as cumulative output increases (Rubin et al., 2015[27]). For example, production costs in renewable energy typically fall by around 15% each time the cumulative installed capacity doubles, with higher learning rates in earlier stages of deployment (Grubb et al., 2021[28]). The presence of economies of scale and learning-by-doing provides a justification for demand-side subsidies to increase cumulative output, until cost reductions are exhausted.

Second, even if problems associated with incomplete appropriability of the returns to R&D are solved, it may still be difficult or costly to finance such investments using capital from sources external to the firm. Information about the potential of a new technology is held by the innovator, creating a fundamental asymmetry of information that pushes investors to favour projects with the least uncertain and highest short-term benefits (Hall and Lerner, 2009[29]). These imperfections in the capital market, such as risk aversion, limit the amount of private capital available for low-carbon R&D. Firms developing clean innovations seem to face particularly high financial constraints, as shown by Howell (2017[30]). Generally, projects related to the low-carbon transition suffer from high risks, including the choice of technology, the regulatory environment and uncertain market demand. Profitability may therefore be insufficiently attractive in relation to the level of risk, which is likely to divert most financial actors from this type of investment compared to products of investment considered safer and with higher returns. As a consequence, lack of adequate financing along the entire innovation chain is one of the main obstacles in the commercialisation of science. Many countries face a structural problem with access to financing for disruptive science and R&D-based companies (“deep-tech”), especially for early-stage companies whose products are not finalised and therefore cannot obtain seed funding.

Thirdly, low-carbon innovation is affected by the traditional problem of environmental externalities. Because carbon pollution (and the damages it generates) is not priced by the market, the market for technologies that reduce emissions will be limited because the lack of economic incentives imply low financial returns for environmental innovations. This in turn reduces incentives to develop such technologies. Provision of inefficient government subsidies for the wasteful consumption of fossil fuels and failure to take environmental externalities into account (e.g. negative externalities from fossil fuel-based technologies, or positive externalities from low-emissions technologies), means that prices under-incentivise the uptake of low-emissions innovations. Unregulated emissions in some countries/sectors or misaligned fiscal policies favouring fossil fuel-based technologies reduce the size of the future market for green technologies, which in turn reduces innovation. In other words, private investment in green technologies will increase if the demand is large enough, so policies should align the private costs with the public (environmental) costs. Despite efforts to price this information in, there is significant room for improving market pricing, as shown in Figure 14 and Figure 15.

Path dependency, inertia and systemic barriers

Beyond market failures, a number of factors create inertia in economic systems and therefore impede innovation. These include systemic barriers to change and innovation, barriers to competition, lack of co-operation within an innovation system, prevailing norms and habits, and technology lock-in.

Social barriers result from lack of public acceptance and engagement with new technologies in general (e.g. due to lack of information or perceived negative health and safety consequences). Communicating, preventing, correcting and mitigating adverse effects have all become important for the deployment and diffusion of new technologies. This is increasingly challenging as innovations become more complex.

Path dependency represents another major constraint which favours incumbent technologies and may require government intervention. In economic models of “directed technical change”, innovation typically exhibits *path dependence*: it tends to be directed toward the most advanced sector (the sector where most innovation activity has occurred to date), i.e. the “dirty” (or polluting) sector (Acemoglu et al., 2012[31]). Aghion et al. (2019[32]) identify five determinants of path dependence: knowledge spillovers (as innovations build upon prior innovations in cumulative ways), network effects (when the attractiveness of a technology depends upon networks of other users or suppliers), switching costs (the cost of switching to a different technology, e.g. due to the need for different infrastructure and of overcoming incumbent interests), positive feedbacks (when technologies benefit from scale) and complementarities (when technologies have complementary roles, such as renewables and storage). A consequence of path dependence is that the longer the government waits, the larger the gap between clean and dirty technologies before the policy intervention becomes, and the longer the intervention needs to be – and thus the larger the costs associated with the transition from dirty to clean technologies. Therefore, taking path dependence into account calls for early public intervention to reduce the cost gap between clean and dirty technologies.

Barriers to a dynamic business environment, such as limitations to competition, can slow down any transition. Encouraging the entry of new, innovative firms (and the exit of less innovative and less productive firms), is important as new firms are often the vehicle through which radical, game-changing innovations enter the market, as older incumbent firms often focus on incremental changes to established technologies. Lack of business dynamism (i.e. lack of market entry and exit) means that low-emissions innovations may not overtake fossil fuel-based incumbents and secure their place in mainstream markets, even if they are more efficient. Concentration of market power can also be a challenge as long-term investors (e.g. asset-heavy banks, institutional investors) may favour incumbents because of perceived stable returns. Though alternative forms of financing (e.g. business angels and venture capital) can allow for greater risk-taking, they typically do not invest with a sufficiently long time horizon to drive the transition.

Other features of the business population might affect the speed at which the transition can happen. Compared to large firms, smaller firms are more dependent on external sources of technology and knowledge. Managers of small firms may have insufficient information about production processes or are unaware of best available low-emissions technologies and practices applied elsewhere.

Lack of capabilities

Lack of capabilities amongst workers and managers implies the absence of enabling conditions for productive investment in innovation. These constraints reduce the choices of firms and other actors to invest in innovation. For example, new technologies require new skills to enable new technologies to be developed and diffused. Thus, a successful green transition will likely need, upgrading the skill sets of workers and managers in industries experiencing only minor adjustments; gearing up educational institutions and firms to provide the new skills for occupations and sectors emerging from the green economy; and retraining and realigning skills in sectors that will decline as a result. More generally, strong innovation capabilities will be required. This includes not only the training of researchers, but a well-functioning innovation ecosystem.

Government failures

Government policy may also be a barrier to low-carbon innovation. Government failures include a preference for incumbents, lack of policy predictability and stability, and regulatory barriers.

An important feature of the green transformation is that - at least in the short term until green technologies become cost-competitive with brown technologies - demand for green goods depends on supportive public policies. Policy uncertainty, in particular, has been shown to depress investment and economic growth (Bloom et al., 2018[33]). A recent study shows that climate policy uncertainty, as measured by an indicator based on newspaper coverage frequency, is associated with economically and statistically significant decreases in investment, particularly in pollution-intensive sectors that are most exposed to climate policies, and among capital-intensive companies (Berestycki et al., 2022[34]).

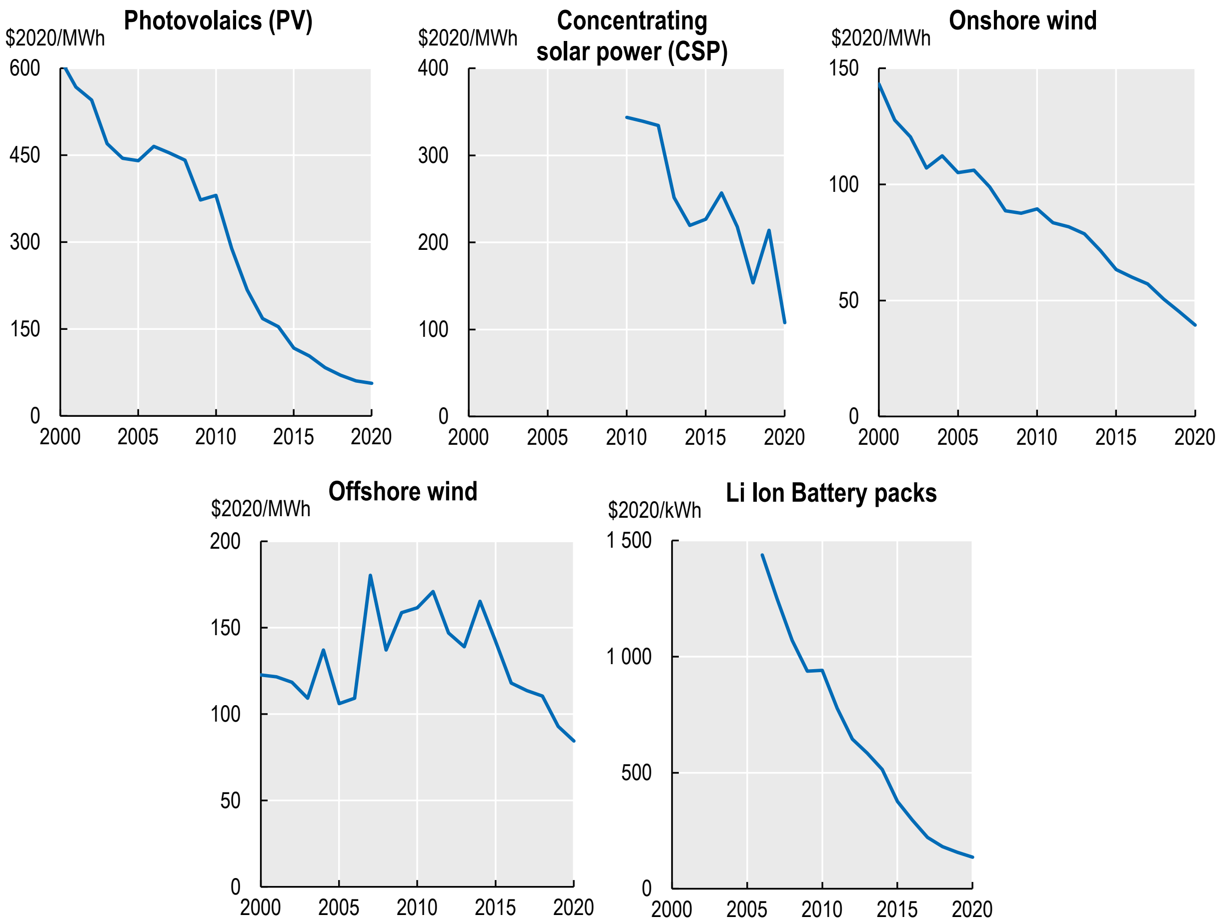
Political and institutional barriers result from governance and co-ordination failures due to incoherence or inconsistent timing across policy areas. Misalignments can be horizontal (i.e. between innovation policies and sectoral policies), vertical (i.e. between ministries and implementing agencies) or multi-level. For example, diffusion of low-emissions vehicles is hindered not only by price or battery storage capacity, but also by the lack of a charging network in cities and along motorways.

STI&I policies reduce the cost of reaching climate objectives

Because innovation is induced by new environmental policies, there is evidence that the ex post actual costs of new environmental regulations are typically much lower than the ex ante anticipated costs of these regulations (Harrington, Morgenstern and Nelson, 2009[35]).

Indeed, technological progress – which originates from investments in R&D activities but also from learning-by-doing – reduces the costs of emissions reduction policies, as demonstrated by sharp declines in the costs of batteries and solar photovoltaics, which have both experienced a 90% reduction over the past decade, as shown in Figure 16. As a result, many carbon-free activities (especially renewable energy) are already cheaper than fossil fuel.

Figure 16. Declining renewable energy and battery costs since 2010



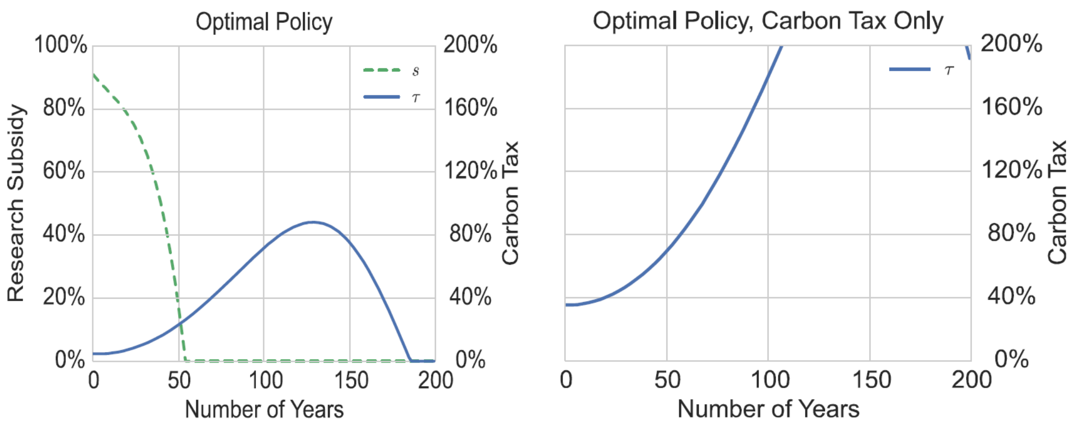
Note: The lines indicate average unit cost in each year. For batteries, costs shown are for 1 kWh of battery storage capacity; for renewables, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced.
Source: (IRENA, 2021[36]), (IPCC, 2022[1])

A consequence of the cost reductions brought about by technological progress is that STI&I policies reduce the cost of reaching climate objectives, as shown by model-based analyses of climate policy packages, e.g. Fragkiadakis et al. (2020[37]). Figure 17 illustrates this by showing the required carbon tax necessary to keep global temperature below 2°C, when combined (left panel) or not (right panel) with research subsidies to clean innovation (Acemoglu et al., 2016[38]). The optimal climate policy requires large subsidies to clean research coupled with an initially modest but growing carbon tax (left panel). The research subsidy is very high initially, to compensate for the initial advantage of dirty innovation, but can be phased out as soon as clean research is sufficiently productive. However, if the government can only rely on a carbon tax to meet its climate policy objectives, the tax starts higher than in the optimal policy scenario and increases to much higher levels (right panel). Using only a carbon tax to redirect innovation towards clean technologies requires a much higher tax level and is also much more costly socially (because the marginal costs of production of clean technologies are initially significantly higher than those of dirty technologies).

Recent empirical research similarly shows that, given the current technology mix available, meaningful emission reductions would require extremely high (and politically difficult) carbon prices. By reducing the costs of low-carbon technologies, innovation policies can increase the responsiveness of emissions to carbon prices. With current technologies, a minimum carbon price of EUR 175 per ton of CO_2 across OECD Member countries (i.e., much larger than the current levels shown in Figure 14) would be necessary to cut emissions by 35% as compared to 2018 levels. However, if low-cost low-carbon technologies were available and assuming that they could double the responsiveness of emissions to carbon prices, the same emissions reduction could be reached with only a EUR 60 carbon price (D'Arcangelo et al., 2022[39]).

