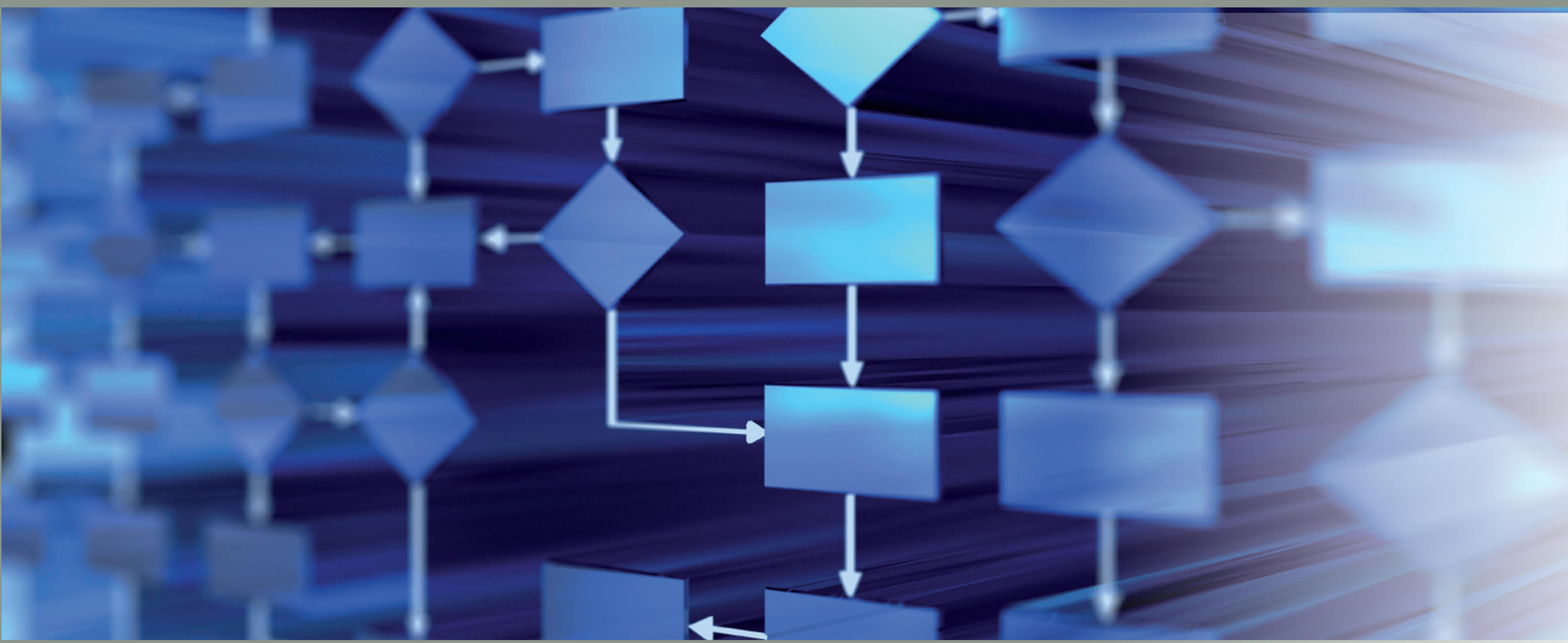
Economic Research Working Paper No. 72

Directing innovation towards a low-carbon future

Joëlle Noailly



April 2022

WIPO
WORLD
INTELLECTUAL PROPERTY
ORGANIZATION

Directing innovation towards a low-carbon future

Joëlle Noailly[1]

Abstract:

Achieving the ambition of limiting global warming to 1.5°C to 2°C by the end of the century as enacted in the Paris Climate Agreement will require massive investments in environmental technologies and a forceful change of path away from high-carbon technologies. This report presents novel descriptive evidence on global trends in patenting in low-carbon technologies, with a particular focus on the energy and road transport sector. The analysis discusses the role of public policies in driving the rate and the direction of innovation for a low-carbon future.

JEL Classification: Q55 ; O31 ; Q42 ; L62

Keywords: *Climate change, Innovation, Clean technologies, Patents, Energy, Electric vehicles, Environmental policy, Technology Policy*

Disclaimer:

The views expressed in this article are those of the author and do not necessarily reflect the views of the World Intellectual Property Organization (WIPO) or its member states.

[1] Head of Research of the Centre for International Environmental Studies (CIES) and Lecturer in the Department of International Economics at the Graduate Institute, Geneva, Switzerland. Associate Professor in Environmental Economics at Vrije Universiteit Amsterdam and Research Fellow at Tinbergen Institute, The Netherlands.

1. Introduction

As of November 2021, world leaders raised their ambitions in terms of emissions reductions at the COP26 in Glasgow in order to meet the goal of limiting global warming to 2°C – and to strive to 1.5°C – by the end of the century as agreed in the 2015 Paris Climate Conference. Many countries representing 80% of the world economy have announced targets of net-zero emissions by 2050, and large emitters such as China and India have voiced similar goals for 2060 and 2070, respectively. Achieving such ambitious climate goals within the time scale of a few decades will require massive investments in environmental technologies – i.e. technologies leading to greenhouse gas reduction, improved resource use, energy efficiency, waste minimization, reuse and recycling – and a forceful change of path away from polluting technologies.

Fifteen years ago, the Stern Review, one of the most influential reports on climate change, called to embark on "*a revolution that will surpass the scale and impact of previous world-changing technologies such as railways and personal computers*" (Stern et al., 2006). Yet today, low-carbon innovation represents only 6% of worldwide patenting activities and many obstacles remain for a swift transition to low-carbon technologies. Many of these technologies are still more expensive than high-carbon ones and face limited market demand. In addition, high-carbon technologies still benefit from the fact that our economies have a long history of fossil-fuel dependency. Despite this, new hopes are being brought by our ability to develop Covid-19 vaccines in record time, rapid declines in solar PV costs, and countries' renewed climate ambitions. The European Union has recently adopted several policy measures as part of the European Green Deal to reduce emissions by 55% with respect to 1990 levels, and thereby achieve climate neutrality by 2050. About 35% of the EUR 100 billion budget under Horizon Europe, the EU's research and innovation program, will be allocated to address climate change. The US pledges at the COP26 aim to cut the country's emissions by 50% from 2005 levels by 2030. Joe Biden's $1.85 trillion 'Build Back Better' infrastructure bill includes $555 billion toward fighting climate change – the largest ever climate action in US history – among which $300 billion for 10-year tax incentives schemes to promote wind, solar, nuclear and electric vehicles. Finally, China also committed to achieve carbon neutrality by 2060 and to strengthen research on cutting-edge technologies such as nuclear fusion, smart grids and new materials. Other promising public-private initiatives, such as the collaboration between Breakthrough Energy from Bill Gates and Mission Innovation, a 20+ countries initiative, have been announced at the

COP26 in Glasgow to accelerate the commercialization of critical clean energy technologies, such as green hydrogen, sustainable aviation fuel, direct air capture and long duration energy storage.

The objective of this study is to provide new descriptive evidence on the world's progress on innovation towards low-carbon technologies and to review the main drivers of this change. The study is organized as follows. Section 1 defines low-carbon technologies and provides general trends. Section 2 presents the key mechanisms which can contribute to a reorientation of innovation towards low- (and away from high-) carbon technologies, contrasting technology-push versus market-pull drivers. Sections 3 and 4 provides an overview of historical trajectories and recent progress for the two largest CO2-emitting sectors, namely energy generation and transportation, respectively. Finally, Section 5 concludes and discusses implications for building a coherent policy framework.

2. Definitions and global trends in low-carbon technologies

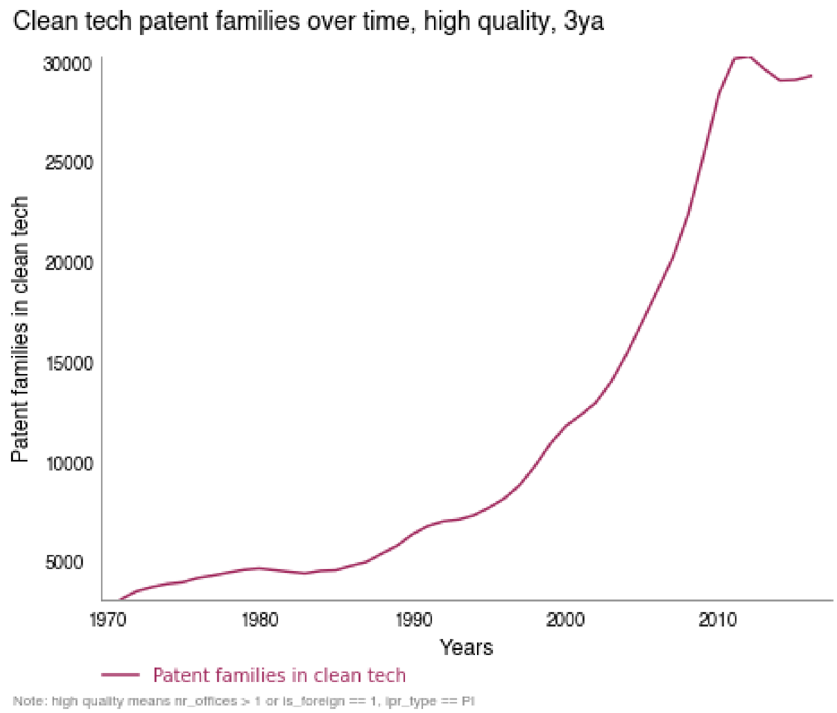
A large set of environmental technologies contributes to reduce the carbon and environmental footprint of economic activities. According to OECD classification[2], this set encompasses technologies related to 1) environmental management (air pollution, water pollution and waste), 2) water-related adaptation technologies, 3) capture, storage, sequestration of greenhouse gas emissions and 4) climate change mitigation technologies (CCMT) related to energy, transportation and buildings (Haščič & Migotto, 2015). Looking at trends in patenting activities (see Box 1 on how environmental patents are identified) in environmental technologies provides insights on the evolution of these technologies over time. Environmental patents represent today only a small share of total patenting activities, namely about 6% of worldwide patent families in 2019. Figure 1 plots the evolution over time of patents covering all environmental technologies groups. After the initial take off in the 1970s and 1980s, patents slowly resumed growth over the 1990s. Most remarkably, the sector witnessed exponential growth over the 2000-2010 period, where the number of patent families rose from 10,000 to 30,000 yearly, witnessing a 3-fold increase in just a decade.

[2] http://stats.oecd.org/wbos/fileview2.aspx?IDFile=0befc58e-d72f-4ff9-b27e-84e446240e34

Box 1 – Patent statistics

Patent data are extracted from the PATSTAT database to measure the evolution of innovation activities in environmental technologies. Patent data present the advantage of being highly disaggregated at the technology level. Detailed search strategies for environmental patents based on International Patent Classification (IPC), Cooperative Patent Classification System (CPC) and extensive keywords searches are available thanks to extensive work from the OECD, EPO and IEA over the past decades (EPO, OECD/IEA, 2021; Haščič & Migotto, 2015). The Y02 tagging scheme for CCMT technologies developed by the European Patent Office represents in particular a significant advance (EPO, 2016). The search strategies presented in this report are based on Haščič & Migotto (2015) for environmental technologies. Complementary analysis on road transport also relies on the classification of Aghion et al. (2016) to compare 'clean' (electric and hybrid), 'grey' (improved fuel efficient combustion engines) and 'dirty' (standard combustion engines) innovation in the automobile industry. All graphs included in this report have been provided by the team from the Economic Department at WIPO. Graph plots represent 3-year moving averages of the total number of patent families in a given technological hierarchy level based on Haščič & Migotto (2015). Only patent families filed in at least two patent are selected in order to focus on high-quality patents.

