Climate change policy, innovation and growth

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Policy brief
January 2016

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Acknowledgements

This policy brief draws on material from Dechezleprêtre and Popp (2015). We thank Stefan Ambec, Simon Bennett, Maria Carvalho, Chris Duffy, David Hemous, Yang Liu and Dimitri Zenghelis for very helpful comments. Financial support has come from the Global Green Growth Institute, the Grantham Foundation for the Protection of the Environment, as well as the UK Economic and Social Research Council through the Centre for Climate Change Economics and Policy.

Executive summary

Actions to stimulate low-carbon innovation – a global policy priority – are moving full speed ahead. Twenty countries from across the developed and developing world, including the UK, the US, China, India, the United Arab Emirates and Australia, recently signed up to 'Mission Innovation' at the 2015 United Nations Climate Change Conference in Paris, promising to double their public investment in low-carbon energy innovation and to promote increased international cooperation. Alongside this, a global group of 28 key investment players from 10 countries, including Bill Gates, Mark Zuckerberg and Richard Branson, are mobilising to deliver 'truly transformative energy solutions for the future' as part of the new 'Energy Breakthrough Coalition'. In addition, the European Commission is developing a strategy to support low-carbon innovation, to be published with the second State of the Energy Union report in late 2016.

This policy brief provides evidence to inform these and other initiatives seeking to stimulate low-carbon innovation. Key findings include:

Public policies that put a price on carbon (emissions trading systems, carbon taxes or energy efficiency mandates) are a crucial driver for the adoption of environmentally friendly technologies and induce innovation in low-carbon technologies. The impact appears both large and rapid: much of the innovative response to climate change policy measures occurs within five years or less. Thus, climate change regulations can help economies break away from a polluting economic trajectory and move to a 'low-carbon' one.

A crucial challenge for climate change policies is ensuring that low-carbon innovation activity is either additional to current research and development (R&D) expenditures, or at least displaces innovation in polluting technologies rather than other socially valuable innovation. Policies that change the relative price of low-carbon and high-carbon inputs, such as carbon markets or fuel taxes, can play this role effectively.

Price-based instruments, such as carbon markets, and quantity-based instruments, such as renewable energy targets, tend to favour innovation in technologies that are closest to the market. Thus, they need to be complemented by direct support to emerging technologies that will be essential to long-term emissions reduction targets through public funding of R&D and feed-in tariffs. To drive investment, these policies must be credible and stable.

Current deployment efforts should be augmented with additional R&D support, such that the marginal euro spent on low-carbon technologies should go to R&D rather than deployment. European countries have been emphasising technology deployment through feed-in tariffs for renewable energy production over direct R&D support, but this approach may not provide sufficient stimulus to develop the next generation of low-carbon technologies. From a political point of view, an additional advantage of direct support to R&D is that by definition it is targeted at domestic manufacturers, while feed-in tariffs may encourage innovation activity mostly in foreign countries.

Public spending on low-carbon R&D needs to increase significantly over the next few decades if the world is to realise the goals of the Paris Agreement to limit global warming to well below 2°C and to achieve net zero global emissions of greenhouse gases in the second half of this century. It is difficult to give a precise figure for increased public investment, but the literature agrees that it should at least double. Some of the greatest funding increases are needed in low-carbon transportation, carbon capture and storage (CCS), smart grids and industrial energy efficiency. For instance, In Europe, a doubling of public R&D expenditures over the next 10 years (from €4bn to €8bn a year) corresponds to the growth that was observed between 2001 and 2011 and thus seems achievable. Assuming an average carbon price of €11 per tonne, a doubling of public R&D funding for low-carbon technologies represents only 10 per cent of the expected revenues from auctioned emissions allowances over the next decade.

Increasing public support for low-carbon R&D may also be politically attractive because low-carbon innovations have larger economic benefits than the carbon-intensive technologies they replace. Low-carbon patents have been found to be of high social value. They have broad application across the whole economy (i.e. they have high 'knowledge spillovers'). Their application is similarly wide to patents in other growth sectors such as information and communications technology (ICT) and nanotechnologies. Taken together, this means that innovation induced by climate change regulations can help to boost economic growth and offset the policy costs for firms.

Moreover, the knowledge spillovers from low-carbon technologies have a strong local component. For Europe as a whole, 61 per cent of spillovers occur domestically. However, European countries with smaller or more open economies retain a smaller share of spillovers domestically: 28 per cent for France, 15 per cent for the UK, 10 per cent for the Netherlands. **As such, coordination of European Union research policy is theoretically justified and there is a strong case for European institutions to fund R&D.**

There is scope for increasing investment in several Member States if the European Union is keen to strengthen its competitive advantage on low-carbon innovation. Ranking European Union Member States by the number of low-carbon inventions per billion US dollars of GDP shows that Germany and the Scandinavian countries are at the forefront of innovation. The UK is approximately midway in the ranking, ahead of countries such as Belgium, Norway, Italy, Spain and Poland, but behind France, the Netherlands and others (see Figure 8 on page 16).