There are two important policy consequences from this result. First, including effective STI&I policies in the climate policy mix allows for much lower carbon prices to reach the same climate target. Second, STI&I policies can partially substitute for low carbon prices (although not fully), which is important as these are often difficult to implement politically. Moreover, suboptimal carbon prices, as are in place today, support the case for even stronger STI&I policies.

Figure 17. Subsidies to clean research allow for much smaller carbon taxes



Note: *s* is the rate of subsidy to clean research (dashed green line), t is the tax on dirty production, or carbon tax (solid blue line).
Source: (Acemoglu et al., 2016[38])

STI&I policies are widely socially accepted, making them politically attractive

There is another important political argument for STI&I policies in the overall climate policy mix. A nationally representative population survey recently implemented across 20 OECD and non-OECD countries shows that subsidies to low-carbon technologies are systematically the most favoured climate policy compared to carbon pricing, bans or regulations (Figure 18). Similarly, support for a carbon tax is largest if its revenues are used to fund green infrastructure or to subsidise low-carbon technologies. From a public acceptability point of view, STI&I climate policies thus appear to be an attractive option. The U.S. Inflation Reduction Act adopted in 2022, which has been presented as "the single largest investment in climate and energy in American history" with USD 369 billion of public investment in climate-related solutions and technologies, illustrates the greater political acceptability of STI&I policies compared to carbon pricing instruments. The previous major US climate bill, the American Clean Energy Security Act of 2009 (known as Waxman-Markey), was set to create an economy-wide cap-and-trade program but failed in the Senate.

Figure 18. Public support for climate policies is strongest for STI policies

	High-income	Australia	Canada	Denmark	France	Germany	Italy	Japan	Poland	South Korea	Spain	United Kingdom	United States
Support for Main Climate Policies													
Green infrastructure program	57	49	56	53	57	42	78	48	58	68	71	54	50
Ban on combustion-engine cars	43	35	47	41	28	32	54	41	44	52	54	45	39
Carbon tax with cash transfers	37	34	41	30	29	28	47	35	36	53	44	34	33
Support for Other Climate Policies													
Subsidies to low-carbon technologies	67	62	65	67	56	64	79	69	75	71	73	65	57
Mandatory and subsidized insulation of buildings	66	70	64	70	64	60	73	59	72	72	71	70	53
Ban on polluting cars in city centers	60	53	60	66	57	50	76	64	61	52	64	65	49
Funding clean energy in low-income countries	54	49	50	53	48	48	76	53	55	57	65	51	50
Ban on combustion-engine cars w. alternatives available	48	38	47	42	42	41	58	51	48	58	57	52	44
Tax on flying (+20%)	45	35	44	60	46	53	41	47	44	42	44	46	33
Tax on fossil fuels ($45/tCO2)	36	36	40	43	31	31	38	35	27	42	39	38	34
Support for Carbon Tax With:													
Funding environmental infrastructures	63	60	48	60	65	60	76	56	68	78	69	63	56
Subsidies to low-carbon tech.	63	58	49	52	57	66	76	68	71	79	69	59	53
Reduction in personal income taxes	57	52	48	38	62	54	72	64	69	62	67	52	49
Cash transfers to the poorest households	53	51	48	41	55	47	68	54	50	59	63	57	46
Cash transfers to constrained households	50	50	42	36	55	47	62	47	39	62	61	52	44
Tax rebates for the most affected firms	48	41	41	38	52	34	66	49	61	59	55	41	43
Reduction in the public deficit	48	40	39	34	49	39	66	50	56	48	62	44	48
Equal cash transfers to all households	38	37	38	27	45	31	42	43	37	42	44	33	38
Reduction in corporate income taxes	37	29	32	24	37	25	55	38	48	48	50	26	29
Support for Cattle-Related Policies													
Subsidies on organic and local vegetables	56	42	50	59	52	56	71	46	73	62	65	49	43
Ban of intensive cattle farming	42	32	41	31	55	49	64	17	44	44	43	50	36
Removal of subsidies for cattle farming	34	31	33	32	28	38	42	16	34	31	42	37	38
A high tax on cattle products, doubling beef prices	30	24	27	31	29	40	37	19	30	26	31	31	31

	Middle-income	Brazil	China	India	Indonesia	Mexico	South Africa	Turkey	Ukraine
Support for Main Climate Policies									
Green infrastructure program	78	77	82	80	80	84	73	76	69
Ban on combustion-engine cars	65	60	72	77	65	67	53	62	58
Carbon tax with cash transfers	59	47	80	71	67	55	52	55	39
Support for Other Climate Policies									
Subsidies to low-carbon technologies	73	77	75	68	79	66	75	75	68
Mandatory and subsidized insulation of buildings	75		80				73	75	75
Ban on polluting cars in city centers	71	65	73	74	85	72	66	60	67
Funding clean energy in low-income countries	73	63	71	75	81	74	76	66	78
Ban on combustion-engine cars w. alternatives available	68	60	78	77	72	66	62	64	63
Tax on flying (+20%)	52	39	61	64	68	51	43	45	36
Tax on fossil fuels ($45/tCO2)	48	35	58	64	58	41	38	52	28
Support for Carbon Tax With:									
Funding environmental infrastructures	75	78	76	71	81	73	79	73	69
Subsidies to low-carbon tech.	73	74	79	68	79	71	78	66	65
Reduction in personal income taxes	69	69	74	68	74	69	68	66	64
Cash transfers to the poorest households	73	67	82	69	86	66	65	82	62
Cash transfers to constrained households	64	59	69	63	74	59	60	65	61
Tax rebates for the most affected firms	62	59	72	65	68	54	63	55	56
Reduction in the public deficit	63	62	72	65	70	61	62	57	52
Equal cash transfers to all households	61	45	70	64	76	62	57	59	53
Reduction in corporate income taxes	58	54	67	60	67	61	50	60	42
Support for Cattle-Related Policies									
Subsidies on organic and local vegetables	68	62	79		77	58	59	80	58
Ban of intensive cattle farming	39	38	50		45	46	28	32	25
Removal of subsidies for cattle farming	39	43	47		51	47	27	31	22
A high tax on cattle products, doubling beef prices	36	33	48		49	37	30	26	24

Note: 2000 respondents per country, representative sample of the population stratified by age, gender, region and income level. The numbers in the boxes show the percentage of people supporting the policy (either “strongly support” or “somewhat support”). The larger the number, the higher the support. The colours indicate if the share of support for a policy is above 50% (blue shades) or below 50% (red shades).
Source: (Dechezleprêtre et al., 2022[40])

Low-carbon technologies, reallocation and economic opportunities

Innovation and diffusion are the main sources of productivity improvements and of modern economic growth. This implies that the transition to a zero-carbon economy is not only compatible with long-term economic growth; it also opens a vast range of economic opportunities for businesses. The structural transformation of the economy made necessary by this transition – like all previous industrial revolutions that the world has undergone – presents market and business opportunities across all economic activities, and can reignite innovation, diffusion and productivity growth at the macro level.

A well-managed transition to a greener economy will create opportunities for businesses and workers. Firms that will supply clean technologies, products and services are expected to grow, as these can be expected to diffuse widely over the coming decades. For example, renewable energy manufacturers, electric cars producers, and more generally sectors operating at a low carbon intensity will see the demand for their products increase as consumers look for substitutes to high-carbon goods. Opportunities will arise all along the supply chain, from technology providers to users of more energy-efficient technologies. Some sectors will grow more than others, and some will decline in importance, but within each sector, companies using resources more efficiently will have a competitive advantage. There will also be significant opportunities for financial institutions, which will play an important role in directing investment towards sustainable projects.

There is evidence that the green economy is already growing at a fast rate across numerous sectors (Denmark's wind industry is a prime example), and this trend will likely only become stronger in the years ahead. There is also empirical evidence for greater economic returns from clean energy infrastructure over fossil fuel investments, with estimates suggesting they create twice as many jobs per dollar spent (Pollin et al., 2008[41]). In the long term, the economic multipliers are also estimated to be high, as renewable energy and energy efficiency are more labour-intensive in terms of electricity produced than either coal- or gas-fired power plants (both in terms of short-term construction phase jobs, and in terms of average plant lifetime jobs), and energy cost savings are passed on to the wider economy (Hepburn, Pless and Popp, 2018[42]; Blyth et al., 2014[43]; Hepburn et al., 2020[44]).

Alongside the direct economic benefits, there are broader benefits for the transition to a low-carbon economy such as reduced air pollution, improved health outcomes and wellbeing. These broader benefits can be framed as bolstering natural, social, human and physical capital, which can all contribute to the long-term sustainability of growth.

However, the transition to a low-carbon economy will also lead to reallocations both between and within economic sectors and firms. Modelling results tend to point to very limited overall reallocation of jobs (sum of created and destroyed jobs) - around 0.3% for OECD countries and 0.8% for non-OECD countries in the case of a 450ppm CO2 concentration target in 2035 (Chateau, Bibas and Lanzi, 2018[45]). One of the main explanations for these limited consequences is that the heavily impacted sectors (mostly energy sectors) represent only a small share of total employment (82% of the largest CO2 emitting non-agricultural sectors comprise only 8% of total jobs in 27 OECD countries). However, a key factor explaining the low estimated transition "costs" is that the simulation is based on a global, uniform carbon tax, which would exclude leakage across borders. Such models also abstract from any short-term adjustment costs, as they focus on longer-term reallocation. Therefore the actual short-term costs are likely to be higher than these estimates.

Job losses specifically coming from the low-carbon transition are expected to be concentrated in "brown" sectors, broadly defined as carbon-intensive industries and sectors related to extraction and processing of fossil fuels. For example, employment in 'Mining and fossil fuel supply' and "Fossil-fuel electricity generation" is predicted to decrease by around 8% in OECD countries compared to baseline estimations (Chateau, Bibas and Lanzi, 2018[45]).

The expected job reallocation rates – taken at face value – do not seem something a well-functioning job market cannot handle. They are relatively small compared to the reallocation observed during the past decades: job reallocation rates averaged at 20% over the 1995-2005 period in OECD Member countries (OECD, 2009[46]). These reallocations also appear small when compared with those linked to other major macroeconomic trends such as globalisation and the diffusion of new information and communication technologies – though they admittedly would add to these on-going trends. Ever-increasing computing power, Big Data, Artificial Intelligence (AI), the Internet-of-Things and online platforms are among the developments radically changing prospects for the type of jobs that will be needed in the future, and how, where and by whom they will be done. Recent estimates suggest that 14% of existing jobs could disappear as a result of automation in the next 15-20 years, and another 32% are likely to change radically as individual tasks are automated (OECD, 2019[47]). In comparison, therefore, the green transition appears manageable.

However, even within narrowly defined sectors, i.e. beyond the scope of cross-sectoral modelling exercises, there will be reallocations between firms (or even within them), as energy and emission efficiency becomes a competitive asset. In a global firm-level study, Albrizio, Kozluk and Zipperer (2017[48]) show that within-sector effects appear much more important than effects across sectors. At the firm-level, a tightening of environmental policies leads to an increase in the productivity growth of firms close to the technology frontier, but to a decrease in productivity growth for those further away from the frontier. Only one-fifth of the firms are estimated to benefit from environmental policies, while the bottom 30% of firms are negatively affected in terms of productivity growth. Since smaller firms tend to be further away from the productivity frontier, they are more exposed to the negative effects, possibly because they have limited resources to adapt to the policy changes.

Comparing firm and industry-level results on the productivity effects of environmental policies suggests that part of the adjustment, particularly for less technologically-advanced firms, may take the form of firm exit. The exit of the least efficient firms would raise overall industry productivity, cancelling out the negative productivity effects linked to the survival of less efficient firms. Indeed, one may consider the negative effect on the least productive firms as one way to reallocate resources previously locked in firms that were at the margin of exit (Andrews, Adalet McGowan and Millot, 2017[49]).

Similar differences between small macroeconomic effects and large microeconomic impacts have been found for the effect of environmental policies on employment. Dechezleprêtre, Nachtigall and Stadler (2020[50]) show that, at the sector level, increases in energy prices and in the stringency of environmental policies have a small negative and statistically significant impact on total employment in the manufacturing sector. However, the effects are heterogeneous across sectors: energy-intensive sectors (e.g. non-metallic minerals, iron and steel) are most affected, while the impact is not statistically significant for less energy-intensive sectors. Within sectors, higher energy prices also increase the probability of firm exit. Accelerated firm exit then allows surviving firms to expand, boosting employment in these firms. Some firms lose, others win, explaining why the effects appear small at the macro level.

Reallocation has multiple dimensions: reallocation between sectors, between firms within sectors and within firms, across technologies, products and activities. Firms will exit and enter, but all firms will need to reallocate resources to reduce the carbon footprint of their activities. Structural policies will be required to facilitate reallocation, boost competition and innovation, strengthen skills, reduce frictions and support people through transitions (OECD, 2021[51]).

4 Making low-carbon innovation policies work for decarbonisation

Innovation policies

Framework policies for innovation and diffusion aim at strengthening the conditions under which innovative activities can thrive and diffusion of innovation supported. They include an educated and skilled workforce, a sound business environment, a strong and efficient system for knowledge creation and diffusion, and strong incentives to engage in innovation and adoption and in entrepreneurial activity (OECD, 2015[21]).

More specific innovation and industrial policies focus on increasing the rate of innovation, with a view to promoting competitiveness and structural change in the economy. These policies range from applied research to late development and include financial subsidies and grants to incentivise investment in business R&D, especially by small firms, and rewards to the outputs of innovation activities, e.g. reducing the taxes owed on the economic returns to R&D (see Box 1 for an overview of such policies as reported in the OECD's "STI policies for net zero" portal, and Box 2 for specific examples). One of the features of innovation policies aimed at low-carbon innovation is that they go beyond increasing the rate of innovation, but rather aim at affecting the direction of innovation, away from fossil-fuel based energy systems towards greater sustainability. Therefore, a core component of innovation and diffusion policies for carbon neutrality are those that directly encourage firms to engage in innovation and entrepreneurial activity related to low-carbon technologies, rather than in carbon-emitting technologies.