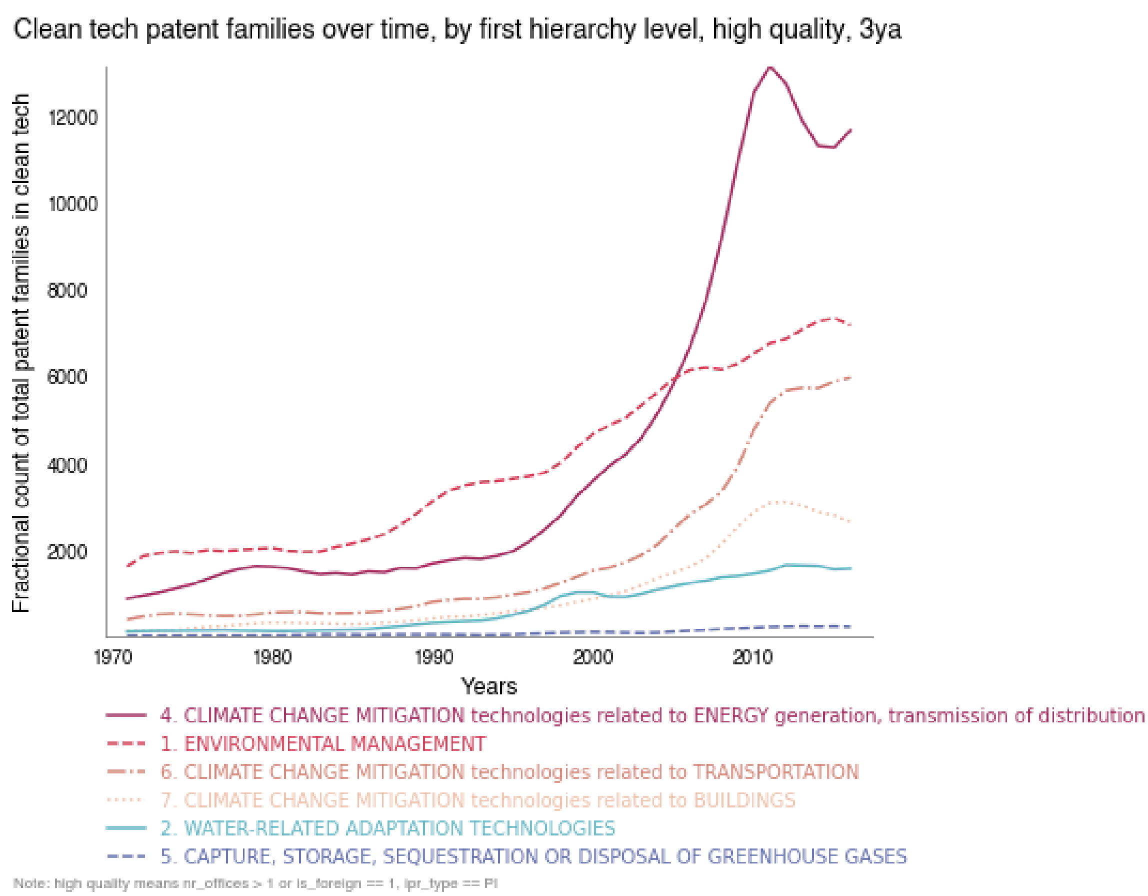
Figure 1. Global evolution of patenting activities in environmental technologies



Source: WIPO computations

Looking in more details at specific technologies (Figure 2), the impressive growth in environmental technologies since 2000 is mainly explained by the rise in CCMT related to energy. Patent families in this technology group account for about one third of all environmental innovation. The next largest groups are composed of patents in environmental management (air pollution, water pollution, waste management), and CCMT in transportation and buildings. In the remainder analysis, we will focus on CCMT technologies, coined as 'low-carbon' technologies, in particular related to energy systems (Section 3) and transportation (Section 4), as these two key sectors account for 34% and 14% of global greenhouse gas emissions worldwide, respectively (Lamb et al., 2021).

Figure 2. Global evolution of patenting activities, per category of environmental technologies



Source: WIPO computations

An important attribute to classify technologies as 'low-carbon' is obviously their capacity to reduce emissions. Low-carbon technologies are technologies that generate relatively low CO2 emission levels when used for a given process, such as electricity generation or mobility. Accordingly, solar energy and electric vehicles fall in this category, but also nuclear energy, since it is undeniably low-carbon, as well as coal-fired power plants coupled with carbon and capture storage (CCS), as this sequestration technology contributes to substantial reductions in carbon emissions compared to standard coal-fired plants.[3] Yet, the potential for CO2 emission reductions of a given technology is not always clear-cut. For electric vehicles for instance, many emissions depend on how the electricity for charging stations is produced (e.g. coal versus solar) and on life-cycle considerations (e.g. emission-intensive production of batteries or recycling). Most definitions so far mostly ignore life-cycle considerations as these involve complex calculations.

Another dimension of low-carbon technologies considers whether these technologies rely on renewable or fossil-fuel energy to classify them either as 'green'/'clean' or 'brown'/'dirty', respectively. This view considers that addressing climate change will necessarily require moving away from fossil-fuels at a rapid pace. Accordingly, even though both solar energy and gas-fired power plants coupled with CCS may generate low levels of carbon emissions, a strong focus on gas-fired technologies would not imply moving away from the fossil-fuel paradigm and would not represent a substantial transition towards a low-carbon world. Keeping on improving and supporting fossil-based technologies even with CCS may run the risk of locking-in future technologies and infrastructure into non-desirable pathways, thereby crowding out non-fossil-based technologies.

To reflect these various considerations, a common convention is to depict *improved* fossil-based technologies as 'grey' or 'blue' (by opposition to 'brown/dirty' and 'green/clean' technologies). Accordingly, conventional vehicles based on internal combustion engines (ICE) are classified as brown/dirty technology, while their improved fuel-efficient version are an example of 'grey' technology. Similarly, while 'green' hydrogen refers to the production of hydrogen from electrolysis using only renewable energy, 'blue' hydrogen from steam-methane

[3] Note that the International Energy Agency (IEA) official definition of low-carbon technologies for energy systems include: renewable energy sources, nuclear power; carbon capture, utilisation and storage (CCUS); hydrogen derived from low-carbon energy sources; technologies that improve the efficiency of energy transformation, other non-fossil power and storage options; and cross-cutting technologies that result in minimal emissions of CO2 and pollution (IEA, 2020). In this background document, our descriptive analysis excludes nuclear energy.

reforming associated with CCS, 'grey' hydrogen from steam reforming via natural gas, while the 'brown' version would typically be produced from coal. In practice, establishing an official clear-cut taxonomy of clean versus dirty technologies is not straightforward and any attempt in this direction will necessarily be subject to political capture by interest groups.[4]

3. What drives the rate and direction of innovation towards low-carbon technologies?

In the 1950s and 1960s, scholars debated on whether technical change is triggered by the supply-side – generic progress in science (technology-push) – or by the demand-side – changes in market demand (demand-pull). Today, these theoretical debates have reached a consensus that both technological-push and demand-pull factors interact and drive the rate and direction of technical change. This section first reviews technological push and demand-pull mechanisms for low-carbon innovation, emphasizing the lack of market demand for low-carbon technologies, and then discusses how these can be combined to alleviate the current carbon lock-in of our fossil-based economies.

3.1 Technology-push versus demand-pull factors

The technology-push perspective considers that technological change progresses from fundamental science to applied research and commercial products, following a linear cumulative increase in our scientific understanding. Since knowledge is a public good and innovating firms cannot prevent other firms from benefiting from their new knowledge, firms have low incentives to invest in new technologies. Such 'knowledge externality' underpins the justification of advancing science via technological push government intervention, so that government support of basic R&D compensates for firms' underinvestment in innovation. Typical policy instruments in the technology-push perspective are government-sponsored R&D, education and training of scientists, R&D tax credits, access to finance for startups, public-private knowledge exchange, and demonstration projects.

4 An illustration of this is the recent discussion on developing a standardized Green Taxonomy for sustainable activities to support the European Green New deal. https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

Theoretically, the optimal level of R&D support for clean technologies should reflect the magnitude of the knowledge spillovers (i.e social returns) from these technologies and there is evidence that such spillovers can be large (Dechezlepretre et al., 2017; Noailly & Shestalova, 2017). Dechezlepretre et al. (2017) show for instance that spillovers from clean technologies, as measured by patent citations trails, are up to 40% higher than for the average innovation and comparable to spillovers from other emerging technologies such as those in the IT sector. This justifies important government public investments for developing early stages clean technologies. Yet, such investment may be slow to materialize. (Popp, 2016) shows that a lag of up to 10 years exists between initial funding and new clean energy academic publications, and more than a decade persists between publication of such articles and the filing of new technology patents. In addition, not all government R&D support is always socially productive. Government programs have had a poor record of accomplishment in the past with many failures, with interest groups attracting large government spending on low-carbon demonstration projects, with mixed outcomes (Nemet et al., 2018).

In contrast to technology-push, the demand-pull perspective sees technological progress as directed towards answering certain needs from markets to solve specific problems. For instance, firms wanting to lower the share of labor costs will invest into labor-reducing technologies such as automation. The concept of 'induced innovation' theorized by this perspective recognizes R&D as a profit-motivated activity: when the price of a input (e.g energy) increases, firms will innovate to save on this factor. Additional mechanisms through which market growth leads to innovation is via learning-by-doing and economies of scale, as larger markets provide more opportunities for exploiting and improving existing products and to benefit from scale economies, triggering cost reductions (Hoppmann et al., 2013; Nemet, 2019).

In the case of low-carbon technologies, however, markets do not provide by themselves the right types of incentives. In the absence of a price on carbon, there is no market demand for CO2 reductions, which implies that the demand for low-carbon technologies is also low. Because of this 'environmental externality', firms tend to underinvest in low-carbon innovation and government intervention is justified to create markets for low-carbon goods and technologies. Typical instruments in the 'demand-pull' perspective belong to the toolbox of environmental policy: namely, carbon taxes, cap-and-trade systems, environmental standards and regulations, environmental subsidies, but also information instruments (eco-labels) and voluntary schemes[5] implemented by private actors.