Increased investment in low-carbon R&D should be slow and sustained. While it is welcome that countries such as the UK have committed to doubling public funding for low-carbon R&D by 2020 as part of 'Mission Innovation'; **countries should be encouraged to set public R&D targets as far ahead as 2030.** Targets would vary between countries and may need to be set within a range, but such long-term targets would reduce public funding spikes and associated adjustment costs, and ultimately could reduce the overall cost of decarbonisation.

1. Introduction

According to the latest report by the Intergovernmental Panel on Climate Change, (IPCC, 2014) stabilising global carbon emissions in 2050 requires a 60 per cent reduction in the carbon intensity of global GDP (assuming a 2.5 per cent annual GDP growth). To achieve this long-term decarbonisation of the economy, the world needs to implement a radical change in the mix of technologies used to produce and consume energy. This in turn will likely require massive investments in innovation activities. The IPCC also made it clear that future investments in research, development and demonstration (RD&D) will be the determining factor for the cost of emissions reductions policies.

Importantly, the diversity of energy uses, systems, resources and national contexts means that addressing climate change and other environmental issues will require innovation across the whole range of existing and potential low-carbon technologies and at all stages of technological change – from the creation of new ideas (e.g. invention and innovation) to the diffusion and adoption of new technologies throughout the economy (IEA, 2008). The cost of existing low-carbon technologies, such as offshore wind turbines or solar panels, needs to be brought down so that they can be deployed on a large scale, while fundamental research needs to advance the frontiers of technologies such as smart grids or energy storage.

With a global agreement on climate change now in place,[1] low-carbon innovation is likely to become a high priority for policymakers worldwide. Individual countries and multilateral organisations such as the European Union already have policies in place to support low-carbon innovation. This policy brief evaluates these policies to provide insights and lessons to aid future policy development. Questions considered are: what impact do these policies have on the development of new low-carbon technologies? What policies should be adopted to provide the highest encouragement to cost-effective low-carbon innovation? What could be the impact of the increased volume of innovation activity directed at low-carbon technologies on economic growth? What level of resources should be allocated to directly supporting innovation activities in low carbon technologies? What is the right balance between research and development (R&D) and deployment budgets?

The brief is divided into three main sections. The first part analyses the impact of climate change policies on innovation. The second part explores the implications of policy-induced innovation activity in the low-carbon sector for economic growth. The third part discusses which policies should be adopted to support the development and deployment of low-carbon technologies. A final section summarises the main findings and presents policy recommendations.

1 The Paris Agreement, adopted by 196 Parties to the United Nations Framework Convention on Climate Change in December 2015.

2. The impact of climate change policy on innovation

Climate change policies, either based on market signals or on command-and-control regulation, can have significant impact on investment in low-carbon technology. Furthermore, when resources and skills are limited, climate change policy appears to lead to a shift in innovation efforts from polluting technologies to low-carbon ones.

Interestingly, the effect of policy on innovation happens very quickly, even within two to three years. This can be particularly valuable for local or national governments which tend to be in place for no more than four or five years and are therefore keen to see short-term results.

This chapter outlines the evidence supporting these claims.

2.1 The effects of climate change policy on innovation in low-carbon technologies

Many studies find that public policies are a crucial driver for the adoption of low-carbon technologies, particularly in the heavily regulated and policy-driven energy sector (especially electricity). Examples include Kerr and Newell (2003) on the removal of lead from gasoline in the US, Kemp (1998) on the effect of effluent charges on biological treatment of wastewater, Snyder et al. (2003) on the diffusion of membrane-cell technology in the chlorine manufacturing industry, and Popp (2009) on NOX pollution control technologies at power plants.