These specific innovation policies need to be complemented by reforms to education and training systems, and to skills policies more broadly, to ensure the existence of a skilled workforce that has the knowledge and skills to generate new ideas and technologies and to adopt and adapt them across the economy. They include notably policies aimed at science, technology, engineering and mathematics (STEM) graduates as well as management and digital skills. International mobility of talent also plays an increasingly important role in meeting emerging skills needs.

Supporting the development of strong and well-governed universities and public research institutes, as well as mechanisms that facilitate the interaction among knowledge institutions and economy and society, is critical to strengthen innovation performance by expanding fundamental knowledge and diffusing it throughout society. Investment in infrastructure, notably broadband and other digital networks, can encourage knowledge diffusion, including at the international level.

Box 1. Mapping the STI policy mix to support low carbon technology

The OECD's STI policies for net zero portal provides an overview of STI policies for low carbon innovation. As of February 2022, the Net Zero portal contained approximately 250 STI policy initiatives targeting net zero goals. Figure 1 classifies these initiatives by theme such as national strategies, project grants for public research, networking and collaborative platforms, and centres of excellence grants.

Figure 19. Policy instruments reported the Net Zero portal(338 instruments)

Policy instrument type	Count (% in total)
Strategies, agendas and plans	81(24%)
Project grants for public research	78(23%)
Grants for business R&D and innovation	59(17%)
Networking and collaborative platforms	28(8%)
Institutional funding for public research	16(5%)
Centres of excellence grants	12(4%)

National strategies, agendas and plans

Figure 2 analysis the diversity of economic sectors that are the subject of national net zero strategies, agendas and plans. The energy sector is the primary target, but transportation, agriculture and several other industries are also targeted. For example, alongside energy R&D, Korea's Implementation Plan for the Climate and Environment R&D Programme targets the transportation, telecommunications and IT sectors. Portugal's Roadmap for Carbon Neutrality considers agriculture and the transportation sector among its top priority. Meanwhile, Figure 3 shows that more than half of national strategies, agendas and plans take a holistic approach targeting multiple parts of innovation systems.

Figure 20. Specific sectors targeted in national strategies, agendas and plans (in 81 initiatives)

Specific sectors targeted	Count (% in total)
Energy	56(69%)
Automotive and road transportation	16(20%)
Other manufacturing	13(16%)
Agriculture	12(15%)
Other services	10(12%)
Other primary industries	8(10%)
Food	7(9%)
Telecommunications and IT	6(7%)
None specifically targeted	5(6%)

Figure 21. Focus on National innovation system in national strategies, agendas, and plans (in 81 initiatives)

National innovation system focus	Count (% in total)
Research	47(58%)
Business (innovation and/or entrepreneurship)	43(53%)
Governance	21(26%)
Education and skills	10(12%)
Other	9(11%)

Source: EC-OECD (2022), STIP Compass: International Database on Science, Technology and Innovation Policy (STIP), edition February 9, 2022, https://stip.oecd.org

R&D funding

Figure 4 illustrates that financial support for net zero focuses on funding for applied research, experimental development followed by demonstration and testing. Figure 5 shows that while many grants for public research focus on basic research, up to a quarter of public research funding initiatives target demonstration efforts. In addition, 16% support multidisciplinary research. A significant number of initiatives for net zero R&D offer a range of financial support covering the entire 'research and innovation value chain'. For example, in Germany, the Seventh Energy Research Programme, three ministries responsible for different phase of innovation chain coordinate and complement a wide range of technology developments, from fundamental research to commercialisation. Another example is the Austrian Energy Research Programme, established and implemented by multiple ministries with a view to strengthening links between research and industry.

Figure 22. Grants for business R&D and innovation (in 59 initiatives)

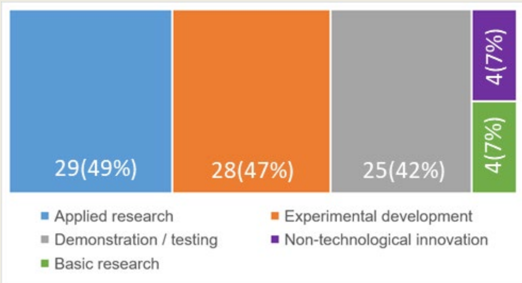
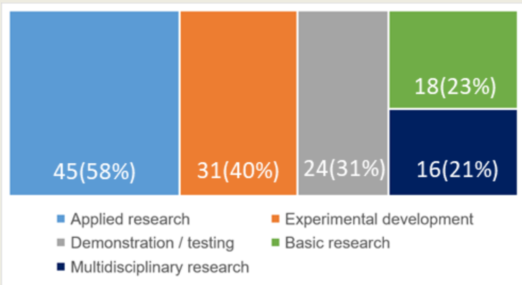


Figure 23. Project grants for public research (in 78 initiatives)



Networking and collaborative platforms

Countries employ a variety of collaboration and networking initiatives to facilitate co-operation between public research actors and business on net zero. For instance, the Institutes for Energy Transition (ITE) are interdisciplinary platforms bringing together industry and public research actors to strengthen innovation ecosystems in photovoltaic solar and wind and marine energies. Another example is the Smart Energy Programme in Finland that aims to develop and internationalise automated smart energy systems.

Supporting science

Mobilising science to address the climate challenge

Science has the potential to make at least three important contributions to helping societies and governments address the challenges posed by climate change.

First, science provides critical theories, data and knowledge to help understand the phenomenon of climate change itself and project future changes. For example, scientific observational data from paleoclimatology – the study of past climate change – feed into global climate models of temperature, precipitation, and sea levels. Scientific data can also help test the robustness of climate models that are used to inform governments and citizens about the potential impacts from climate change.

Second, science contributes to business innovation and the development of climate mitigation technologies directly and indirectly (as shown in Figure 3 and Figure 4 on science-patent linkages). This requires investment in the natural and physical sciences as well as the social sciences and humanities. It also requires investment in large-scale research infrastructures, computing power and data repositories and software to make data available for analysis to researchers globally.

Third, interdisciplinarity and trans-disciplinarity are critical features of climate change solutions. The complexity of the interactions between different elements that influence climate change - from the earth's oceans, atmosphere, geological forces, biodiversity and the impact of human and animals on GHG emissions - mean that climate science must not only draw on different scientific disciplines, but it must also engage different stakeholders (citizens, business, policy makers) to produce both new scientific knowledge and solutions for practitioners. Most public funding however is discipline-oriented and follows the structure of academic departments and scientific journals. Recently, government research funding councils and ministries have increased funding for sustainability research and new scientific journals have emerged that provide an outlet for interdisciplinary and transdisciplinary research.

Providing access to scientific knowledge

Science has impact when it is diffused across societies and open science is a way to make the output of publicly funded research more widely accessible in digital format to the scientific community, the business sector, or society more generally (OECD, 2015[52]) Making research data open can improve the efficiency and effectiveness of climate science and innovation by reducing duplication costs in collecting, creating, transferring and reusing data and scientific materials, thus allowing more research from the same data. Open data can also multiply opportunities for domestic and global collaboration. The OECD has been promoting common principles for the access to data from publicly funded research as well good practices for the sharing and access to data, including commercial data held by companies that may be relevant setting and monitoring net zero goals and targets.

Science, policy and society

Science informs society and can help frame complex issues. It can also help policy makers make decisions regarding the challenges and opportunities associated with climate change. Besides knowledge, science also provides evidence to help policy makers identify key pathways for decarbonising production and consumption and preserving the biosphere. In this regard, national and international scientific institutions play an important role.

Although levels of public trust in science remain relatively high, the COVID-19 pandemic has shown that trust in science can be eroded by politics, disinformation and weakened institutions. This in turn feeds scepticism on climate science and climate mitigation and adaptation policies (International Science Council, 2021[53]). At all scales, the quality of scientific advice depends on scientific capacity and access to relevant data and information. These vary enormously across countries and regions within a country. Of course, science advice is only one input to policy and decision-making and the weight that is attributed to that advice depends very much on specific national contexts and political considerations.

Transparency and accountability are critical factors for ensuring public trust in scientific advice (OECD, 2018[54]). At the same time, conflicting scientific viewpoints –and their public communication in traditional and social media – have led to confusion and lack of trust in scientific advice. As the COVID pandemic has shown, it is important to go beyond the traditional science-policy interface to build a science-policy-public interface (OECD, 2021[55]). Direct engagement is needed with those outside the scientific community, and a deeper understanding of how citizens receive and respond to climate related messages, both individually and collectively.

In this context, science education and science literacy are important, as they provide citizens with the intellectual tools to engage in societal debates and make informed choices about the available options in adapting to and mitigating climate change. But scientists also need the tools to engage in societal debates and understand societal concerns as much as citizens need to understand science.

Governments can support the various roles of science by investment in public research and the training of the researcher population; investing in public understanding and awareness of science, including through science museums, science communication campaigns, science projects that engage with citizens and scientific advice. Ultimately, however, if science is really to answer the challenge and help generate the tools (knowledge and technologies) that are required to provide sustainable solutions for climate change – rapidly and at scale – then it needs to be mobilised in the way that it has been during the COVID-19 pandemic. This requires strategic direction and leadership, changed incentives and evaluation systems, inter- and trans-disciplinary research, support for human resources and stronger international collaboration on both low-carbon research and low-carbon innovation.

Support to business R&D and demonstration

Support to private R&D: tax credits, grants and prizes

A way government can help firms internalise the knowledge externalities associated with innovation is to directly subsidise the innovation activities of firms through research grants, R&D tax credits or technology prizes.

The literature on the impacts of direct R&D funding on firm innovation is still emerging. Pless, Hepburn and Farrell (2020[56]) report that, of the 1700 papers on the impact of direct funding for innovation reviewed by the What Works Centre for Local Economic Growth, only 42 use rigorous statistical methods. In general, the empirical evidence suggests that R&D tax credits have positive effects on firms' innovative activity. On average, one extra unit of R&D tax support translates into 1.4 extra units of R&D, with the effect on experimental development about twice as large as the effect on basic and applied research and heterogeneous effects across types of firms (OECD, 2020[57]; Bloom, Van Reenen and Williams, 2019[58]). For example, Lokshin and Mohnen (2012) find that small firms (below 200 employees) have a larger cost elasticity of R&D than larger firms. R&D tax incentives not only increase expenditures but also the level of human resources that firms report to dedicate to R&D. They do not appear to affect R&D unit labour costs, suggesting that the effects of tax incentives are not absorbed into higher wages (OECD, 2020[57]). A few countries have introduced R&D tax credits specifically for green innovation activity (see Box 2) but no evaluation of the impact of these initiatives is available.

Direct R&D grants also have positive effects on firms' innovative activity, but the effect seems concentrated on small firms that are likely to be more financially constrained (Bronzini and Piselli, 2016[59]; Bronzini and

Iachini, 2014[60]). In addition, grants and tax credits can be complementary for small firms but substitutes for larger firms (Pless, 2019[61]).

There is little evidence on the impact of R&D subsidies or tax credits designed to promote specifically cleaner technologies. Only a few studies focus on energy-related innovation. Yet, this sector possesses many features (high capital intensity, long time horizons, little product differentiation, among others) that might affect the innovation process. Howell (2017[30]) is a notable exception and analyses the impact of the US Department of Energy's Small Business Innovation Research program. The paper shows that receiving a grant increases patenting, survival rate and the probability of subsequently receiving venture capital among recipients, with stronger effects for firms likely to be more financially constrained. Within energy research, Howell (2017[30]) also shows that R&D subsidies can increase clean innovation specifically (in hydropower, carbon capture and storage, building and lighting efficiency, and alternative automotive technologies) but have no measurable effect on conventional energy technologies (natural gas and coal), likely because firms developing these technologies are less financially constrained.

In general, compared to direct public funding of R&D, firms applying for R&D tax credits retain control over the type of R&D projects they pursue. Thus, while tax credits may make marginal projects profitable, firms will still focus on projects with the greatest short-run returns (David et al., 2000). As such, tax credits may not be the best policy tool to promote new technologies that are not close to the market. Direct subsidies are likely a better instrument to support low-carbon technologies that are not mature yet compared to R&D tax credits. However, there is currently no globally comparable data available on the amount of support to private R&D through either direct subsidies or tax credits specifically targeted at low-carbon technologies.

Using prizes for promoting new energy technologies is attractive, as the risk of failure is borne by companies, rather than government. However, the use of prizes also comes with challenges, as shown by Williams (2012). One failed example is a prize offered by a group of U.S. electric utilities for an energy efficient refrigerator. While Whirlpool was able to develop a refrigerator meeting the required technical specifications, the model was not popular with consumers, and thus Whirlpool did not sell the necessary number of units to receive the prize. In the case of technologies for which consumer demand is likely to be low, monetary prizes will need to be sufficiently large to entice firms to take on the related risks.

Support for demonstration

The last RD&D phase is the demonstration phase, which corresponds to the design, construction and operation of a prototype of a technology, at or near commercial scale, with the purpose of providing technical, economic and environmental information to industrialists, financiers, regulators and policy makers (OECD, 2015[62]).

A critical part of the climate innovation policy package is to close the funding gap for large-scale demonstration projects, in order to help breakthrough innovators escape the well-known “valley of death” of clean tech venturing (between research and commercialisation). The amount of funding which needs to be made available for demonstration support on technologies that still have a low technology readiness level is very significant, particularly in the industry sector. For example, a single 100 MW electrolyser for green hydrogen production costs between EUR 50-75 million; in the case of CCS, demonstration projects currently cost around USD 1 billion, take five years or more to build, and have a market value of around one-tenth of their cost (OECD, 2021[4]).

In comparison, the amount of public funding available for demonstration projects appears generally small. For example, the European Union recently introduced the Innovation Fund as a new funding mechanism for the demonstration of innovative low-carbon technologies. The fund focuses on Innovative low-carbon technologies and processes in energy intensive industries, including products substituting carbon intensive ones; CCU; Construction and operation of CCS; Innovative renewable energy generation; and energy storage. The Innovation Fund is the successor of the NER300, which focused mostly on renewable energy.