A substantial body of theoretical and empirical literature shows that environmental policy instruments help to foster low-carbon technological innovation (Fischer & Newell, 2008; Johnstone et al., 2009; Newell, 2010; Noailly, 2012; Popp, 2002, 2002; Requate & Unold, 2003). Although the exact ranking is ambiguous, market-based instruments (such as energy or carbon prices) are typically favored above command-and-control policy instruments (such as technology standards), as they provide for continuous and flexible incentives. Firms' innovation response to energy pricing tend to be quick and of a large magnitude with a price elasticity of patents between 0.5 and 1.5 depending on the specific study[6] (Grubb et al., 2021, Popp, 2002; Aghion et al., 2016a; Calel & Dechezlepretre, 2016). A follow-up question in this literature examines how carbon pricing can affect the direction of technical change towards clean and especially *away* from dirty innovation. Evidence from the electricity and automobile sectors confirms that higher fuel prices are associated with an increase in clean technologies, such as renewable and electric vehicles, and a decrease in dirty innovation, i.e. fossil-fuel energy and conventional vehicles (Aghion et al., 2016b; Noailly & Smeets, 2015). The effectiveness of carbon prices on redirecting innovation crucially depends, however, on the assumption that clean technologies can easily substitute for dirty ones in the production structure of the economy. Renewable energy may be a good substitute for coal, gas and oil energy, provided it can be effectively stored and transported[7]. Similarly, electric vehicles are only a good substitute for conventional cars, provided enough charging stations are available.

Finally, other types of environmental policy instruments such as information or voluntary approaches ('soft' instruments) provide complementary incentives to leverage the markets for low-carbon technologies. Additional market failures, such as imperfect information, or behavioral anomalies hinder the diffusion of low-carbon technologies and thereby the scaling up effect of markets. Consumers may not know that a cheaper low-carbon alternative exists or may not be

5 Information and voluntary approaches are also coined as 'soft' policy instruments (Costantini et al., 2017).

[6] The price elasticity of patents is defined as the ratio of change in patents to the change in energy price: a value of 1 indicates that a 1% increase in energy price is associated with a 1% increase in patents.

[7] The literature tends to find various values for the elasticity of substitution between clean and dirty energy ranging from 0.5 to 2 in the electricity-generating sector (M. Pelli, 2012; Papageorgiou et al., 2017). Enabling technologies, such as energy storage in particular, are key to improve the substitutability between renewable and fossil-fuel production of electricity. Lazkano et al (2017) find a negative impact of coal prices on renewable innovation in the electricity sector, which suggests that until viable energy storage become available, intermittent renewable energies will always rely on conventional power plants as buffer.

able to distinguish low- from high-carbon products. In the case of electricity generation for instance, consumers are not always able to observe whether the electricity they consume comes from low or high-carbon sources. In addition, information tends to diffuse slowly across technology users and Graziano & Gillingham (2015) show for instance that rooftop solar PVs tend to diffuse slowly across neighborhoods, as nearby peers and neighbors increasingly become aware of the opportunity. Behavioral anomalies in energy and automobile markets have recently received a lot of attention, as studies have shown that consumer behavior tends to differ from the standard assumption of self-interested individual agents able to process information appropriately to maximize their utility (Gillingham & Palmer, 2014). In reality, agents exhibit incorrect beliefs about the future, limited attention, and tend to prefer immediate over long-term reward. When buying a new car for instance, many consumers largely undervalue fuel-savings, either because they find other attributes more important or because this involves too complex decision-making. As a result, the market for fuel-efficient cars remains small, even though these investments have positive net present value and are profitable in the long-term. Energy labeling regulations can greatly improve the operation of consumer product markets, despite practical challenges in establishing criteria for accuracy and credibility of the information (Cohen & Viscusi, 2012). Regulators and third-party certification agencies (such as NGOs) have a key role to play to improve the liability of information provided to consumers (Delmas & Burbano, 2011). Voluntary approaches can also help to promote knowledge exchange and foster innovation, although evidence on their effectiveness tends to be mixed.[8]

3.2. Path-dependency and carbon lock-in

Summing up results from the academic literature shows that both technology-push and demand-pull drivers are important and that both approaches are necessary and complementary in the 'policy mix' for clean technologies – a technological opportunity must be connected to market opportunities in order to be successful (Costantini et al., 2017). Combining both types of policy instruments is also relevant in view of the large range of feedbacks between R&D and markets. In practice, knowledge production does not follow a linear process along the sequential stages of scientific research, to applied research and commercialization. Instead,

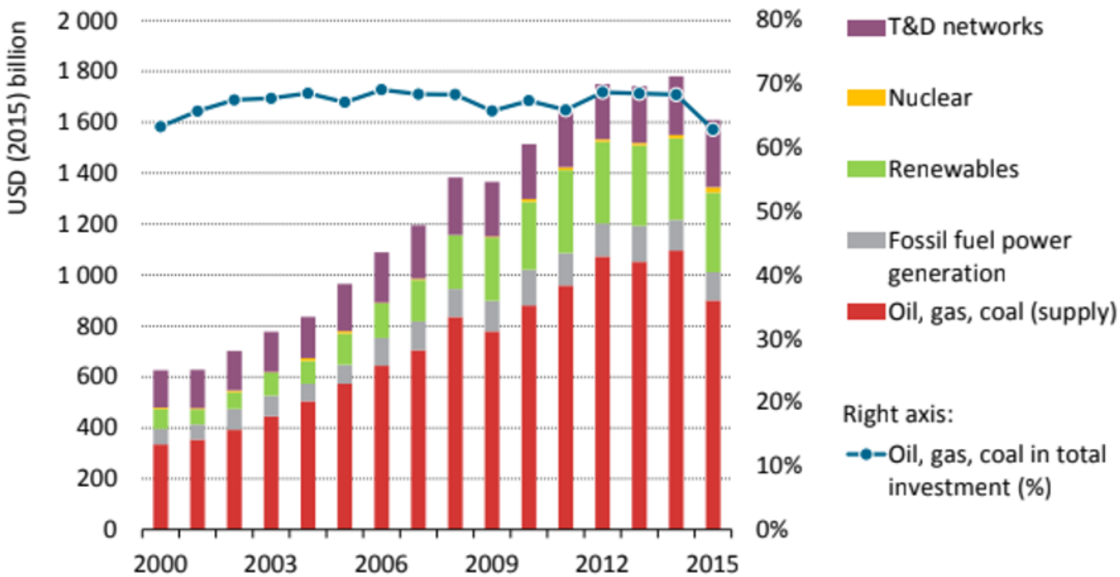
8 Carrion-Flores and Innes (2010) find for instance short-term increases in environmental patenting among firms participating into the voluntary US EPA 33/50 program. However, several years after the end of the program, participating firms had fewer environmental patents.

experience in various stages generate feedbacks to earlier stages. Commercialization and production can for instance inform scientists on how to improve technologies, so that markets and innovation affect each other endogenously: markets drive innovation decisions and vice versa, since innovative, cheaper and better products gain larger market shares. Yet, such feedbacks and non-linearities between R&D and markets can lead to path-dependency in innovation and technological lock-ins - a typical example being the current 'carbon lock-in' of our economies (Unruh, 2000), explained by our long historical dependency on fossil-based energy.

Path-dependency in innovation occurs as the direction of research typically "builds on the shoulders of giants": past advances in one sector make future advances in that sector more profitable and more effective (Acemoglu et al., 2012). Firms may prefer to do incremental rather than disruptive innovation since it is more profitable for them to continue exploiting their existing knowledge base.[9] Both Aghion et al. (2016b) and Noailly & Smeets (2015) find evidence that path-dependency is stronger in dirty than clean innovation, for the automobile and energy sectors respectively. In addition, Acemoglu et al. (2019) show that high prices for coal may lead to a substitution towards shale gas rather than renewable energy as path dependency in fossil fuel technologies tend to favor innovation in fossil fuels. Larger and more profitable markets for fossil-fuel technologies reinforce firms' incentives to direct innovation towards these technologies, rather than clean ones. Today, fossil fuels still dominate the market for energy demand and there are important sunk costs of switching to new types of infrastructures. About 60% of current global investment in energy supply still takes place into oil, coal and gas (Figure 3) and fossil-fuel supporting infrastructure such as pipelines, refineries and gasoline stations expand market opportunities for fossil-fuel technologies.

[9] In the energy sector, this explains why some of the major energy firms promote carbon capture and storage technologies, rather than renewable energy to further prolong profitability in the industry. As Dirk Smit, vice president of exploration technology at Royal Dutch Shell acknowledges: "If it is necessary to pump carbon dioxide underground to deal with climate change, no one has a better head start on knowing how to do this than oil companies." (Bullis, 2013).

Figure 3. Global investment in energy supply over time



Source: IEA, Global Energy Investment report, 2016

Breaking the current lock-in into fossil-fuel technologies requires a coherent mix of policy instruments, combining both technological push policies to increase technological diversity with demand-pull instrument to support low-carbon markets and move away from high-carbon ones. Acemoglu et al. (2012) finds that path-dependency in innovation justifies the need to combine carbon taxes with (temporary) research subsidies specifically targeted at clean R&D. Once there is sufficient accumulated knowledge in clean technologies, research will automatically be directed towards these technologies without the need of further government intervention.[10]

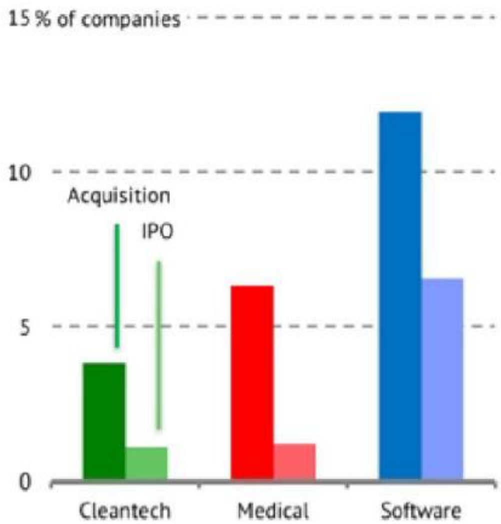
On one side, relying only on technology-push policies would not sufficient to scale up innovation efforts from early stage emerging technologies to the commercialization of mature

[10] Anecdotally, another way to combine demand-pull with technology-push is to design carbon taxes such that revenues are recycled for clean energy R&D.

low-carbon technologies. R&D tax credits for renewable energy would for instance help to support low-carbon technologies, regardless of whether these replace hydroelectricity, gas or coal. A carbon tax instead would reward low-carbon technologies, while incentivizing moving away from high-carbon ones. Related to this, there is still significant action needed worldwide to remove current fossil-fuel subsidies and implement corrective pricing policies to escape the current carbon lock-in (Monasterolo & Raberto, 2019).

On the other side, relying only on demand-pull instruments would require very stringent and socially costly policies to counteract the current path-dependency in fossil innovation. Acemoglu et al. (2012) shows that relying only on carbon pricing to redirect innovation without clean R&D subsidies is sub-optimal, as it would imply sacrificing too much economic growth. Typically, demand-pull policies also runs the risk of focusing on incremental rather than disruptive innovation, as they tend to favor mature technologies close to commercialization. By contrast, less mature technologies benefit from technology-push policies, such as the creation of niche markets (Nill & Kemp, 2009), R&D demonstration projects, or startup finance. On the latter, there is evidence that large incumbent firms tend to focus on improving existing technologies, while startups firms and new entrants are the source of more major and radical innovations (Akcigit 2011; Kamien and Schwartz 1975). In the energy sector, the entry of small firms specialized in renewable innovation considerably helps reducing the innovation gap between fossil-fuel and renewable patenting activities (Noailly & Smeets, 2015). Yet, despite their critical role, small firms in low-carbon technologies face important barriers to scale up their activities. Gaddy et al. (2017) find for instance that cleantech startups have less exit opportunities than biomedical or software startups (Figure 4), as large companies are not willing to acquire promising renewable startups at the risk of potentially cannibalize their own business based on fossil fuels. As a result, access to finance for young firms active in emerging clean technologies is particularly difficult and in any case more difficult than similar firms active in the fossil-fuel business (Noailly & Smeets, 2021). This justifies specific R&D support for small firms active in immature low-carbon technologies, for instance in the form of early-stage research grants (Howell, 2017). Complementary policies, such as competition regulation can also help sustaining entry in the industry.