Thirty-nine projects were selected at the European level for NER300, but 20 of them have since been withdrawn, including all projects related to ocean energy, PV and CCS, generally because of regulatory, technical or financing issues. The budget for the Innovation Fund for 2020-30 is projected to be around EUR 10 billion (or EUR 1 billion per year on average), but figures are uncertain as the resources come from the auctioning of EU ETS allowances whose price fluctuates on the market. The first call for large-scale projects (above EUR 7.5 million of total capital costs) was opened in 2020, and attracted 311 applications for innovative clean tech projects, including 58 for renewable energy, 204 for energy-intensive industries (out of which 56 in hydrogen), 35 for energy storage and 14 for CCUS. However, the proposed projects have requested a total of EUR 21.7 billion in funding, while only around EUR 1 billion is available.

This example illustrates that the funding gap for demonstration projects appears large. Similarly, in the IEA's Net Zero Emissions scenario, in order to complete a portfolio of demonstration projects before 2030 in electrification of end-uses, CCUS, hydrogen and sustainable bioenergy (mainly for long-distance transport and heavy industrial applications), governments need to mobilise at least USD 90 billion. Therefore, bridging the demonstration funding gap should be a priority for climate innovation policy going forward. Recent announcement by 16 countries at the September 2022 Clean Energy Forum to commit USD 94 billion for clean energy demonstration therefore goes in the right direction.

Support for deployment

As shown in Section 2, the existence of learning-by-doing and economies of scale provides a justification for subsidising the deployment of low-carbon technologies and reducing their production cost until it becomes competitive with high-carbon alternatives. In the renewable electricity domain, these subsidies have taken the form of feed-in tariffs and auctions, which have been instrumental in inducing the massive cost reductions observed in the last couple of decades (Nemet, 2019[63]). For electric vehicles, subsidies can lower up-front purchase costs for consumers.

Public procurement can play an important role, for example to incentivise the use of low-carbon steel (Grubb et al., 2021[64]). In the European Union, public procurement is estimated to amount to about 16 percent of GDP, including large expenditures in sectors that are key for the net-zero transition, such as buildings and construction (EUR 100 bn per year) and transportation (EUR 19 bn per year). This illustrates the magnitude of the role that public procurement could play in accelerating the growth of clean technology markets (Tagliapietra and Veugelers, 2020[65]).

An important question for policy is how much to spend on deployment, in particular compared to R&D. The answer to this question depends on the relative intensity of market failures associated with technology development, mainly knowledge spillovers at the R&D stage and learning-by-doing at the diffusion stage. This depends on the degree of maturity of the technologies considered.

For example, Fischer, Newell & Preonas (2017[66]) model the US energy system and determine the optimal distribution of public spending between R&D support and deployment under various scenarios. They find that the optimal ratio of deployment spending to R&D spending does not exceed one for wind energy in almost all scenarios. With extreme assumptions on the magnitude of learning-by-doing, this ratio goes to 6.5. The ratio of public spending on deployment to R&D exceeds one for solar energy but not by much. The ratio reaches 10-to-1 under the "high learning-by-doing" scenario.

The relative importance of deployment support (market pull) vis-à-vis R&D support (technology push) should increase, as one moves from highly immature technologies towards technologies close to market competitiveness. For example, Kavlak et al. (2018[67]) estimate that over 1980–2000, public R&D and spillovers accounted for almost 50% of cost reductions in renewable energy technologies, double that attributable to economies of scale and learning-by-doing combined. From 2001 to 2012, however, these forces reversed: public R&D and spillovers accounted for one quarter of the observed cost reduction, whilst scale economies and learning-by-doing accounted for half. Overall, existing studies highlight the major role played by both public and private R&D in enabling the cost reductions observed, a strong role for economies of scale, and a smaller role for pure learning-by-doing.

Box 2. Country examples of low-carbon innovation policies

Innovation Process	Policy Instruments	Country Examples
Applied research	Institutional funding	UK government is supporting the Faraday Institution with a 22.6 million GBP (in 2021) to accelerate commercially relevant research needed for future battery development.
	Research Grant	The Integral Knowledge and Innovation Agenda (IKIA) in Netherland consists of 13 multi-year programs designed to stimulate fundamental research, development and market-introduction of effective CO2-reduction technologies.
Early development	Business R&D Grant	EUDP in Denmark has helped funding almost 600 projects and has advanced the technological maturity level (TRL) of the funded technologies from an average of 4.3 to reaching an average of 7 since 2007.
	Loan and Equity Financing	Clean Energy Innovation Fund in Australia was created in 2016 to invest $200 million in early-stage companies focusing on technologies and businesses that have passed beyond research stage to help them progress to development stage.
	Venture Capital	NYSNØ Climate Investment in Norway invests in unlisted firms (from 2018) that develop solutions to climate change, primarily targeting transition from technology development to commercialisation.
Late development	Tax Credit	Italy has an R&D tax credit for "GREEN" innovation of 15% against expenditure on green innovation activities granted up to a maximum of 2 million euro annually.
	Infrastructure	Low Emission Transport Fund by New Zealand focuses on innovative transportation solutions, particularly to demonstrate, accelerate diffusion, and stimulate wider replication, including provision of infrastructure.
	Public Procurement	SCALE Act in US supports CO2 utilisation by authorizing the Department of Energy to provide funding for municipalities and states to procure CO2-based products for infrastructure projects
	Adoption Subsidy	ISDE (Investeringssubsidie duurzame energie en energiebesparing) in the Netherlands is a household green adoption subsidy. ISDE includes detailed requirements about qualifying technologies in addition to minimum efficiency standards.

Source: OECD "STI policies for Net Zero portal, Net zero portal | STIP Compass (oecd.org)

Blending public and private financing to support technology development and diffusion

Blended finance has emerged as a way to address the problem of high risk and uncertain returns that characterise investment in sustainability projects with a technology component such as clean energy, notably in developing countries. Blended finance combines different financing sources (e.g. public with private sources), different types (e.g. concessional with non-concessional loans), and different purposes (e.g. using funds for development purposes to mobilise funds with commercial purposes). It works by combining risk mitigation tools, such as first-loss mechanisms, with debt and equity funds to help firms cross the "valley of death" at various stages of the innovation cycle, thus crowding in private investment. Despite its potential to crowd in private investment in support of sustainable development projects, total blended finance remains limited in the range of USD 50 billion per year between 2018-20 (OECD, 2022[68]). Furthermore, the use of blended finance in science and technology policy is in its infancy; with limitations on blending subsidy support to firms with equity investments for example due to state aid rules and a 'funding' rather than financing approach to public support to business R&D. Nevertheless, in OECD countries such as Norway, Germany, France and the Netherlands national development banks, government pension funds, and investment agencies are experimenting with funds-of-funds or specialised growth funds that allow for blending public and private finance to support technology based firms. (OECD, 2023, Forthcoming[69]).

Intellectual property rights

Intellectual property rights (IPRs), such as patents and copyrights, aim to incentivise innovation by allowing firms to capture a higher share of the returns to their research investments. Successful patent applicants are provided a temporary monopoly, lasting twenty years from the initial application date in the main patent offices, in return for disclosing information on the innovation in the patent document, which is part of the public record. By granting this market power, IPRs help to mitigate potential losses from knowledge spillovers and encourage innovation. IPRs are also supposed to help other innovators since innovation activity is cumulative in nature.

Evidence shows that patents are effective in encouraging innovation in countries with high economic development. However, some sectors are more likely than others to rely on patent protection, because some products are more prone to imitation and more easily codified in a patent document. These include the pharmaceutical, biotechnology, medical instruments and chemical sectors. In other sectors, patents are not perceived as an important means to protect innovation (Cohen, Nelson and Walsh, 2000[70]). This has implications for environmental technologies, which for the vast majority do not belong to the sectors most dependent on patent protection. Hence, changes in IP rights (either strengthening or weakening) would be unlikely to induce significant changes in innovation activity except in a handful of sectors, including for example biotechnology.

However, programmes to accelerate the examination of patents in clean technologies can be useful in helping companies raise capital. For example, in 2022 the US patent office launched a new Climate Change Mitigation Pilot Program to fast-track patent applications for innovations that reduce greenhouse gas emissions. Other similar programmes exist in various patent offices (Dechezleprêtre, 2013[71]). IP sharing mechanisms, including cross-licensing agreements, can also help accelerate diffusion of and knowledge spillovers in clean technologies.

Patent boxes, a special tax regime that applies a lower tax rate to revenues linked to patents, has been a popular tool across OECD countries recently. They have been shown to induce tax competition and simply affect the stated location of taxable income, particularly of multinational companies, without much effect on innovation activity (Gaessler, Hall and Harhoff, 2021[72]). Therefore, patent boxes specifically targeted at low-carbon technologies are unlikely to be successful at encouraging clean innovation and should not be encouraged (Bloom, Van Reenen and Williams, 2019[58]).

What should government efforts focus on?

How much should public efforts increase?

Given the scale of the climate neutrality challenge, it is hardly debatable that an increase in public R&D funding for low-carbon technologies is necessary, but an important question for policy makers is how much to increase government R&D funding on low carbon innovation including by reprioritisation across all areas of R&D. The difficulties associated with estimating the potential benefits from new R&D spending make this question delicate to answer; however, given the need for a diversified technology portfolio to address climate change, it is hard to imagine that there would not be enough deserving technologies for the research funding available. Rather, economic analysis suggests that the constraints are likely to come from other sources, such as the supply of scientists and engineering personnel available to work on low-carbon projects, and how quickly this pool can be grown. That is, the limits to how much can be spent come not from the number of deserving projects, but rather from limits of the existing research infrastructure.

It is worth pointing out, however, that models of climate policy show that the optimal policy heavily relies on research subsidies. For example, Acemoglu et al. (2016[38]) suggest that 90% of all R&D expenditures in clean technologies should be funded by the government during a couple of decades, until the productivity of clean technologies catches up with that of dirty technologies. Earlier IEA estimates suggested that achieving global energy and climate change ambitions consistent with a 50% reduction of energy-related CO_2 emissions in 2050 with respect to 2007 (the 2010 BLUE Map scenario, much less ambitious than the current net-zero pledges) would require a twofold to fivefold increase in public RD&D spending (IEA, 2010). More recently, the IEA called for USD 90 billion of public money to be mobilised globally as soon as possible to complete a portfolio of demonstration projects before 2030. Currently, only roughly USD 25 billion is budgeted for that period (IEA, 2021[2]).

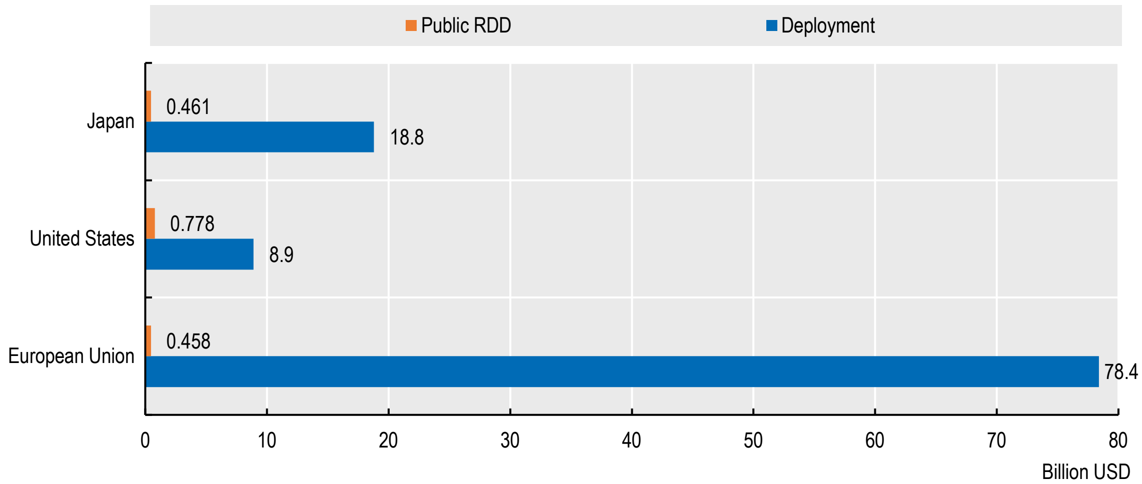
Commitments to fund R&D should have a long-term component. Policy predictability and credibility is important for companies, universities and other research stakeholders to make long-term decisions on innovation and investment choices. To provide political credibility for a long-term commitment, revenues from auctioned carbon permits could provide a source of sustained funding for low carbon R&D. A tension might exist between predictability and flexibility, and policies must remain able to adapt as new evidence emerges on climate impacts or new technologies appear. This calls for ‘predictably flexible’ policies, which include planned reviews at predictable intervals where changes can be made according to the latest information available to policy makers.

Any policy effort to accelerate innovation in clean technologies needs to include a component to train new scientists and technical workers in order to increase the supply of qualified scientists in the long run. As an example, consider the experience of the U.S. National Institutes of Health (NIH), which supports biomedical research in the U.S. The annual NIH budget nearly doubled between 1998-2003, from USD 14 billion to ISD 27 billion. However, after this rapid doubling, research funds were cut. This created a career crisis for the researchers supported by the earlier doubling of support, as there was more competition for funds to start their own research projects (Freeman and Van Reenen, 2009[73]). This NIH experience suggests that growth in clean R&D budgets should be slow and steady, allowing time for the development of young researchers in the field. The training of new scientists through graduate and post-graduate grants should also be an important component of the overall public research funding approach.

What stage of technology development to target?

Evidence indicates that OECD countries have so far put a strong emphasis on deployment policies compared with direct R&D support. For example, European countries spent EUR 458 million in 2018 to support R&D in wind and solar power. The cost to society implied by subsidies for the deployment of wind and solar technologies that same year represented EUR 78 400 million - 150 times more than public R&D expenditures (Figure 24). The ratio is smaller in the US and in Japan, but the emphasis is clearly on deployment.

Figure 24. Public RD&D vs deployment support in renewable energy, 2018 (bn USD)



Source: IEA Energy Technology RD&D Budgets database, December 2022; Taylor, Michael (2020), Energy subsidies: Evolution in the global energy transformation to 2050, International Renewable Energy Agency, Abu Dhabi.

Even in technologies that are far from market maturity, such as green hydrogen, the focus of public policies curiously lies on deployment (Cammeraat, Dechezleprêtre and Lalanne, 2022[5]), while R&D activity and large-scale demonstration projects are critical to bring down the cost of electrolysers.

The growth of climate-related trademarks shown in Figure 7 compared with the decrease in climate-related patents shown in Figure 5 as well as the decreasing share of green venture capital directed at seed and early-stage funding both suggest that the policy emphasis on deployment rather than on R&D translates into a focus by the business sector on diffusion and commercialisation of existing technologies rather than on the development of new innovations. These observations suggest that a re-balancing of STI policies towards R&D support is required.

The recommendation to re-balance STI policies towards more R&D support also has to be considered in light of the role of global value chains. Some countries have specialised in the manufacturing of "clean" goods, with the emergence of the Chinese solar PV industry in the recent decade a prime example of this trend. However, while R&D support policies by nature target domestic firms only, deployment subsidies benefit domestic and foreign firms alike. Indeed, the Chinese solar PV industry was built on the back of renewable energy subsidies in the US, Europe and other regions (e.g. Australia). Therefore, it is of utmost importance that deployment support policies are designed against a clear understanding of the domestic supply-side (firms, talents, infrastructure) so that they do not face constraints, such as skill shortages and lack of infrastructure, in the domestic economy. At the same time, given the global nature of value chains in the production of goods and provision of services that will be needed to achieve climate neutrality, provisions limiting the foreign content of these goods and services might actually slow down the climate transition, especially in the presence of shortages in the domestic economy.

Which technologies to target?

As regards what sorts of technologies should be priority for funding, governments should focus their support on technologies that have a strong public good component[6] (and are therefore less likely to be provided by the market) but are central to any decarbonisation pathway. The goal is to avoid providing public support for research that the private sector would already undertake. This could include projects supporting long-term research needs where the payoff occurs further into the future (such as hydrogen), as well as infrastructure that has a public good dimension (including transportation networks and storage for carbon, smart grids, and infrastructure for electric vehicles).

The scope of public funding also needs to better align with the innovations needed to reach net-zero emissions. In the IEA's Net Zero Emissions scenario, CCUS, hydrogen and sustainable bioenergy account for around 15% of the cumulative emissions reductions between 2020 and 2050. In comparison, CCUS, hydrogen and biofuels currently represent respectively 3.1%, 2.3% and 3.5% of public RD&D expenditures in energy technologies in IEA Member countries.[7] Similarly, just three technologies are critical in enabling around 15% of the cumulative emissions reductions between 2030 and 2050: advanced high-energy density batteries, hydrogen electrolysers and direct air capture (DAC). They collectively represent only at the very most 1.7% of public RD&D expenditures in energy technologies in IEA Member countries.[8] These technologies should therefore be the focus of governments' support.

In general, there is a need to adopt a portfolio approach, in order to diversify both industrial and technology risks. Given the technological uncertainty inherent to the transition to a net-zero economy, countries should support an array of technologies, and, within supported technologies, not focus on particular production processes to avoid lock-in and give all green technologies a fair chance.

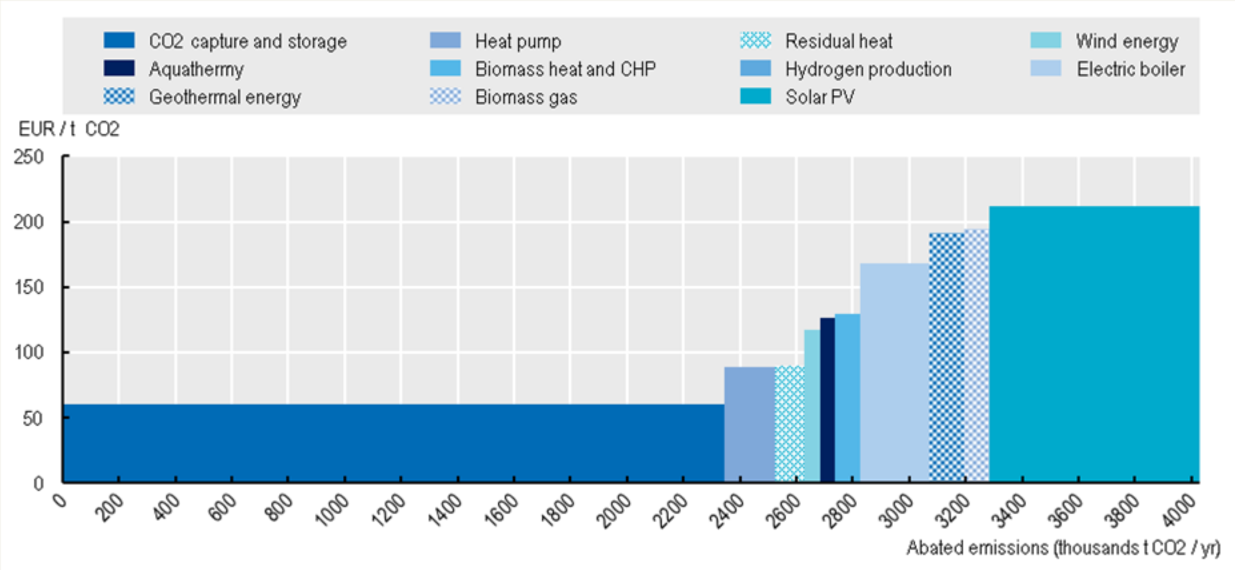
Importantly, specific R&D support instruments are required. Horizontal R&D support has indisputable advantages, including its low administrative cost and technological neutrality, but by construction, it benefits mostly technologies that are closest to the market, as illustrated by the Netherlands' Sustainable Energy Transition Incentive Scheme (Box 3). Support to an emerging technology – such as hydrogen – justifies a stronger focus on targeted instruments for R&D, complementing horizontal instruments.

Box 3. Technology-neutral policy in the Netherlands

The main technology support instrument in the Netherlands is the Sustainable Energy Transition Incentive Scheme (SDE++), which subsidises the additional costs associated with adopting a low-carbon technology. The instrument is allocated to applicants in increasing order of subsidy requirement per tonne of CO2 reduction. While this allocation design is economically efficient and ensures least-cost decarbonisation in the short run, it favours technologies that are close to the market at the expense of more radical alternatives that are still at an earlier stage of development, such as green hydrogen (Figure 25). Similarly, the Netherlands supports R&D mostly through broad tax credits and the Innovation Box, which are technology neutral but, by construction, benefit mostly technologies that are closest to the market. Therefore, the analysis of the Dutch technology support policy package calls for a balanced approach that supports both emerging and mature technologies. Options include holding separate tenders across technology readiness level for deployment instruments, and combining horizontal R&D support with targeted support for emerging technologies.

Figure 25. Technology adoption support in the Netherlands favours mature technologies

SDE++ subsidy demand curve in first tender



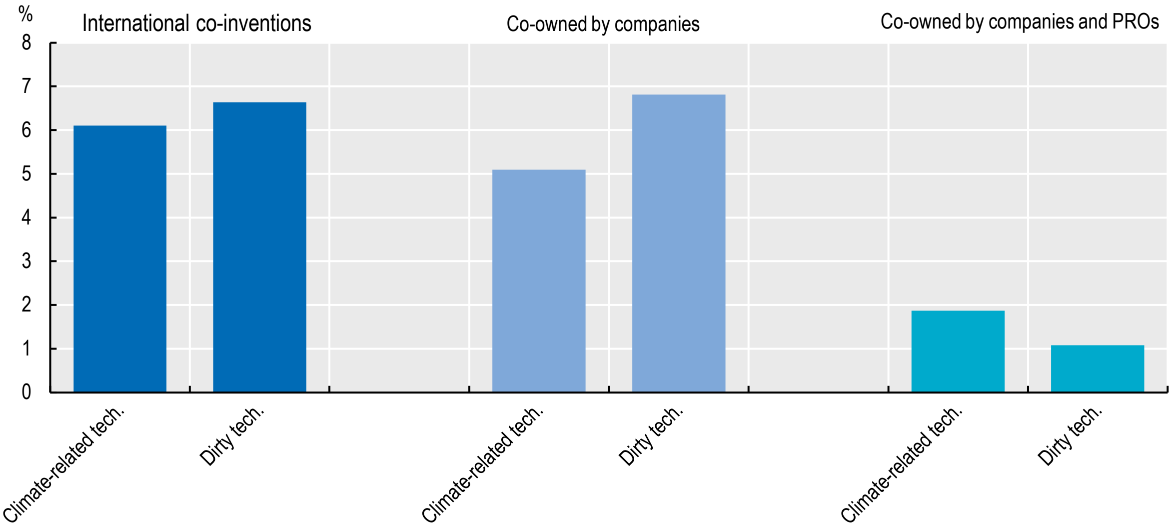
Note: average requested subsidy per ton CO2 at the technology category level inferred from the requested total amount and the eligible energy production, using PBL's emission factors to transform the eligible energy production in avoided emissions
Source: OECD calculations based on RVO and PBL data (Anderson et al., 2021[3])

Supporting collaboration in research and development

Governments can also help create an enabling environment for collaborations across firms and between private actors and the public sector, especially universities and public research organisations. Overall, among patents protecting climate change mitigation technologies filed through the Patent Cooperation Treaty, only 6.1% involved a collaboration between inventors located in at least two different countries and only 5.1% involved a collaboration between several companies (Figure 26). This compares with respectively 6.6% and 6.8% for the "dirty" technologies that climate change-related technologies are meant to replace. This suggests that there is ample room for improvement. In addition, only 1.9% involved a collaboration between a firm and a public research organisation, although in that case the proportion is greater than for dirty technologies (1.1%), probably owing to the relative novelty of low-carbon technologies and their closer proximity with academic research.

Figure 26. Collaborations in patent development for "clean" and "dirty" technologies

Share of patents involving collaboration in total patents by technology domain



Note: Data refer to patent applications filed under the Patent Cooperation Treaty (PCT), by filing date. International co-inventions relate to patents with co-inventors located in different countries. Public research organisations (PROs) include government, universities, hospitals and private non-profit organisations.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, December 2022.

International co-operation in research

Societal challenges, such as climate change, food security, and global health issues, are increasingly targeted in international STI co-operation, mirroring their adoption as priorities in national policies. Climate change in particular has become a significant focus for international co-operation, and efforts are underway to translate this focus into research priorities that national and international funding bodies can pursue.

Coordinated action can accelerate innovation, enhance economies of scale, strengthen incentives for investment, and foster a level playing field where needed. Sharing experiences between countries and industries can reduce individual risks and accelerate progress towards viable solutions. Measures and commitments to deployment can accelerate economies of scale and corresponding cost reductions.

As mentioned above, at COP21 in Paris, 20 countries from across the developed and developing world[9] promised to double their clean energy R&D investment over five years as part of a global initiative called "Mission Innovation". This commitment to innovation was matched by the private sector through the Breakthrough Energy Coalition. The commitment also included a pledge by members to freely share information between one another in relation to their energy R&D programmes and (where mutual interests exist) collaborate on joint research and capacity building. It has been proposed to use Mission Innovation as a platform to share lessons from successes and failures in both technology and policy design and implementation (Myslikova and Gallagher, 2020[74]).

International co-ordination of R&D funding across different technologies and stages of innovation will be critical to developing the next generation of clean technologies. A relevant model is the International Thermonuclear Experimental Reactor (ITER) nuclear fusion project, funded by the EU, India, Japan, China, the Russian Federation, Korea and the United States. At least two major platforms for international R&D collaboration already exist for climate technologies – CGIAR for agriculture and the IEA Technology Collaboration Programmes (TCPs) for energy. There are currently 38 IEA TCPs, which facilitate collaborative energy R&D in end-use for buildings, electricity, industry, transport, fossil fuels, fusion power, renewable energy and hydrogen. The UNFCCC's Climate Technology Centre and Network (CTCN) could also play a role on this front, but it is grossly underfunded (USD 10 million a year) in view of its ambitious mandate.[10]

International technology diffusion

Wide access to clean technologies is crucial to meet the Paris Agreement goal of limiting the increase in global temperatures to well below 2 degrees Celsius. This requires considerable technology diffusion from North to South as 90% of the increase in global carbon emissions until 2050 is expected to occur in the developing world (OECD, 2012[75]) while the vast majority of low-carbon technologies are still invented in developed countries. For example, Japan, USA, Germany, Korea, China and France together account for 78% of the low-carbon inventions patented globally from 2013 to 2017 (Probst et al., 2021[76]).

Fostering technology transfer involves considerable policy and economic challenges because developing countries cannot bear the financial costs of catching up on their own, while firms in industrialised countries are reluctant to share strategic intellectual assets. This has led to an intense debate on policies that affect technology diffusion, with a particular focus on the role of IPRs, which developing countries view as a barrier to technology diffusion (Glachant and Dechezleprêtre, 2016[77]). By contrast, industrialised countries argue that IPRs provide innovators with incentives to disseminate their inventions through market channels, such as foreign direct investment (FDI) and the international trade of equipment goods. Empirical evidence indeed suggests that strong intellectual property laws increase international technology transfer, including specifically for climate-friendly technologies (Dechezleprêtre, Glachant and Ménière, 2012[78]).

The literature also suggests that restrictions to the international trade of equipment goods (through higher tariff rates) and barriers to foreign direct investment both negatively impact the international diffusion of patented knowledge (Dussaux, Dechezleprêtre and Glachant, 2022[79]). Therefore, reducing trade barriers for "green" products (through reduced tariffs on low-carbon technologies), encouraging foreign direct investment and resolving intellectual property issues in emerging economies all constitute important levers to encourage international technology diffusion and, ultimately, innovation in the developing world. A further key determinant of international diffusion is the domestic level of technological development, or technological capabilities.