Figure 4 Fewer acquisitions for cleantech companies compared to other sectors



Source: (Gaddy et al., 2017)

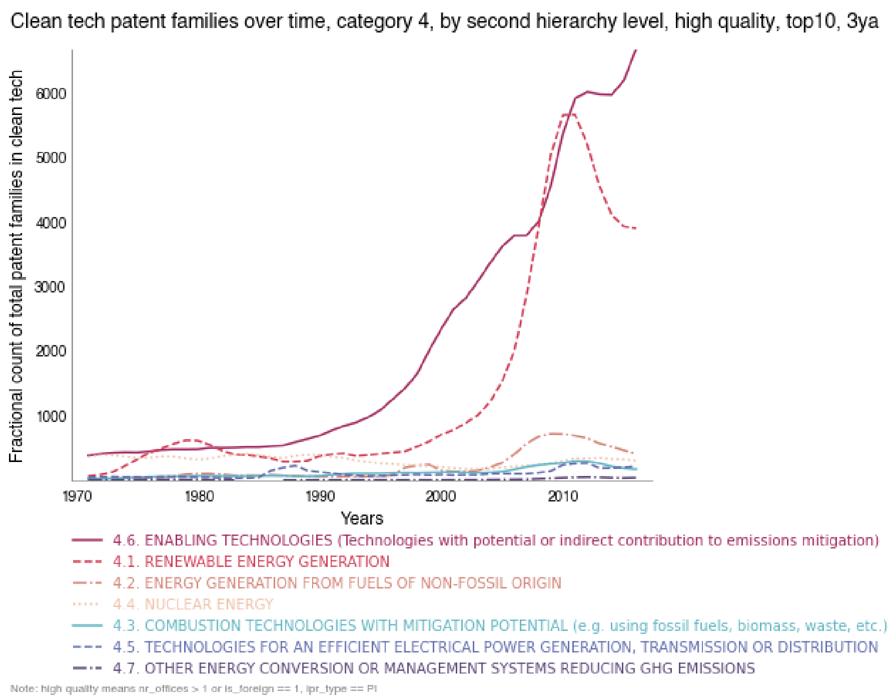
Sales and market growth for low-carbon technologies also highly depends on having access to a supply of scientists with the right skills and expertise for developing and deploying low-carbon technologies. Markets for solar PV cannot for instance expand without a sufficient supply of trained installers (Fabrizio & Hawn, 2013). As 'green' jobs are sensibly different from 'brown' ones - in terms of levels of education, work experience and job training (Consoli et al., 2016) – 'technology-push' education and training policies need to consider funding human capital directed towards low-carbon technologies.

Finally, balancing demand-pull with technological push policies is important to mitigate potential leakage of technological spillovers across borders. There is evidence in the literature that governmental energy R&D mainly incentivize domestic innovation, while demand-pull policies influence both domestic and foreign innovation (Dechezleprêtre et al., 2015; Peters et al., 2012). German renewable policies led to important market growth for solar PV, which in turn triggered the development of technological capabilities in solar energy abroad and in particular in China (Nemet, 2019).

4. Energy technologies

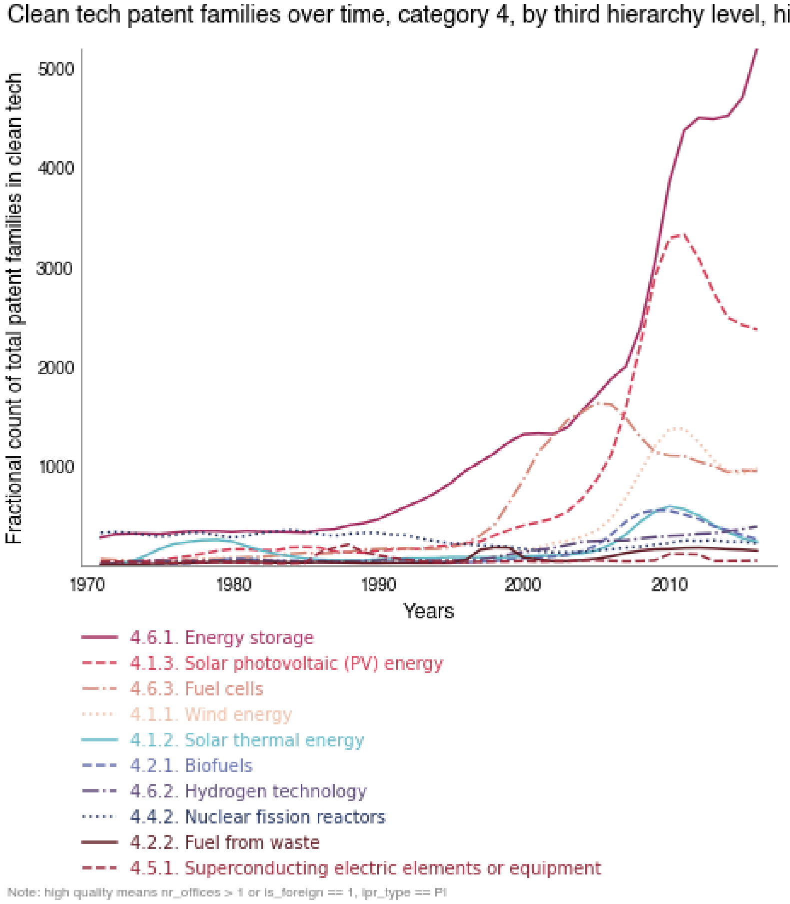
This section discusses the historical evolution and drivers of technological innovation in the CCMT related to energy. Figure 2 in Section 1 depicts the evolution of global trends in CCMT energy-related patenting activities. Figures 5 and 6 below provide a breakdown of various energy CCMT, namely renewable energy, enabling technologies and biofuels. The trends show that renewable energy technologies and in particular solar, wind, as well as enabling technologies (e.g. storage) but also fuel cells explain much of the growth over the 2000-2010 decade.

Figure 5 – Global evolution of patenting activities in energy-related CCMT (second hierarchy level)



Source: WIPO computations

Figure 6 - Global evolution of patenting activities in energy-related CCMT (third hierarchy level)



Source: WIPO computations

We briefly review the four4 main historical periods of development of technological change in clean energy over the last fifty years: 1) early developments in the 1970s-1980s, 2) rapid acceleration at the end of the 1990s-early 2000s, 3) the downturn after the financial crisis and 4) the recovery from the last few years.

Early progress in low-carbon energy technologies in the 1970s originate from two important developments. First, the oil crises of 1973 and 1979 were transformative for the energy industry. As global oil prices suddenly more than doubled in 1973 it became urgent to save energy and to find alternatives to oil. Several countries started implementing important energy policies to safeguard energy security. France launched a major nuclear energy program, Japan initiated an energy efficiency program and Brazil started to investigate the production of ethanol from sugarcane. Although wind turbines and solar cells for electricity production were first developed in the 1920s and 1950s respectively, the technologies were still at experimental stage in the early 1970s. Technology push programs after the oil shocks were critical in advancing these technologies from prototypes to demonstration projects.

In the US, the NASA became a key actor in energy technologies programs hoping to learn from tentative space applications. From 1974 to 1981, the US Federal Government adopted a $1.7 billion R&D program for solar PV and another $380 million of US Federal money was spent on wind turbine development over the 1973-1988 period (Jones & Bouamane, 2011; Nemet, 2019). The federal emphasis on solar PV created a burgeoning solar industry and led to several technological breakthroughs, with the costs of modules dropping by a factor of five between 1974 and 1981 (Nemet, 2019). The R&D program for developing large wind turbines, however, did not meet the same success. Developing multi-megawatt wind turbines based on aero and spatial technologies proved to be too difficult and a dead-end for the US wind industry. In the meantime, in Denmark, small firms such as Vestas originally from agricultural equipment manufacturers were more successful in developing small-scale wind turbines, building on the Danish tradition of collaborative learning networks (Jones & Bouamane, 2011). Rising oil prices in the 1970s-1980s supported the market for alternative energy technologies. Popp (2002) documents that rising energy prices in this period had an important positive impact on the number of patents in energy-supply (solar, batteries, fuels cells).

A second important development in the 1970s, which proved critical for the uptake of environmental technologies, is the mounting awareness of environmental problems in the public opinion. The publication of Rachel Carsons's book "Silent Spring" in 1962 on the devastating environmental impacts of DDT, the first images of Earth from space in 1969, and recurrent smog and air pollution in many developed cities such as Los Angeles, London and Tokyo sparked the implementation of environmental regulations across many countries and at the international level. In the US, the Clean Air Act passed into law in 1965 and the US Environmental Protection Agency was created in 1970. The OECD also adopted the "polluter pays principle" in the early 1970s and the first European Environmental Action Program was launched in 1973 based on this principle. Environmental activism and in particular anti-nuclear groups in Germany and Denmark encouraged governments to develop alternative sources of energy, such as wind and solar. Pollution regulation forced firms to adopt more environmental-friendly technologies. There is evidence for instance that the Helsinki Protocol in 1985 (followed by the Olso Protocol in 1994) as parts of the Convention on Long-Range Transboundary Air Pollution provided important incentives for technological innovation and diffusion of SO2 abatement technologies (Dekker et al., 2012).