While international co-operation will be important to accelerate the development and diffusion of low carbon technologies, it is important to recall that the scope of technology uptake may be limited by natural resource constraints, such as lithium for battery storage, fresh water for hydrogen electrolysis, platinum for fuel cells and digital technologies, etc.

In addition, measures to encourage international technology diffusion complement but do not substitute for domestic policies that aim to create a market for low-carbon technologies, notably demand-side policies mentioned above including regulation, standards, adoption subsidies, market-based instruments, public procurement, infrastructure provision, etc.

5 Policy packages to encourage low-carbon innovation

Although STI&I policies have an important role to play in carbon neutrality strategies, they are insufficient on their own and need to be part of broader packages of climate policies. Although technology policy can help facilitate the creation of new environment-friendly technologies, it provides little incentive to adopt these technologies on a broad scale, unless R&D activities manage to make clean technologies competitive with high-carbon alternatives on economic grounds. Until then, incentives for adoption need to be provided by industrial policies, including demand-side measures, which can make low-carbon options more attractive economically, and supported by a range of other instruments.

While innovation policy tends to relate mostly to research, development and demonstration policies, industrial policy includes all types of instruments that intend to structurally improve the performance of the domestic business sector (Criscuolo et al., 2022[80]), boost growth and competitiveness and foster the emergence of new industries at scale. It therefore extends well beyond R&D and other 'technology-push' investments to also include targeted demand–pull policies, infrastructure provision, state-backed finance, and coordination and institutional frameworks. Combined with an overarching strategy designed to achieve a predefined objective, this set of policy instruments constitutes an industrial strategy.

Green industrial strategies

In the last few years, a growing number of economies have launched ambitious, long-term "green" industrial strategies. The common objective of green industrial strategies consists in re-directing technological innovation and deployment away from dirty production processes and towards low-carbon technologies to achieve decarbonisation goals. Green industrial strategies include for example the European Green Deal, Germany's Climate Action Programme 2030, Japan's 2050 Zero Carbon Cities, the UK's Industrial Strategy and The People Republic of China's 13th Five-Year Plan for Economic and Social Development (2016-2020). Each strategy consists of numerous instruments, targeting many climate-related industries, as well as final consumers.

These green strategies share several common features, reviewed by Criscuolo et al. (2022[80]):

- Mission-oriented approaches to reach specific objectives under high technology uncertainty. The strategies articulate public objectives without prior knowledge on how to reach them nor guaranteeing their technological/political possibility (i.e. a problem-led pathway). While in standard government strategies, goals were set by a stocktaking of the currently available technologies, modern mission-oriented green strategies put the emphasis on specific objectives (e.g., achieving zero-CO_2 emissions by 2050, banning the sale of gas/diesel vehicles by 2050, deploying sustainable alternative transport fuels), rather than on the way to reach these (see Box 4 for more detail on mission-oriented policies for climate). This is directly linked to the long-term horizon of such strategies, typically up to 30 years, and the huge uncertainty about technological progress at this horizon.

- Demand-side instruments play a central role. As the primary role of these strategies is to correct for environmental externalities, demand-side instruments, such as product regulation and standards, and Pigouvian taxes and subsidies, are fundamental tools of these strategies.
- Complementary supply-side instruments. As, in some instances, innovation incentives may be insufficient and there may be a need to tackle coordination failures in the production system, green strategies also include all kinds of supply-side instruments. They are rather considered as complementary instruments, compared to the indispensable role of demand-side instruments. Supply-side instruments are used to facilitate and accelerate the technological development into the right direction to meet the goals and requirements by expected future regulations (e.g., promote the development of a network of public charging stations for electric vehicles by a certain date). In general, they also include skill strategies, to ensure that the new jobs created by the green economy can be filled (Consoli et al., 2016[81]).
- International, national and local coordination fora. As mission-oriented strategies deal with a large number of industries that are supposed to provide complementary inputs to reach the targeted objectives, green strategies also include coordination mechanisms. These are not only about coordinating investments by domestic industries, but also about coordinating the anticipation of stakeholders, including consumers and international co-ordination (e.g. in the context of the IPCC, UNFCCC COPs, etc). A green strategy often includes several sub-strategies, in which many stakeholders are required to discuss and coordinate their roles.
- Governance. Some strategies, such as the Germany Climate Action Programme 2030, embed a legal monitoring and evaluation mechanism by annually defining reduction targets by sector to ensure that the targets are met, but this is not explicit in the other strategies.

Box 4. STI mission-oriented policies for climate and net zero goals

Mission- oriented innovation policies (MOIPs) and programmes have re-emerged in the past few years as governments seek to tackle specific “societal challenges”. MOIPs are defined as a co-ordinated packages of policy and regulatory measures tailored specifically to mobilise science, technology and innovation in order to address well-defined objectives related to a societal challenge, in a defined timeframe (Larrue, 2021[82]). These measures span different stages of the innovation cycle, from research to demonstration and market deployment, mix supply-push and demand-pull instruments, and cut across various policy fields, sectors and disciplines. Missions require a “market-shaping” framework, rather than the more traditional and passive “market-fixing” framework focused on correcting market failures (Mazzucato, 2018[83]). Compared to the traditional mission orientation, the new missions focus more clearly on the demand side and the diffusion of innovations; seek coherence with other policy fields; and focus both on incremental and systemic innovations.

Lessons from government interventions suggest that although governments have succeeded in some technological missions (e.g. the Apollo “Man on the Moon” mission), they have struggled in others that are systemic in scope and include a dimension of social change. These lessons warrant caution, and attention to the design and evaluation of mission-oriented approaches. Some essential interrelated questions arise when analysing the new mission orientation and its potential for addressing global challenges. The technological challenges and measures required to cope with climate change differ radically from those characterising defence and space-related mission R&D programmes, where the main supplier and buyer was the government. Today, the private sector performs most of the R&D in many OECD countries, but it is not directed towards societal goals. Public investment in innovation directed to low-carbon goals can however crowd-in private investment and facilitate the development and diffusion of such innovations across the economy. Examples of new mission-oriented policies include Norway's Green Platform, Denmark's Green missions, Ireland's "zero emissions challenge", the UK Industrial Strategy Challenge Fund and the Netherlands' Mission-Driven Top Sectors policy or the EU's missions on climate change and climate-neutral and smart cities. Mission-oriented innovation approaches focus on improve co-ordination through the collective development of a strategic agenda, the setting of a dedicated governance structure, and the implementation of a tailor-made and integrated policy mix. A recent OECD analysis of -80 net zero innovation missions shows that, despite displaying some systemic features, existing net-zero missions remain for the most part focused on support to research and innovation, led by national science, technology and innovation agencies or departments and drawing almost exclusively on STI funds (i.e the STI-only trap). In addition, the many of the missions focus on the monitoring of the strategic agenda and less on implementation, in particular the scaling up of private investment (i.e. the orientation trap).

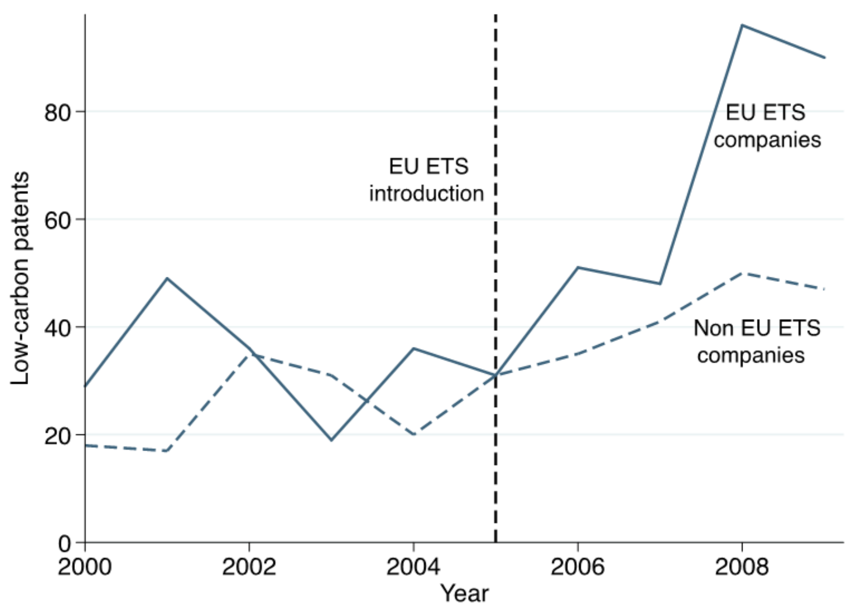
Source: OECD, 2023 (forthcoming): STI Outlook 2023, Chapter 5. OECD Publishing.

Carbon pricing and removal of fossil fuel subsidies

By making polluting emissions costly, carbon pricing policies and the removal of fossil fuel subsidies change the relative costs and benefits of competing technologies. For example, carbon taxes make coal relatively more expensive than natural gas or renewable energy. Thus, policies that force agents to internalise pollution externalities encourage the diffusion of environment-friendly technologies. This, in turn, also encourages innovation. Because private R&D is a profit-motivated investment activity, innovation responds to the change in the expected diffusion of technologies induced by carbon pricing.

For example, there is ample empirical evidence that carbon pricing, by encouraging the diffusion of low-carbon technologies, affects innovation activity further up the technology supply chain, favouring R&D in clean technologies and discouraging it in conventional (polluting) technologies (Dechezleprêtre and Kruse, 2022[84]). The impact on innovation is estimated to be both large and rapid. For example, Figure 27 shows how the European Union carbon market (EU ETS), which obliges 12,000 industrial facilities across Europe to purchase allowances to cover their carbon emissions, has increased innovation activity in low-carbon technologies among regulated companies (Calel and Dechezleprêtre, 2016[85]). The figure plots the low-carbon patenting activity of firms regulated under the EU ETS against that of a carefully selected control group of unregulated but similar firms. Both groups showed similar innovation activities before the introduction of the EU ETS, but companies having to pay a price on their carbon emissions from 2005 reacted by filing 30% more patents in low-carbon technologies, particularly in renewable energy, energy storage, energy efficiency and carbon sequestration. The innovation response to policy was not only significant but happened quickly.

Figure 27. Carbon pricing induces low-carbon innovation



Note: Around 3000 companies regulated under the EU ETS are included in the sample. "Non EU ETS companies" are a group of 3000 European companies that are not regulated under the EU ETS but operate in the same country and the same economic sector and are comparable in size and innovation capacity to companies regulated under the EU ETS.
Source: (Calel and Dechezleprêtre, 2016[85]).

As shown in Section 2, carbon remains largely unpriced globally (Figure 14). Adequate carbon pricing (i.e. fully pricing the negative environmental externalities associated with carbon emissions) would increase incentives to develop new low-carbon technologies and contribute to a cost-efficient decarbonisation. Since it is expectations over future prices that determine innovation, rather than current prices, long-term regulatory consistency is crucial for new technology development. Commitments to raising carbon prices in the future and clear carbon prices trajectories can already induce innovation even if current carbon prices are low. Carbon Contracts-for-Difference (CCfD), experimented in Germany, can decrease uncertainty thanks to forward-contracts on the price of abated greenhouse gases (Neuhoff, May and Richstein, 2022[86]). The Dutch carbon levy, a top-up on the EU ETS with an explicit carbon price trajectory, is another example of how well-designed carbon pricing instruments can reduce uncertainty for investors (see Box 5).

Carbon pricing can also provide revenues to fund support to new green technologies. For example, the European Union created the NER300 programme, which was funded from the sale of 300 million emission allowances from the New Entrants' Reserve (NER) set up for the third phase of the EU's Emissions Trading System, which generated EUR 2.1 bn. The aim of the programme was to fund innovative demonstration projects in CCS and renewable energy. The NER300 was followed by the Innovation Fund, also funded by revenues from the auction of 450 million emission allowances from the EU ETS. It will provide around EUR 20 billion of support over 2020-2030 (depending on the carbon price) for the commercial demonstration of innovative low-carbon technologies.

Carbon prices are also an important complement to innovation and industrial policies in that they can serve as a backstop against possible rebound effects induced by efficiency improvements brought about by technological change.

Box 5. Carbon pricing and technology deployment support in the Netherlands

The OECD recently conducted a comprehensive evaluation of the set of policy instruments in place in the Netherlands to reach its 2050 decarbonisation objectives in the manufacturing sector 2050 (Anderson et al., 2021[3]). The Netherlands illustrates the strength of an approach that combines a strong commitment to raising carbon prices with ambitious technology support. These two pillars can be mutually reinforcing, as a clear trajectory of increasing carbon prices helps make the business case for investment in low-carbon technologies.

The first pillar of the Netherlands' approach, the carbon pricing signal, includes a carbon levy on industrial emissions that sets an ambitious price trajectory to 2030. This levy provides a strong incentive to encourage low-carbon investment in industry. It is designed so that the additional carbon price kicks in gradually, thus avoiding immediately burdening businesses with new taxes. However, the overall carbon price signal is tempered by provisions that grant extensive preferential treatment to energy-intensive users, including in the form of energy tax exemptions, lower tax rates for large energy consumers, and freely allocated carbon emissions allowances.

The second pillar of the Netherlands' decarbonisation strategy aims at supporting the uptake of low carbon technologies, focusing on the cost-effective deployment of both mature (e.g. renewable electricity) and radically new technologies (e.g. hydrogen) through subsidy programmes and corporate tax incentives. The main instrument is the Sustainable Energy Transition Incentive Scheme (SDE++), which subsidises the additional costs associated with adopting a low-carbon technology.

Standards and regulation

Standards have been a key instrument for implementing environmental policy, for example in air quality and waste regulation, and have been the driving force behind the development of clean technologies such as scrubbers, catalytic converters, and incineration plants (Vollebergh and van der Werf, 2014[87]). As such, they can effectively complement emission pricing and incentive-based policies to create demand for low-carbon innovations and induce technological change (D'Arcangelo et al., 2022[88]).

Different types of standards can be used. For instance, a performance standard sets a uniform control target for firms, but do not dictate how this target is met (e.g. emission quotas). Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation, such as by requiring that a percentage of electricity be generated using renewable sources.

A usual problem with standards is that while market-based policies such as carbon pricing provide rewards for continuous improvement in environmental quality, standards penalise polluters who do not meet them, but do not reward those who do better than mandated. However, an advantage of standards is that while market-based instruments will lead firms to focus on adopting technologies closest to market, technology mandates can more effectively encourage the deployment of more expensive emerging technologies that are not yet cost-effective.

Moreover, standards can be especially effective in certain cases, for example when behavioural anomalies result in consumers paying little attention to the benefits of energy efficiency. Such behavioural anomalies provide support for policies such as product labelling or minimum performance standards that reduce the burdens on consumers to seek out energy-efficient products. They can also be helpful to restrict and phase out high-emitting activities or technologies that are particularly undesirable (D'Arcangelo et al., 2022[88]).

Working with stakeholders to develop technical standards is particularly important to help create markets for emerging technologies. For green hydrogen, this includes standardisation on guarantees of origin, on hydrogen purity, on the design of liquefaction/conversion and regasification/reconversion facilities, for equipment specifications and for blending hydrogen into the gas grid. Another example is standardisation of plugs for electric cars across vehicles and charging stations. Such standards are best set at the international level, and at least call for international coordination of national standards (Vollebergh and van der Werf, 2014[87]). Coordination on standards across countries – in the context of standard-setting organisations – could help to overcome barriers to first deployment created by international competition. In the European Union, it has been argued that the fragmentation in environmental standards may prevent innovative European cleantech companies from scaling up in the way that their US and Chinese competitors do on their domestic markets (Tagliapietra and Veugelers, 2020[65]).

A harmonisation of standards and regulations for scrap and waste is also necessary to facilitate the use of recycled products. Relabelling by-products of steel production (e.g. slag and fly ash) from 'waste' to 'product' would reduce the administrative burden associated with purchasing scrap for companies and increase imports opportunities.

Minimum content requirements and public procurement can help create markets for recycled products and synthetic and bio-based feedstock. While such policy efforts would be ideally implemented at the international level, national minimum content standards and public procurement could already give a necessary boost to the recycling and bio-based industries.

Finally, an important and cost-effective way for governments to increase the necessary investments in green technologies can be achieved through reducing regulatory uncertainty. This is the case across many technologies, such as CCS, where project developers currently run the risk of being held liable for carbon leaks outside of storage facilities or other environmental damage. Defining liabilities would allow investors in CCS to more accurately price and potentially insure this risk.

Structural Policies

Structural reform – in product markets, encouraging competition and enabling new entry; in labour markets, enabling better resource allocation; and in financial markets, helping generate funding for risky investments – is another important pillar to help create a sound business environment that encourages investment in technology and in knowledge-based companies, enable innovative firms to experiment with new ideas, technologies and business models, increase their market share and reach scale. Ensuring access to foreign sources of knowledge is also important for innovation, as most innovation happens outside national borders, and requires reforms to enhance the openness of an economy to trade and investment and facilitate the flows of knowledge and people.

Start-ups and entrepreneurship policies

A rapid shift towards a low-carbon economy, necessary to meet the targets of the Paris Agreement while delivering on economic growth ambitions, requires radical new innovations on top of incremental improvements in existing technologies. Young firms tend to be major drivers of such radical innovation (Andrews, Criscuolo and Menon, 2014[17]; Calvino, Criscuolo and Menon, 2016[18]). The role of innovative start-ups in enabling ‘green growth’ is likely to grow against the backdrop of broader technological and economic trends such as digitalisation (Greenstein, Lerner and Stern, 2013[89]) as well as sector-specific developments such as the increasing use of more modular technologies in the energy sector (Popp et al., 2020[90]).

Venture capital (VC) is instrumental to create markets for and allow the scale-up of the most market-ready technologies. VC is a key complement to government support for technology, as it helps entrepreneurs through the “valley of death” by financing pilots and demonstrations of innovative ideas and prospective technologies, which are often the output of government-funded R&D (Breschi et al., 2019[91]). VC is also important for small companies to move beyond an initial niche market.

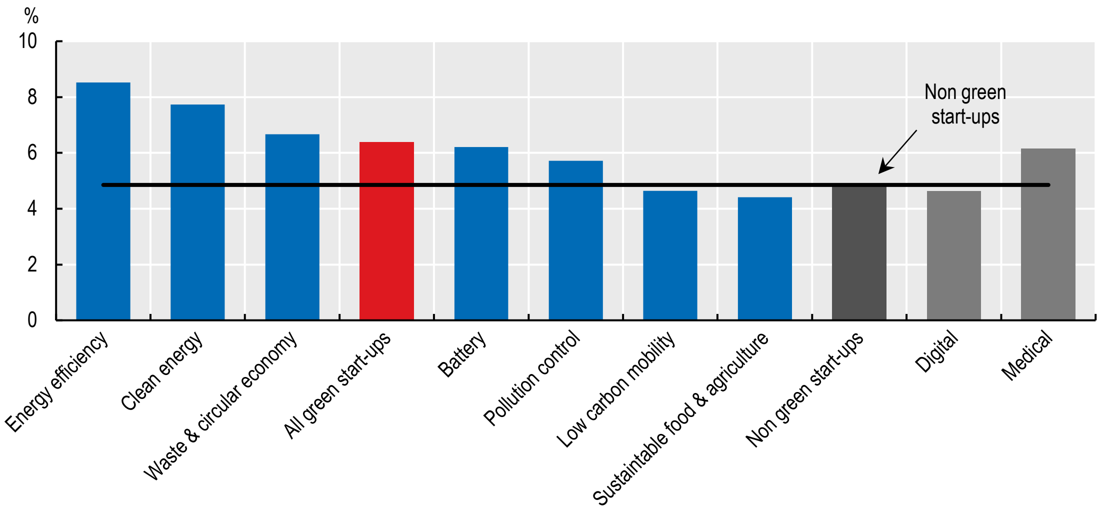
However, as shown in Section 2 (Figure 8), after a large increase in the last decade, global VC investment in climate-related start-ups has levelled off recently, and the share of total VC funding going to climate-related start-ups has remained fairly stable since 2010. It has been argued that clean technologies do not fit the VC model well, because of high capital intensity, long development lead times and high technological and regulatory uncertainty (Lerner and Nanda, 2020[92]).

Policymakers can reduce the barriers to the private funding of clean innovation via angel finance or venture capital by providing patient capital (i.e., capital that does not require a very fast payback period) through low-interest or subsidised loans for young firms (Hepburn, Pless and Popp, 2018[42]). This long-term horizon is particularly important for developing climate technologies, since it takes more time for climate tech start-ups to make a profit compared to other sectors, such as ICT.

Government Venture Capital financing—that is, the use of public funds to invest in young innovative firms—has emerged as a policy tool to help fund start-ups that do not fit the “VC profile” and thus complement private venture capital (VC). Government venture capital can help develop the private venture capital markets through learning-by-doing (Lerner and Watson, 2008[93]) and may provide a “stamp of approval” for start-ups, which may help firms obtain follow-on funding from private sources (Guerini and Quas, 2016[94]). Government VC may also serve as a resource to help entrepreneurs finance projects with high social value, such as firms engaging in climate-friendly innovation.

A recent landscaping exercise has identified 217 Government Venture Capital entities across the 38 OECD member countries (Berger et al., forthcoming). Evidence suggests that start-ups developing environment-friendly products and services (“green” start-ups) are more likely to receive funding from government-owned Venture Capital entities than start-ups operating in other areas (Figure 28). Over the period 2010-2020, government-owned VCs were involved in 4.9% of VC deals across all sectors but in 6.4% of VC deals involving green start-ups specifically.

Figure 28. Involvement of government Venture Capital in funding of green and non-green start-ups, 2010-2020



Note: the graph shows the average share of venture capital deals in which a government-owned venture capital is involved for green start-ups, non-green start-ups, and sub-categories within these groups, over the 2010-2020 period.
Source: OECD, STI Micro-data Lab: Start-ups database, December 2022.

Public-private partnerships, associating public with private capital, could be an interesting option to provide start-ups with sufficient funding, particularly at the expansion and later stages , when technological challenges have been overcome and capital intensity surges in order to scale up business. Over 2018-2020, 68% of government VC deals in green start-ups also involved a private VC (so-called mixed deals), which is an encouraging development.

Competition and business dynamics

Decarbonisation policy instruments aim at affecting the structure of the economy and, therefore, interact with business dynamics and the level of competition. In general, horizontal instruments intended for the green transition that affect firms across the board are not detrimental to competition; on the contrary, they can contribute to fostering business dynamism to the extent that they promote innovation. By contrast, targeted instruments – either technology-specific or location-specific – may give an advantage to specific firms over others if badly designed and may create barriers to firm entry and exit which may slow down reallocation, innovation and decarbonisation.

Encouraging the entry of new, innovative firms and the exit of less productive, less energy efficient firms is thus key and complementary to decarbonisation incentives, because new entrants are not subject to the path dependence in the direction of innovation, which is often a disincentive for low-carbon innovation. Start-ups are often the vehicle through which radical innovations enter the market, while older incumbent firms often focus on incremental changes to established technologies. Lack of business dynamism may prevent low-carbon innovators from overtaking fossil fuel-based incumbents and secure market shares, even if they are more efficient. By enabling entrants and small firms to compete and eventually challenge large incumbents, reallocation can have direct and indirect positive effect on both challengers' and incumbents' incentives to innovate, in particular in low-carbon technologies.

Skills and labour market policies

Decarbonisation and the transition to the net-zero emission economy will affect both labour supply and demand in the industry. On one hand, skills associated with "green" occupations (such as wind energy engineers, fuel cell technicians, recycling coordinators, electrical engineering technologists, biochemical engineers, etc.) will be increasingly demanded in the low-carbon economy (Vona et al., 2018[95]). On the other hand, decarbonisation will bring about some labour reallocation of economic activity, as described above, which will also affect skill demand.

The adequate provision of green skills – defined as those "needed by the workforce, in all sectors and at all levels, in order to help the adaptation of products, services and processes to the changes due to climate change and to environmental requirements and regulations" (OECD/Cedefop, 2014[96]) – is particularly important for firms engaging in low-carbon technology deployment and scale-up, and likely to promote investment. More generally, it contributes to the overall absorptive capability of the industry, which is a necessary condition for reaping the benefits of R&D and translate it into local deployment. Re-skilling and up-skilling displaced workers with green skills through active labour market policies and adult training is necessary both to address social concerns and to contribute to reducing skill shortages in the future low-carbon industries. Cross-sector training programmes can ease labour market transitions from surplus to shortage sectors. Timely and transparent information on sectoral labour markets can help workers to anticipate future labour needs and policy makers to monitor and accompany the changes. With a view to the longer run, education programmes need to incorporate new subjects and competences in curricula, so that the next cohort of workers can cope with the low carbon transition in the workplace.

Adequate green skills supply is also an important complement to green supply-push policies. For example, investment made through the American Recovery and Reinvestment Act adopted after the Great Financial Crisis (which included over USD 350 billion of direct government spending, of which 17% was directed at green investments, including energy efficiency retrofits, investments in public transport and clean vehicles, and brownfield sites clean-ups) was more effective in geographic areas where green skills were more prevalent (Popp et al., 2020[97]). In other words, the green stimulus was particularly effective in enhancing opportunities in communities already in a position to support the green economy.

Scientific institutions also have an important role to play in providing the necessary skills, e.g. in training researchers and teachers in climate related scientific fields. Besides educational supply-side considerations, it is important that higher education institutions encourage research mobility between the public and private sectors so that knowledge and education circulate throughout the society. Doctoral education and postdoctoral training need to be geared not only to careers in academic research but also increasingly for research careers beyond academia, or in non-research careers that can benefit from the advanced skills of doctorate holders (OECD, 2021[98]).

Public infrastructure

Infrastructure needs are extremely important for the decarbonisation of the transportation and heavy industry sectors. In particular, the transition to a low-carbon economy requires infrastructure for renewable electricity production and distribution, power system flexibility (e.g. energy storage, smart grids, long-distance and cross-border power transmissions), the heat network, hydrogen production and distribution, carbon transportation (potentially using the existing gas pipeline infrastructure), charging stations for electric vehicles, and public transportation.

Investment towards upgrading communication networks, such as universal broadband internet and enabling technologies including Artificial Intelligence (OECD, 2020[99]) is also important for climate neutrality, in particular as they can help to make behavioural changes triggered by the Covid-19 pandemic (teleworking and teleconferencing) persistent. However, such investments may need to be accompanied by new regulation that facilitates and encourages these behavioural changes over the longer term, including flexible working arrangements or a right to work from home when feasible.

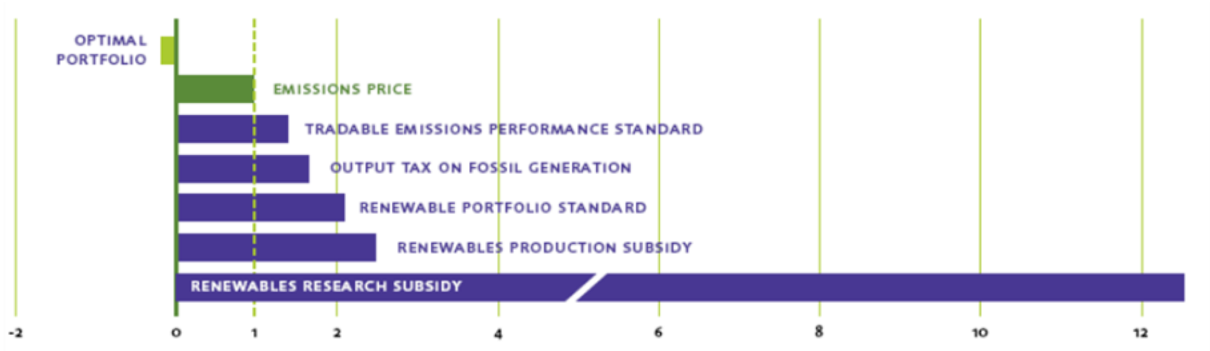
Visibility over future infrastructure plans is key for firms to undertake investments in low-carbon technologies. Bringing more clarity at the national, regional and local levels seems pressing to reduce uncertainty and induce the necessary investments in low-carbon technologies that depend on public infrastructure for their deployment.