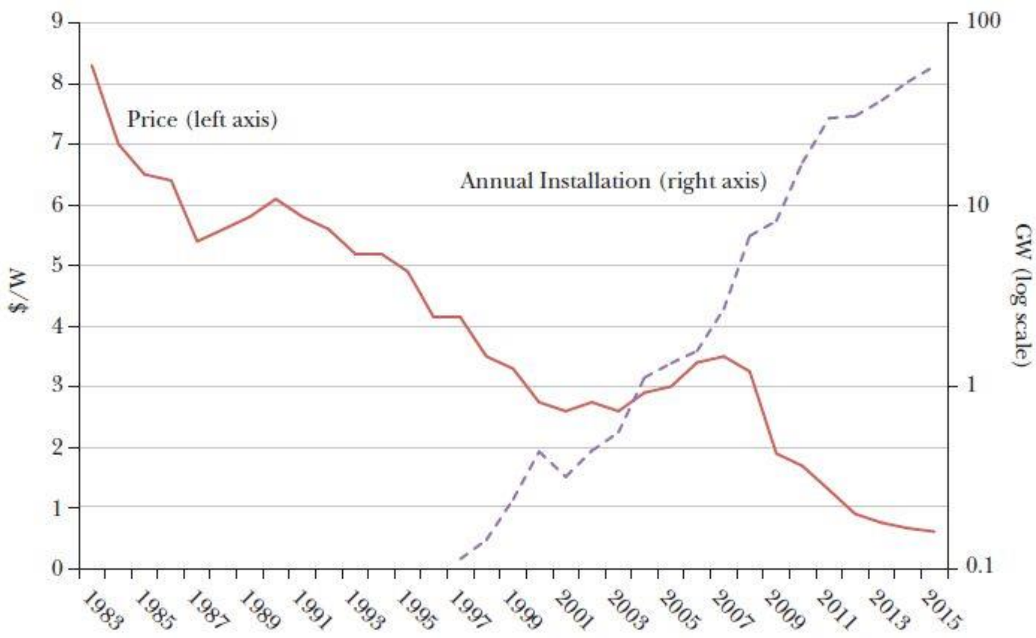
After this initial start in the 1970s and 1980s, low energy prices and slower progress on the environmental policy agenda in the 1990s were less favorable for the development of clean energy innovation, and patenting activities leveled off. Towards the second part of the 1990s and early 2000s, however, several countries started to experiment with the first feed-in tariffs that provided guaranteed payments for electricity produced from solar and wind over lengthy periods. The rise in renewable patents observed after 2000 largely explained by the growing number of renewable energy policies over the period (Johnstone et al., 2010, Hoppmann et al., 2013). In Germany, the Renewable Energy Law (Energiewende) passed in March 2000 increased the levels of feed-in tariffs, thereby providing massive subsidies for solar panels. For a number of years, there were no limits on the amount of income tax deductions that could be made for investment in solar and wind energy in Germany. The German policy was so successful for solar (albeit expensive) that it has been coined as "*a gift to the world*" (Nemet, 2019).

This significant early push in demand initiated by demand-pull government interventions over the period contributed to an induced innovation effect for renewable technologies. For solar energy, the size of the market for PV applications created massive economies of scale and enabled companies to raise finance for their technological innovations and to scale up production, considerably lowering down the price of solar panels (Gerarden, 2018). According to Nemet (2006), economies of scale in solar PV created by markets accounted for 43% of declines in costs reductions. Figure 7 shows the spectacular increase in worldwide installed capacity in solar panel since the end of the 1990s, together with the magnitude of cost reductions. The price of solar modules dropped from 9 $/W in 1983 to 0.5 $/W in 2015, accompanied by an impressive rise in installed capacity since the end of the 1990s.[11]

[11] Today, the current levelized cost of electricity in Europe for electricity produced by solar PV is now lower than for gas and nuclear (respectively 55$/MWh, against 100 $/MWh for gas and 150 $/MWh for nuclear). Wind power accounts for over 5% of global power supply and solar PV for about 2.5% of global power supply (IEA, 2020). The IEA forecasts that by 2050 solar would be the largest source of energy, accounting for 1/5 of energy supply worldwide, with solar PV capacity increasing by 20-fold between now and 2050 (IEA, 2021).

Figure 7. Solar panel price indexes

Solar Panel Price Indexes Excluding Subsidies and Cumulative Worldwide Installed Capacity, 1983–2015

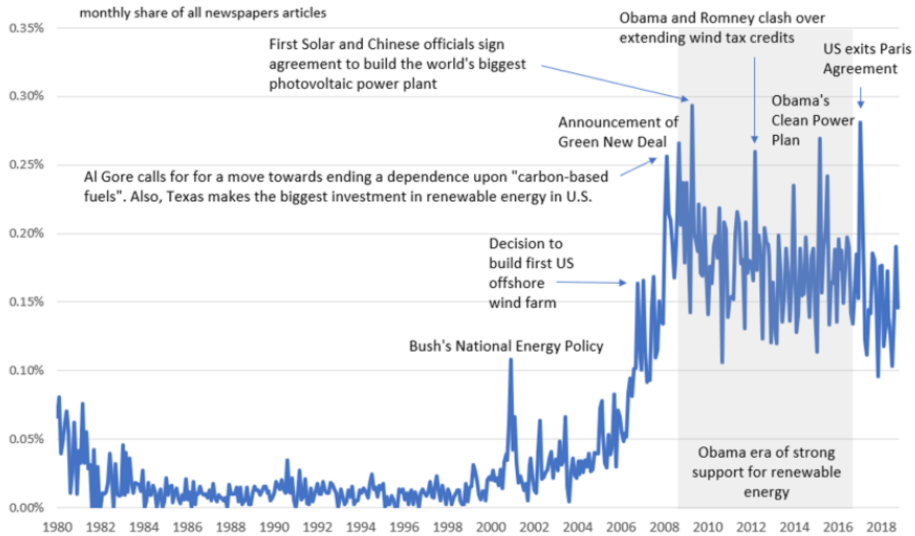


Source: International Energy Agency (2017), Navigant Consulting (2009), and Gerarden (2018).

Reproduced from Gillingham & Stock (2018)

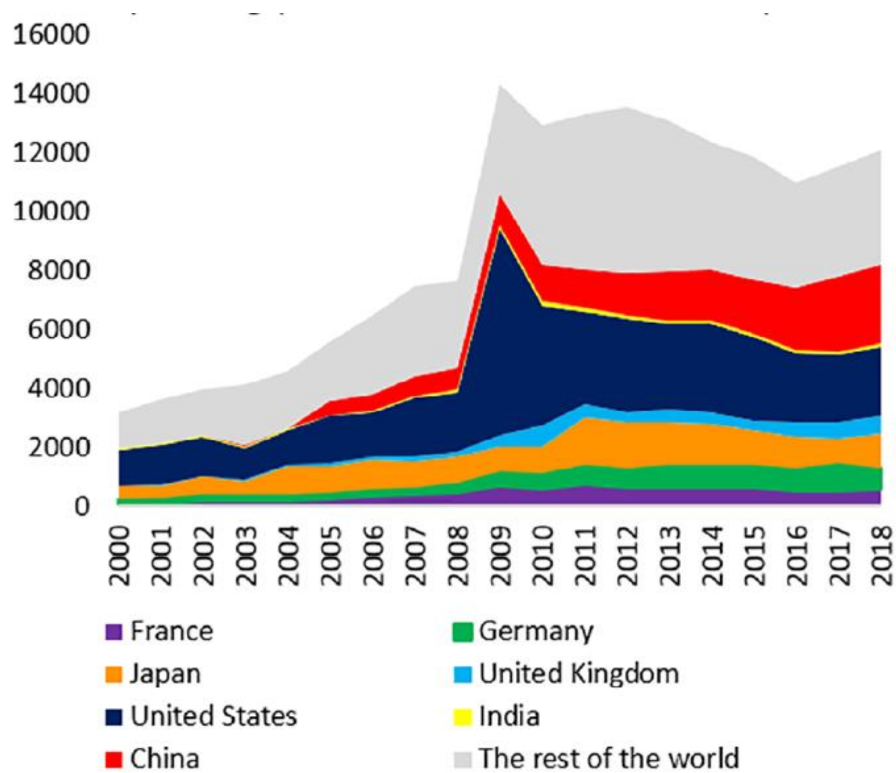
The 2008-2009 financial crisis initiated a new phase for the low-carbon energy industry as several governments implemented stimulus programs, which included support for renewable energy. As shown in Figure 8, in the US, policy support for renewable policies significantly increased after the election of Barack Obama and the announcement of Green New Deal policies. The period corresponds to a growing interest for 'green industrial policy' with countries – notably the US and China - competing for the first place in clean technologies. Recovery stimulus translated into increased spending on clean energy R&D from governments as illustrated in Figure 9.

Figure 8. US media attention on renewable energy policy, 1980-2018



Source: (Noailly et al., 2021)

Figure 9: Global public clean energy R&D spending (Million USD, 2018 PPP prices)



Source: Zhang et al. (2021) - clean energy includes energy efficiency, CCUS, renewables, hydrogen and fuel cells, other power and storage)

After the financial crisis, low-carbon energy innovation witnessed a downturn. As shown in Figure 5, patenting in renewable technologies in particular experience a slump after this period. Several explanations for the decline in renewable patents after the 2010-2011 period have been put forward in the literature; namely the rise in hydraulic fracturing, weakening environmental regulation, diminishing returns to research and evidence for a cleantech bubble, with more patents being filed at the intersection of energy and digitalization technologies (Popp et al., 2020). After the financial crisis, fossil fuel prices have been declining, public funding for clean energy R&D stagnated (see Figure 9) and investors likely readjusted their expectations following the surge in investments induced by Green New Deal policies put in place to remedy the economic crisis (Probst et al., 2021).

At last, very recent years after 2015 seem to depict a new landscape for clean energy technologies, as innovation in enabling technologies becomes increasingly important in this period. Patenting activities in battery technologies experienced an annual average growth of 13% over the 2010-2019 period (EPO, OECD/IEA, 2021). There is evidence that declining costs of Li-ion battery technologies have been driven by a growing demand for electric vehicles. Enabling technologies for the energy sector are technologies, which can help to integrate renewable energy into the electricity grid. Battery storage systems, either utility-scale or behind-the-meter batteries at individual and household scale, are key to create more flexibility in energy systems, as it is challenging to meet peak-demand from consumers with intermittent electricity production from renewable energy. Other enabling technologies are related to digital technologies and connected devices, such as smart energy meters or embedded-sensors in wind turbines or solar panels that sense changing wind or light conditions. Digital technologies can greatly contribute to optimize grid operation and increase grid flexibility to incorporate renewable energy. Certainly, the rise in the adoption of digital technologies due to the Covid-19 pandemic offers renewed opportunities for digital energy-related enabling technologies. Yet, new threats emerge from potential disruption in the supply chain of critical minerals (such as lithium or rare earths), as country with a large demand for critical minerals to feed their clean energy industry – such as the US, the EU and Japan – are largely dependent from imported minerals from a small group of suppliers. For instance, about 80% of US rare earth imports come from China (Hund et al., 2020).

Finally, in order to measure the overall progress of change towards the low-carbon transition in the energy sector, we need to compare progress in clean versus dirty energy technologies.

An acceleration in clean innovation is only meaningful if it comes along with a deceleration or replacement of dirty fossil-fuel technology in the energy sector. According to the IEA (2021), a tipping point may have been reached after 2015 when for the first time - and after a continuous increase in patenting activities over the 1970-2015 period - fossil fuel patenting activity reached a peak and declined for four straight years globally after this. This drop in fossil-fuel patents could reflect lower incentives to patent technologies in the current uncertain market outlook for fossil fuels or simply lower spending on fossil fuel energy R&D. Zhang et al. (2021) documents such a shift of government energy R&D budget away from fossil-fuels in all major economies. The share of public R&D spent on fossil-fuel energy peaked during the financial crisis in 2009 and dropped from 18% in 2009 to 6% in 2018.[12] All these indicators suggest that we may at last have reached a tipping point.

5. Transportation sector

Technologies related to transportation are the third largest category of environmental innovations with more than 6000 yearly patent families worldwide in 2017, a 3-fold increase since 2000 (Figure 2). Transportation technologies are split across various categories including: road transport (conventional, electric, hybrid), rail transport, air and maritime transport, as well as enabling technologies for transport (e.g. electric charging stations). Figure 10 shows that patents in road transport dominate low-carbon innovation in the sector.

The evolution of low-carbon innovation in road transport follows several phases (see Figure 11): 1) early initial developments until the 1990s, 2) acceleration of innovation activities until 2000 - largely explained by ambitious vehicle emissions standards leading to first experimentation of electric vehicles (EV) and hybrid technologies, 3) exponential growth of EV technologies induced by technological maturity and incentives purchase 4) take off of enabling technologies after 2010. We briefly detail these phases in turn.

[12] However, this excludes energy R&D spending of state-owned enterprises from Brazil, Russia, India, Mexico, China and South Africa, which tends to include higher spending on fossil-fuels energy R&D.

Figure 10. Global evolution of low-carbon technologies in the transport sector

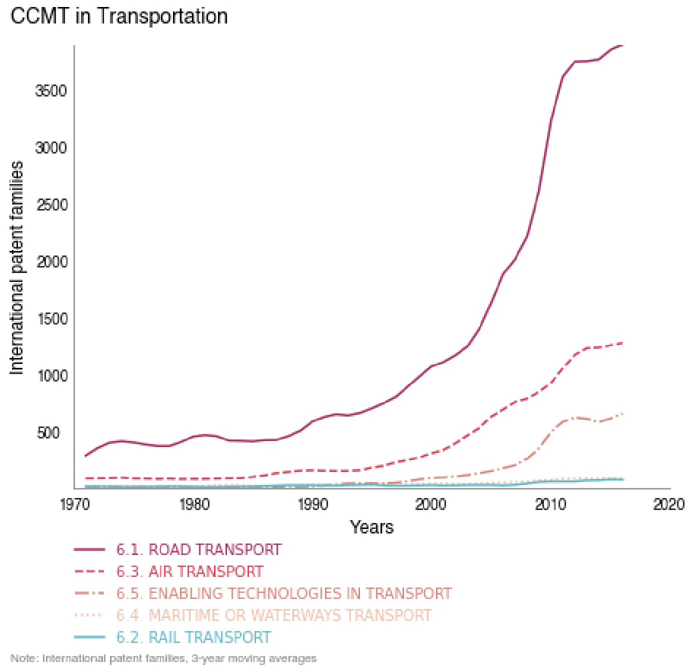
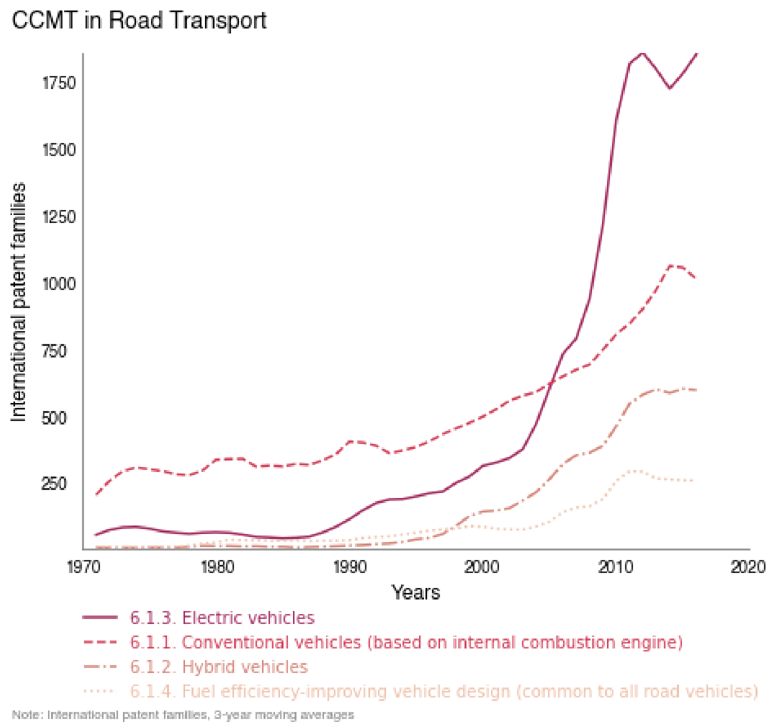


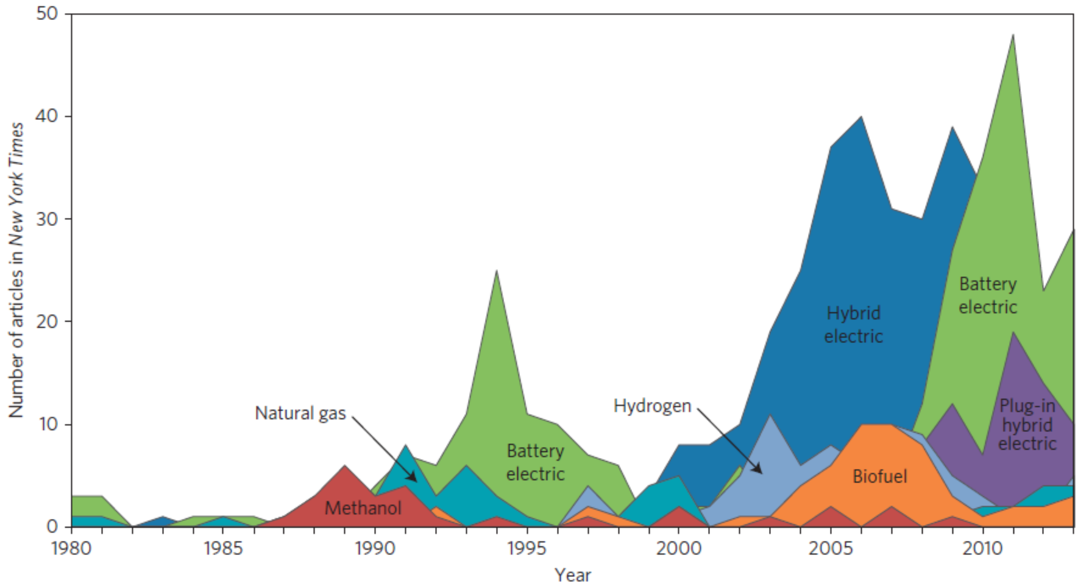
Figure 11. Global evolution of low-carbon technologies in road transport, per technology type



Source: WIPO computations

In the 1970s and 1980s, the level of technological change in clean transport remained relatively low and stable. The two oil crises did not have much impact on innovation in the car industry, as oil was perceived as a very convenient source of energy for road transport and the domination of combustion engine cars was not questioned at that time. In addition, until the late 1980s, US automobile manufacturers successfully managed to delay some of the most stringent regulations imposed by the Clean Air Act, so incentives to innovate into cleaner transportation technologies were very low. Instead, the take off of clean transport technologies in the 1990s is mainly attributed to ambitious demand-pull policies implemented in California. Confronted with important air pollution problems, California started its Low Emission Vehicle program in 1990, a technology-forcing standard requiring that zero emission vehicles accounted for 2% of sales for each automaker firm in California by 1998 (5% by 2001 and 10% by 2003) - a standard beyond existing emission control technological capabilities at the time (Collantes & Sperling, 2008). At the federal level, the US Congress finally introduced stringent standards in the National Low Emission Vehicle program at the end of the 1990s. To comply with more stringent standards, automobile manufacturers started developing electric vehicles, such as the GM Impact based on lead-acid batteries released in 1990 (Bergek et al., 2013). The US Department of Energy supported the development of electric vehicle technologies by increasing the funding from $US 17 million to USD 102 million per year over the 1990-1995 period (Melton et al., 2016). Yet, even though production started, the market did not take off, as electric cars at that time meant too much sacrifice for consumers in terms of prices, driving range, convenience and driving experience. A group of automakers successfully lobbied against the ZEV mandate in the early 2000s and production of electric vehicles stopped. It took another 10 years for new hybrid and EV vehicles to emerge relying on lithium-ion battery technologies. Consumers' interest for hybrid models, especially due to the success of the Toyota Prius model in 2000, led to an increase in patents for hybrid technologies. Reflecting these market trends, Figure 12 plots the evolution of US media attention on various types of low-carbon vehicle technologies over time.

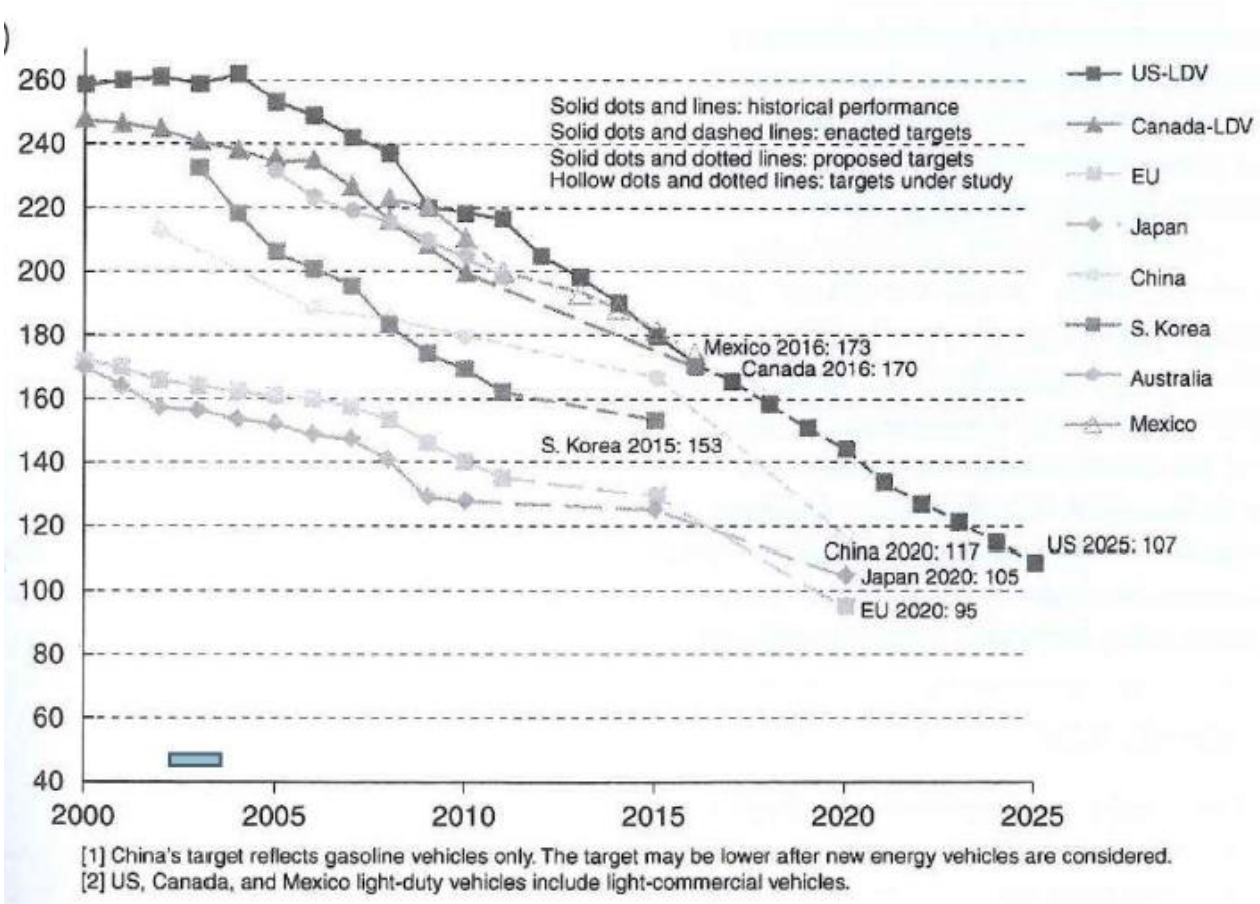
Figure 12: US media attention on various low-carbon vehicle technologies, 1980-2013



Source: (Melton et al., 2016)

Further strengthening of car emissions standards – such as President Obama's announcement in 2009 of revised CAFÉ standards at 35 mpg by 2020 under the Energy Independence and Security Act - triggered further improvements in both hybrid cars and improved international combustion engine cars. Figure 13 plots the evolution of US car emission standards, which became increasingly more stringent after 2005, although less so than European or Japanese ones.