The importance of combining instruments

The presence of multiple barriers and market failures, as detailed in Section 2, implies that several policy instruments will be required to encourage low-carbon innovation. Technology support policies alone can be insufficient on their own: for example, for technologies whose demand is contingent upon the existence of some form of carbon pricing, such as carbon capture and storage (CCS), no R&D would be conducted even with large research subsidies if no carbon pricing were in place. The American Recovery and Reinvestment Act of 2009 provided USD 2 billion to develop carbon capture and storage technologies for coal-fired power plants. Similarly, in 2009 the European Energy Programme for Recovery (EEPR) dedicated EUR 1 billion to co-finance CCS projects. All such CCS projects were later abandoned as low carbon prices rendered it difficult to attract private financing. Although technology policy can help facilitate the creation of new environmentally friendly technologies, it provides little incentive to adopt these technologies, unless R&D activities manage to make clean technologies competitive with high-carbon alternatives on economic grounds. Until then, incentives for adoption need to be provided by demand-side policies, which can make low-carbon options more attractive economically. However, demand-side policy cannot supplant the need for technology policy, given the presence of barriers and market failures at the R&D and demonstration stages.

Studies evaluating the effectiveness of various policy options find that environmental and technology policies work best in tandem, with the appropriate balance between technology support and other environmental policies depending on the maturity of the technology in question. In models to study policies for reducing CO_2 emissions and promoting innovation and diffusion of low-carbon technologies, an optimal portfolio of policies—including emission pricing and R&D—typically achieves emission reductions at significantly lower cost than any single policy, as shown for example by Fischer & Newell (2008[100]) for renewable energy in the US (Figure 29).

Figure 29. Cost of climate change policy under different policy scenarios



Source: (Fischer and Newell, 2008[100]) .

Importantly, carbon prices and technology policy are mutually reinforcing. Technology support policies lower the cost of green technologies, thus making them competitive with existing technologies, which in turn can build the case for stronger carbon pricing (and more ambitious environmental policies more generally) in the future. Innovation and industrial policies, by creating economic winners from the low-carbon transition, can also improve the political acceptability of future climate policies.

6 Conclusion and policy recommendations

Given the significant reallocations implied by the low-carbon transition (between activities, sectors, firms, workers, and technologies, the focus of climate policy is gradually shifting to the transition costs, and to how to mitigate them. Bringing about the necessary cost reductions to make carbon-free technologies competitive with their high-carbon alternatives is therefore a primary objective of climate policy.

Reducing the costs of low-carbon alternatives through innovation would accelerate the diffusion of available technologies, which is critical to reach medium-term carbon emissions reductions. Yet, in the long run, developing new breakthrough technologies that still only exist at the prototype phase is critical to reach climate neutrality objectives. An important question for policy is therefore how to accelerate the diffusion of existing low-carbon technologies further, while reigniting low-carbon innovation in breakthrough technologies.

For these reasons, this paper argues that research, innovation and industrial policies – with a focus on supporting both development and deployment of low-carbon technologies – should constitute a cornerstone of strategies to reach carbon neutrality. Given the large range of barriers and market failures discouraging low-carbon innovation, the theoretical justifications for stronger innovation and industrial policies are very clear, as explained in Section 3 of this report. STI&I policies can also partially substitute for low carbon prices, which are often difficult to implement politically. In fact, STI&I policies are more popular among voters and citizens than other climate change policies (including carbon pricing, bans or regulations), making them an attractive option from a public acceptability point of view. In addition, by reducing technology costs and boosting the growth of new carbon-efficient firms and sectors, such policies will also facilitate the adoption of more ambitious climate policies, including – through international technology diffusion – among emerging economies, where the bulk of future emission growth is projected to take place.

The empirical evidence presented in this paper points to a stagnation in public spending for low-carbon R&D as a share of GDP, a worrisome decrease in climate-related innovation as measured by patent filings, and a stable share of global VC funding directed at climate-related start-ups. In comparison, trademark filings for climate-related goods and services have grown markedly, in line with evidence suggesting a policy emphasis on deployment rather than on R&D support. These findings, combined with the rest of the analysis presented in this report, suggest a number of practical policy recommendations.

First, governments should re-balance STI&I policies, giving greater emphasis on the RD&D stages, particularly for technologies that are not mature yet. Support for early-stage deployment of clean technologies is necessary because of the existence of barriers and market failures also at this stage (e.g., learning spillovers, second-mover advantage) and should continue, but additional efforts should go primarily to RD&D. An increase in public R&D expenditures targeted at technologies still far from market, but necessary to reach carbon neutrality by 2050, is urgent. As the increase might need the research system to adapt and so might be gradual, a larger forward leap can only happen if low carbon RD&D becomes a clear priority in governments' budgets. Post-covid recovery programmes can help increase public R&D budgets, but these will need to be sustained in the long-run, rather than remain one-off increases.

Scientific research remains important for low carbon innovation but its role is not limited to an input to innovation. Science provides the evidence to inform governments and citizens about the potential impacts of climate change. Science also has an important advisory role to play and can help dispel misinformation that can erode public trust in science. It can also enable the public acceptance of low carbon technologies, such as CCUS, and the participation of citizens in climate research.

Support to RD&D undertaken by business should primarily be direct, rather than horizontal and technology-neutral. Climate neutrality will require innovation in breakthrough technologies, which cannot be incentivised through horizontal support (or deployment subsidies). R&D tax credits are unlikely to help for technologies that are far from market and require long development timelines. Technology neutrality – even between various low-carbon technologies – is in reality not neutral: it tends to favour technologies closest to market and with the shortest payback time.

Barriers to external funding should be reduced to help high-risk companies raise funds. Favourable tax schemes, low-interest or subsidised loans for young firms, and a greater mobilisation of government venture capital toward the green transition could all help.

There is ample room for improvement in collaborative R&D, between firms, between firms and public research institutions and between countries, to capitalise on complementary skills and resources at the domestic and international levels.

Although innovation and industrial policies should play a greater role in carbon neutrality strategies, they are insufficient and need to be part of a broader package of climate policies. Carbon pricing, in particular, is necessary to encourage the adoption of clean technologies that are closer to market and thus “redirect” innovation toward low-carbon activities. They can also serve as a necessary backstop against possible rebound effects following efficiency improvements brought about by technological progress, and can provide a useful source of revenue which can be earmarked for technology support policy.

Finally, the low-carbon transition will involve a massive structural transformation that will require the alignment of policy frameworks beyond innovation and climate policies. Competition and entrepreneurship policies play a critical role to encourage business dynamism, the creation of new innovative firms and the reallocation of resources toward the most resource-efficient firms. Education, skills and science policy are necessary to make sure that the transformation can rely on the right set of skills and research. An efficient and cost-effective shift to a low-carbon economy thus requires the engagement of many parts of government beyond those traditionally mobilised in the development of climate change policies. These system-wide changes will require a whole-of-government approach with cooperation and policy action across a wide range of government actors, affecting many stakeholders. Achieving such an approach could involve the development of shared visions and missions, joint programming between agencies, or strategic oversight by high-level cross-departmental committees

Developing such a package requires the development of mission-oriented strategies across all countries committed to carbon neutrality. Mission-oriented innovation approaches, which are increasingly adopted by countries to address a wide variety of societal challenges, can help to promote systemic change because of their integrated nature (Larrue, 2021[82]). They are expected to improve coordination over traditional innovation policies through the collective development of a strategic agenda, the setting of a dedicated governance structure, and the implementation of a tailor-made and integrated policy mix. However, recent analysis shows that, despite displaying some systemic features, existing net-zero missions remain for the most part focused on support to research and innovation, led by STI authorities and drawing almost exclusively on STI funds (Larrue, 2022[101]). To realise their transformative potential, missions for net-zero need to move beyond this ‘STI only trap’.

Endnotes

[1] https://zerotracker.net/

[2] The Internet of Things (IoT), which comprises devices and objects whose state can be altered via the Internet, with or without the active involvement of individuals. It includes objects and sensors that gather data and exchange these with one another and with humans.

[3] Blockchain is a decentralised and disintermediated technology that facilitates economic transactions and peer-to-peer interactions. In addition to supporting information exchange, it enables protocols for value exchange, legal contracts and similar applications.

[4] Trademarks related to climate change mitigation or adaptation are identified based on Natural Language Processing method applied to their textual description. Data on trademark applications relate to trademarks registered at the European Union Intellectual Property Office (EUIPO), the Japan Patent Office (JPO) and the United States Patent and Trademark Office (USPTO).

[5] The new database allows for the tracking of private investment targeting new companies engaged in climate-related sectors and activities. Clean-tech start-ups are identified using information on their sector of operation (e.g. renewable energy) and on the textual description of their activity using natural language processing (NLP) methods, based on a climate change related vocabulary.

[6] A public good is non-excludable (it is impossible for one user to exclude others from using it) and non-rivalrous (when one person uses a good, it does not prevent others from using it). CCS is an example of a clear public good: once captured and stored, it is not possible to exclude consumers who have not paid for the carbon removal to benefit from the reduced emissions and lower climate change damages, and these benefits are shared by all.

[7] Electrification of industrial processes

[8] Respectively 0.71% for batteries (not only advanced high-energy density batteries), 0.44% for hydrogen production (not only electrolysers) and 0.56 for CO2 capture and separation (not only direct air capture).

[9] These included Australia, Brazil, Canada, Chile, China, Denmark, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea, Mexico, Netherlands, Norway, Saudi Arabia, United Arab Emirates, the United Kingdom and the United States.

[10] The CTCN mandate is to "Stimulate technology cooperation and enhance the development and transfer of technologies to developing country Parties at their request".

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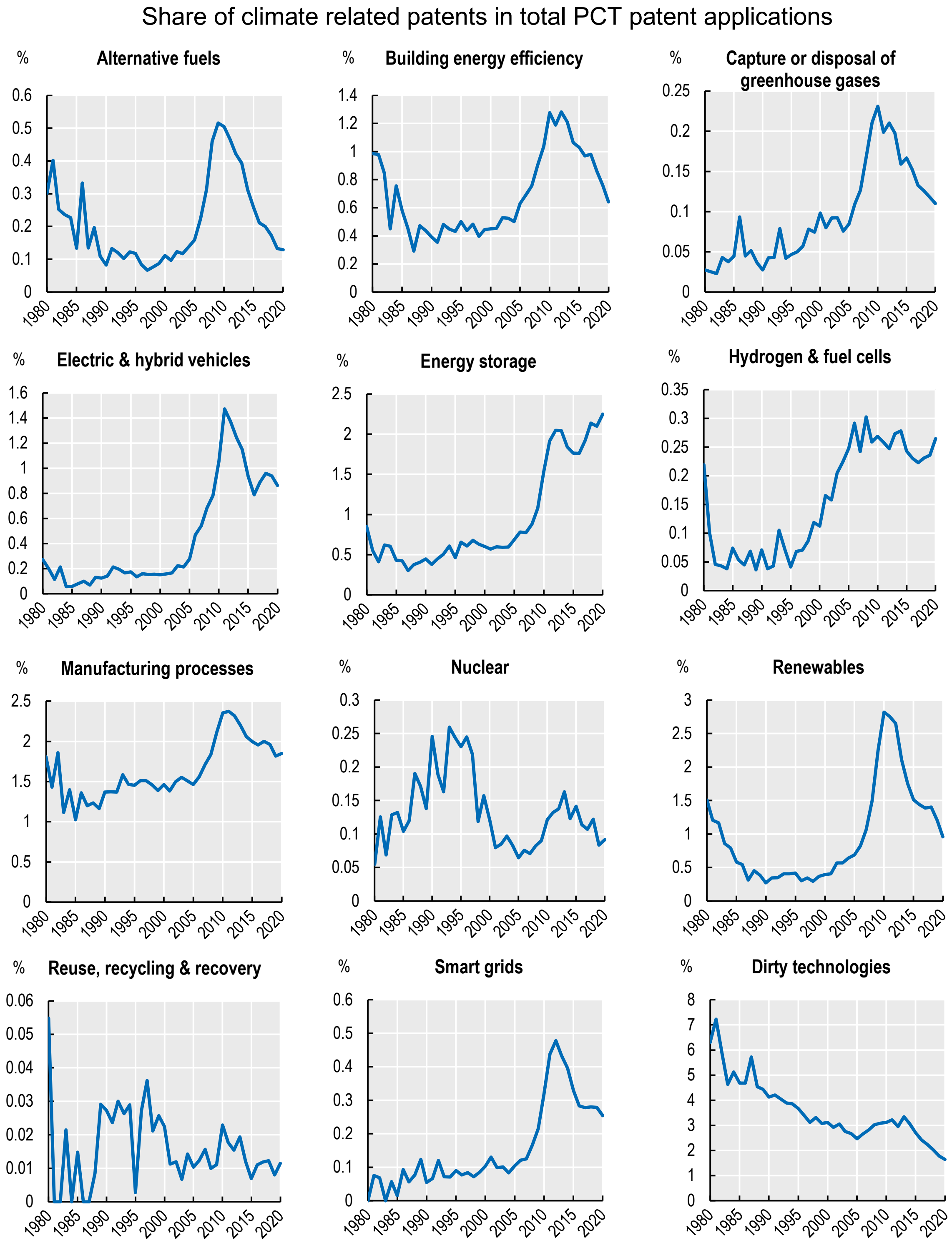
Annex A.

Figure A A.1. Global trends in low-carbon patents by technology



Note: Note: Data refer to families of patent applications filed under the Patent Cooperation Treaty (PCT), by earliest filing date.
Source: OECD, STI Micro-data Lab: Intellectual Property Database, http://oe.cd/ipstats, November 2022.