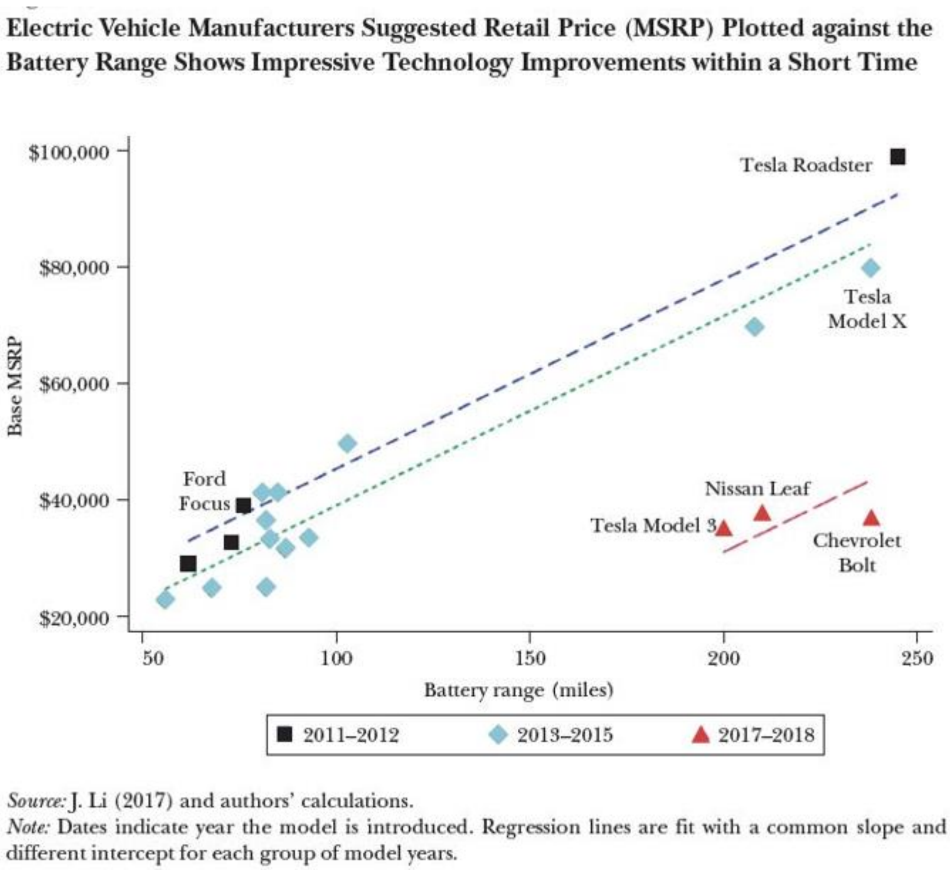
Figure 13 Evolution of emission standards in the automobile industry for different countries



Source: Grubb et al (2013)

Finally, after the mid-2000s, several additional demand-pull policies contributed to create the market for EV. First, several countries implemented generous subsidies for purchasing electric vehicles to overcome cost barriers. In the US, a federal income tax credit of $7,500 has been in place since 2005, as well as other additional state level incentives. These measures were simultaneously accompanied by specific policies to increase the number of charging stations for electric vehicles. As a result of this important policy support, electric cars experienced rapid market growth. Global sales increased by more than 60% every year over the 2014-2018 period. Electric vehicle sales reached 2.1 million in 2019, accounting for 2.6% of the global car market (IEA, 2020). The market take-off led to rapid improvement and cost reductions in technology. By 2017-2018, electric vehicles within the price range $20'000-$40,000 witnessed a 4-fold improvement in battery range compared to the 2011-2012 period (Figure 14).

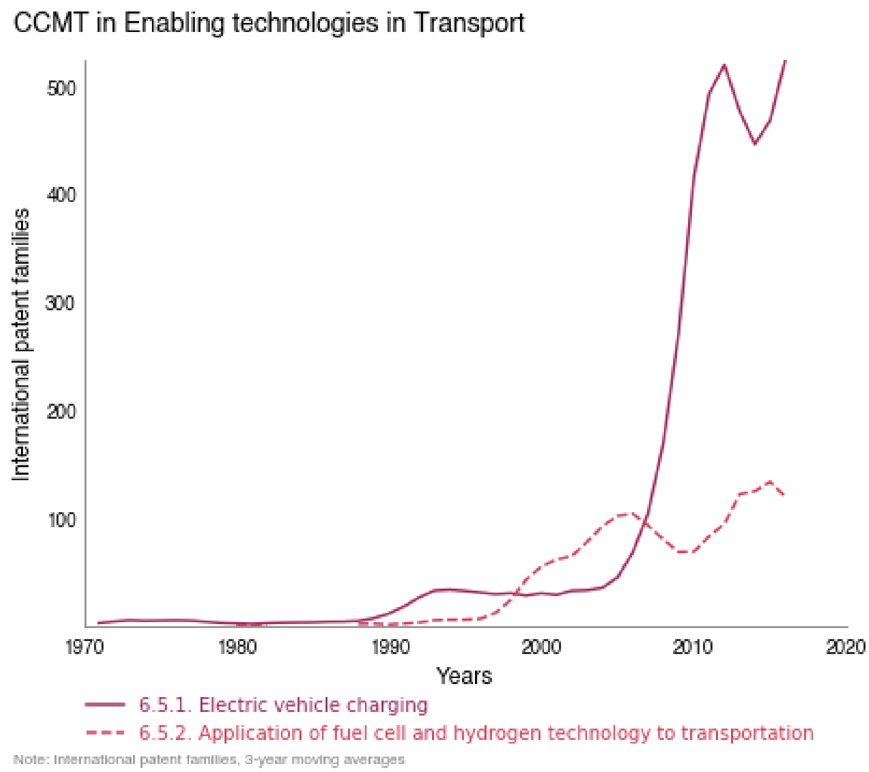
Figure 14: Evolution of electric vehicle suggested retail price



Source: Gillingham & Stock, 2018)

Over the last decade, enabling technologies, in particular related to lithium-ion batteries, but also for (smart) charging stations, digital technologies and connected devices enabling to optimize mobility demand have become increasingly important, as depicted in Figure 15, which plots the evolution of patenting activities for various enabling technologies.

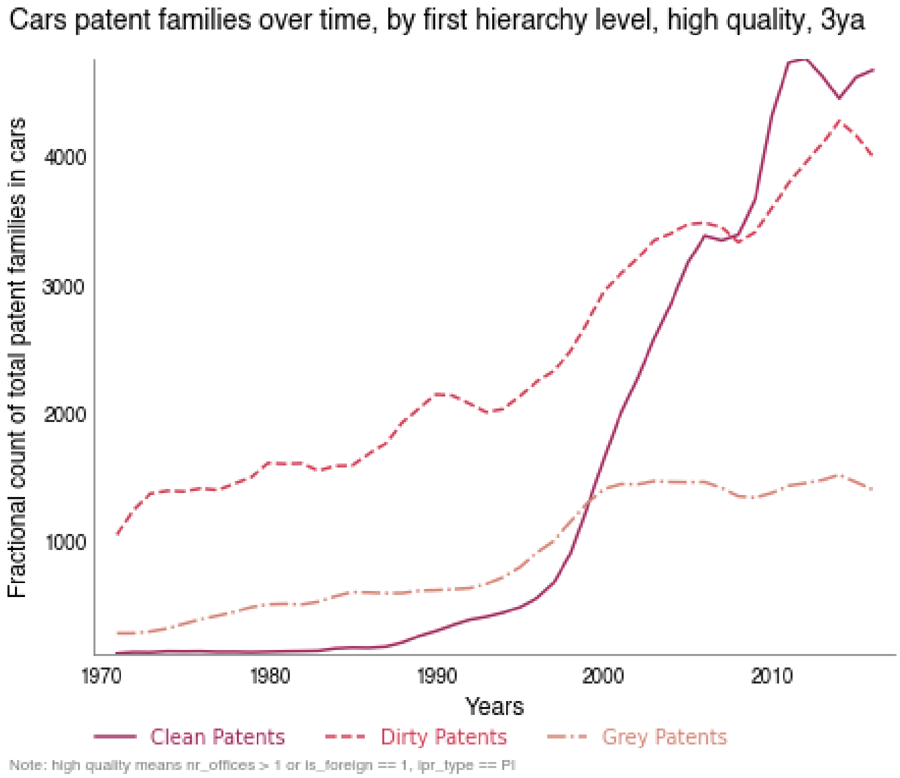
Figure 15 – Global evolution of low-carbon enabling technologies for road transport, per technology type



Source: WIPO computations

Further progress to clean up road transport implies that electric vehicles technologies will fully replace technologies based on internal combustion engines cars. So far, EVs represent only a very small market share of new cars. Yet, in terms of patenting activities, the turning point may have been reached. Figure 16 contrasts the evolution of clean – EV and hybrid – patents versus grey – improved ICE- and dirty – ICE – patents based on patent classification as in Aghion et al. (2016). The figure shows that the number of patent families in hybrid and electric cars surpasses the number of patents in standard internal combustion engines just before the financial crisis. As of 2017, electric and hybrid vehicles represent about half of all road transport patenting activities, with the other half still directed towards (improved) internal combustion engines. Certainly, policies providing incentives to scrap old polluting cars may have played a role in explaining this shift.

Figure 16 Global evolution of clean (electric and hybrid), grey (improved ICE) and dirty (conventional ICE) patents in road transport



Source: WIPO computations

6. Conclusions and policy implications

While low-carbon technologies are finally becoming mature, we have reached a critical moment to enable the massive change in the direction of innovation required to achieve climate targets and net zero ambitions. This change of course needs to combine the further expansion of low-carbon technological pathways with the contraction and destruction of obsolete high-carbon ones. The previous sections highlighted the role of a large set of policy instruments to orient the direction of innovation towards low-carbon technologies. Combining demand-pull policy instruments such as carbon pricing with governmental R&D support targeted at low-carbon technologies is largely justified by the dual externalities – environmental and knowledge externality – faced by firms. Many complementary policies are also required to facilitate the transition to a low-carbon future, for instance in the form of education, finance and competition policies. Beyond specific regulatory instruments, two additional aspects are worth highlighting: namely, 1) the importance of long-term policy commitment and 2) the role of international or supranational policy coordination.

Certainly, much of the lack of significant progress and drop in environmental innovation over the last years is due to recurrent hesitation and lack of clear credibility and commitment of the policy framework (Nemet et al., 2017). Over the course of its mandate, the Trump administration not only announced its withdrawal from the Paris climate agreement but also conducted a comprehensive review of many federal environmental regulations. In addition, despite net-zero goals announced at the COP26 in Glasgow, there are still many uncertainties about whether and how these goals will translate into actual implementation of domestic climate policies. The politics of climate change tend to be particularly volatile, as policymakers often have to balance competing (long-term) environmental objectives with (short-term) economic and electoral priorities. Yet, such lack of long-term commitment is particularly damaging for low-carbon innovation, as firms typically want to know which policy assumptions will be valid for their projects over the next 15 to 25 years. By sanctioning high-carbon markets, carbon-pricing policies can provide strong commitment signals to low-carbon markets and innovators (Rogge & Dütschke, 2018). In addition, they are less likely to be removed than subsidies, as they provide revenues to governments and are thus less subject to budgetary constraints. Nonetheless, in practice, carbon pricing faces low political acceptability in many countries, due to competitiveness concerns and equity issues. Other options are to design policy incentives - such as renewable subsidies - which adjust automatically and in a predictable way to varying market conditions, such as electricity prices and technological costs (Gawel & Lehmann, 2019). This would avoid removing (costly) subsidies abruptly with changing states of the world. Another related example could be to set up R&D support, which evolves according to the maturity of the technology or by adjusting them at predictable and announced time intervals.

Another important feature of the policy framework for low-carbon innovation is to consider international aspects. In recent years, several countries have shown a renewed interest for forms of ‘green industrial policy’, which refers to government intervention aimed at promoting and protecting domestic clean technology sectors in the form of favorable tax treatment and R&D spending. The 2009 Green New Deal of Barack Obama, the post-pandemic European Green New Deal (which includes a large European consortium on lithium-ion batteries) or Joe Biden’s $1.9 trillion Build Back Better plan for economic stimulus and pandemic relief, all include targeted support for the low-carbon industry as a way to fight climate change, boost the domestic economy and gain comparative advantage over other countries. Even though some government risk-taking is warranted, criticisms of green industrial policy tend to emphasize that such “picking winner” policies may result in wasting payers’ funds if governments end up betting on the wrong technology, with the consequence of crowding out resources for other technologies.[13] For instance, Europe may be focusing too much on lithium-ion batteries and not enough on fuel cells. Another criticism is that such government support often invite ‘disguised protectionism’ and rent seeking by lobbying groups wanting to promote their technologies, and might shelter inefficient firms from competition. Finally, implementing domestic policies supporting low-carbon innovation may result in technological spillovers abroad rather than at home, enhancing thus foreign rather than domestic comparative advantage. As an illustration, China PV industry largely benefited from US and German subsidies for solar markets.

Ultimately, accelerating the development and deployment of low-carbon technologies is in the interest of all countries engaged in the fight against climate change. According to the IEA (2020), half of the emission reduction needed to achieve net-zero emissions by 2050 will have to come from technologies not yet commercially available. Scaling up efforts will require increasing policy coordination at the international and supranational level. Examples of supranational demand-pull policies include pan-European feed-in tariffs, or linking existing cap-and-trade systems. Coordinating and scaling up technology push policies can also be very effective to accelerate low-carbon R&D. The Mission Innovation initiative launched by 24 governments after the Paris Agreement led to an increase in R&D spending by 38% since 2015[14] and the creation of an important forum for sharing experience and success on clean energy innovation (Myslikova & Gallagher, 2020). Its recent alliance with the private sector via the Breakthrough Energy Coalition, as announced at the COP26 in Glasgow, offers promising perspective.

[13] The support of the Obama Administration to the California-based solar PV manufacturer Solyndra is an example of such an expensive failure. The company received two federal loan guarantees amounting to 535 million dollars in 2010 before filing for bankruptcy a year later, laying off 1100 employees.

[14] although falling short of its goal of doubling investments by 2020.

References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012). The Environment and Directed Technical Change. *American Economic Review*, *102*(1), 131–166. https://doi.org/10.1257/aer.102.1.131

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., & Van Reenen, J. (2016). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. *Journal of Political Economy*, *124*(1), 1–51. https://doi.org/10.1086/684581

Bergek, A., Berggren, C., Magnusson, T., & Hobday, M. (2013). Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation? *Research Policy*, *42*(6–7), 1210–1224. https://doi.org/10.1016/j.respol.2013.02.009

Collantes, G., & Sperling, D. (2008). The origin of California's zero emission vehicle mandate. *Transportation Research Part A: Policy and Practice*, *42*(10), 1302–1313. https://doi.org/10.1016/j.tra.2008.05.007

Costantini, V., Crespi, F., & Palma, A. (2017). Characterizing the policy mix and its impact on eco-innovation: A patent analysis of energy-efficient technologies. *Research Policy*, *46*(4), 799–819. https://doi.org/10.1016/j.respol.2017.02.004

Dechezlepretre, A., Martin, R., & Mohnen, M. (2017). Knowledge Spillovers from clean and dirty technologies. In *GRI Working Papers* (No. 135; GRI Working Papers). Grantham Research Institute on Climate Change and the Environment. https://ideas.repec.org/p/lsg/lsgwps/wp135.html

Dechezleprêtre, A., Neumayer, E., & Perkins, R. (2015). Environmental regulation and the cross-border diffusion of new technology: Evidence from automobile patents. *Research Policy*, *44*(1), 244–257. https://doi.org/10.1016/j.respol.2014.07.017

Dekker, T., Vollebergh, H. R. J., de Vries, F. P., & Withagen, C. A. (2012). Inciting protocols. *Journal of Environmental Economics and Management*, *64*(1), 45–67. https://doi.org/10.1016/j.jeem.2011.11.005

EPO. (2016). *Finding sustainable technologies in patents*.

EPO, OECD/IEA. (2021). *Patents and the energy transition*. EPO, OECD/IEA.

Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, *55*(2), 142–162.

Gaddy, B. E., Sivaram, V., Jones, T. B., & Wayman, L. (2017). Venture Capital and Cleantech: The wrong model for energy innovation. *Energy Policy*, *102*, 385–395. https://doi.org/10.1016/j.enpol.2016.12.035

Gawel, E., & Lehmann, P. (2019). Should renewable energy policy be 'renewable'? *Oxford Review of Economic Policy*, *35*(2), 218–243. https://doi.org/10.1093/oxrep/grz002

Haščič, I., & Migotto, M. (2015). *Measuring environmental innovation using patent data* (OECD Environment Working Papers No. 89). OECD. http://www.oecd.ilibrary.org/environment/measuring-environmental-innovation-using-patent-data_5js009kf48xw-en

Hoppmann, J., Peters, M., Schneider, M., & Hoffmann, V. H. (2013). The two faces of market support—How deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. *Research Policy*, *42*(4), 989–1003. https://doi.org/10.1016/j.respol.2013.01.002

Hund, K., Porta, D. L., Fabregas, T. P., Laing, T., & Drexhage, J. (2020). *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* (p. 112). World Bank Group.

IEA. (2020). *Energy Technology Perspectives 2020* (p. 400).

Johnstone, N., Haščič, I., & Popp, D. (2009). Renewable Energy Policies and Technological Innovation: Evidence Based on Patent Counts. *Environmental and Resource Economics*, *45*(1), 133–155. https://doi.org/10.1007/s10640-009-9309-1
Jones, G., & Bouamane, L. (2011). Historical Trajectories and Corporate Competences in Wind Energy. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.1831471
Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G. J., Wiedenhofer, D., Mattioli, G., Khourdajie, A. A., House, J., Pachauri, S., Figueroa, M., Saheb, Y., Slade, R., Hubacek, K., Sun, L., Ribeiro, S. K., Khennas, S., Can, S. de la R. du, … Minx, J. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental Research Letters*, *16*(7), 073005. https://doi.org/10.1088/1748-9326/abee4e
Melton, N., Axsen, J., & Sperling, D. (2016). Moving beyond alternative fuel hype to decarbonize transportation. *Nature Energy*, *1*(3), 16013. https://doi.org/10.1038/nenergy.2016.13
Monasterolo, I., & Raberto, M. (2019). The impact of phasing out fossil fuel subsidies on the low-carbon transition. *Energy Policy*, *124*, 355–370. https://doi.org/10.1016/j.enpol.2018.08.051
Myslikova, Z., & Gallagher, K. S. (2020). Mission Innovation is mission critical. *Nature Energy*, *5*(10), 732–734. https://doi.org/10.1038/s41560-020-00694-5
Nemet, G. F. (2019). *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*. Routledge. https://doi.org/10.4324/9780367136604
Nemet, G. F., Zipperer, V., & Kraus, M. (2018). The valley of death, the technology pork barrel, and public support for large demonstration projects. *Energy Policy*, *119*, 154–167. https://doi.org/10.1016/j.enpol.2018.04.008
Newell, R. G. (2010). The role of markets and policies in delivering innovation for climate change mitigation. *Oxford Review of Economic Policy*, *26*(2), 253–269.
Nill, J., & Kemp, R. (2009). Evolutionary approaches for sustainable innovation policies: From niche to paradigm? *Research Policy*, *38*(4), 668–680. https://doi.org/10.1016/j.respol.2009.01.011
Noailly, J. (2012). Improving the energy efficiency of buildings: The impact of environmental policy on technological innovation. *Energy Economics*, *34*(3), 795–806.
Noailly, J., Nowzohour, L., & van den Heuvel, M. (2021). *Heard the news? Environmental policy and clean investments* [CIES Research Paper 70].
Noailly, J., & Shestalova, V. (2017). Knowledge spillovers from renewable energy technologies: Lessons from patent citations. *Environmental Innovation and Societal Transitions*, *22*, 1–14. https://doi.org/10.1016/j.eist.2016.07.004
Noailly, J., & Smeets, R. (2015). Directing technical change from fossil-fuel to renewable energy innovation: An application using firm-level patent data. *Journal of Environmental Economics and Management*, *72*, 15–37. https://doi.org/10.1016/j.jeem.2015.03.004
Peters, M., Schneider, M., Griesshaber, T., & Hoffmann, V. H. (2012). The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter? *Research Policy*, *41*(8), 1296–1308. https://doi.org/10.1016/j.respol.2012.02.004
Popp, D. (2002). Induced Innovation and Energy Prices. *The American Economic Review*, *92*(1), 160–180.
Popp, D. (2016). Economic analysis of scientific publications and implications for energy research and development. *Nature Energy*, *1*(4), 1–8. https://doi.org/10.1038/nenergy.2016.20
Requate, T., & Unold, W. (2003). Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? *European Economic Review*, *47*(1), 125–146.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*, *28*(12), 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7

Zhang, F., Gallagher, K. S., Myslikova, Z., Narassimhan, E., Bhandary, R. R., & Huang, P. (2021). From fossil to low carbon: The evolution of global public energy innovation. *WIREs Climate Change*, *12*(6). https://doi.org/10.1002/wcc.734