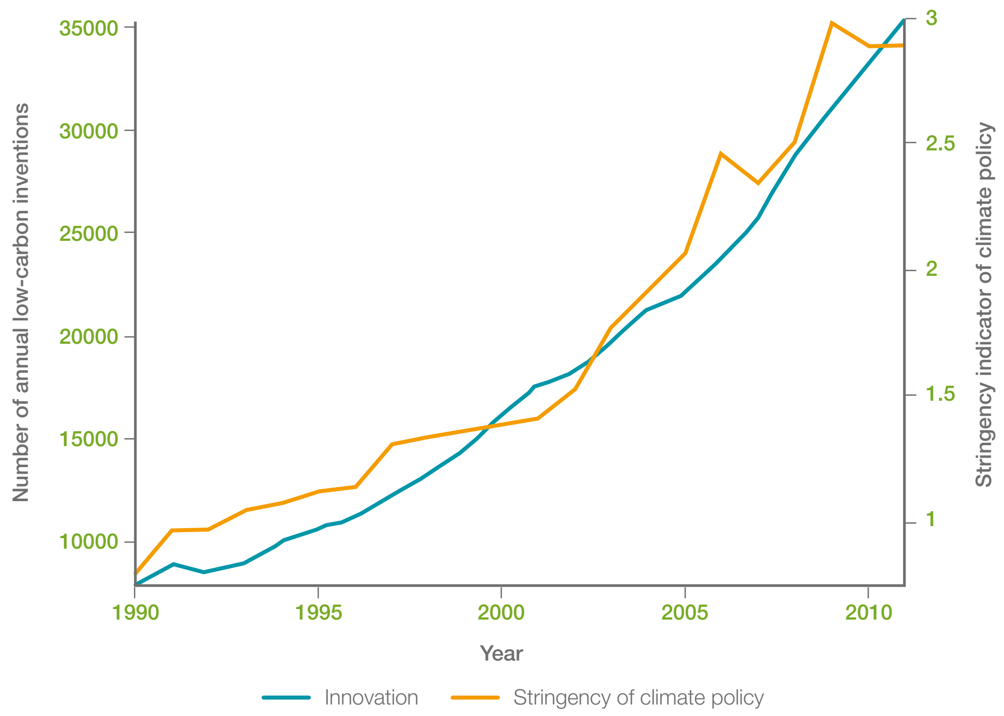
The change in relative prices due to climate change regulation spurs so-called 'induced innovation' (Acemoglu, 2002; Acemoglu et al., 2012; Hicks, 1932). Because research and development (R&D) is a profit-motivated investment activity, inventors respond to the expected increased diffusion of environmental technologies induced by regulations by developing low-carbon technologies. This finding is supported by a large body of evidence (for recent surveys of relevant literature see Popp et al., 2010; Popp, 2010; and Ambec et al., 2013).

To illustrate this point, Figure 1 shows number of low-carbon inventions for which patent protection has been sought by inventors located in OECD countries between 1990 and 2012, along with an indicator of the stringency of climate change policy developed by the OECD (Botta and Kozluk, 2014).[2] The graph shows a striking correlation between innovation efforts, as measured by patent filings, and the stringency of policy.

Analyses of this phenomenon include Lanjouw and Mody (1996), Jaffe and Palmer (1997), and Brunnermeier and Cohen (2003) who show a significant correlation within industries over time between innovative activity and environmental regulatory stringency (proxied by pollution control expenditures). Similarly, Johnstone et al. (2010) find that patenting activity for renewable energy technologies, measured by applications for renewable energy patents submitted to the European Patent Office (EPO), has increased dramatically in recent years, as both national policies and international efforts to combat climate change begin to provide incentives for innovation. Dechezleprêtre and Glachant (2014) show that public policies that encourage the diffusion of renewable energy technologies, such as feed-in tariffs and renewable energy certificates, induce technological change, so that for every 100 MW of new wind power capacity installed in OECD countries, three new inventions are patented on average.

2 The indicator of environmental policy stringency is a composite index of various environmental policy instruments, primarily related to climate and air pollution. See Botta and Kozluk (2014) for details over the construction of the indicator.

Figure 1. Low-carbon innovation activity and climate change policy stringency in OECD countries, 1990-2011



Source: Number of inventions: authors' own calculations from the PATSTAT database; Climate policy stringency indicator: OECD (2014). Individual countries are weighted by their GDP in order to calculate the average policy stringency across the OECD.

Other studies provide evidence on how innovation reacts to higher energy prices resulting from various policies. Newell et al. (1999) show that the energy efficiency of air conditioners and gas water heaters in 1993 would have been one-quarter to one-half lower if energy prices had stayed at their 1973 levels, rather than rising along their historical path. Similarly, both Popp (2002) and Verdolini and Galeotti (2011) find that a 10 per cent increase in energy prices raises energy patenting in the long run by around 4 per cent. Aghion et al. (2016) examine innovation activity in the car industry and show that firms tend to innovate more in low-carbon technologies (i.e. electric, hybrid and hydrogen cars) and less in high-carbon technologies (i.e. internal combustion engines) when they face higher fuel prices. A 10 per cent higher fuel price is associated with about 10 per cent more low-carbon patents and 7 per cent less high-carbon patents.

Moreover, the innovative response to policy happens quickly. Evidence suggests that much of the innovative response to higher energy prices occurs within five years or less. Popp (2006) finds an almost immediate innovative response to the passage of low-carbon air regulations in the US, Japan and Germany. Similarly, Calel and Dechezleprêtre (2014) show that the European Union Emission Trading System (EU ETS) has increased innovation activity (measured by the number of patents) in low-carbon technologies[3] among participating companies. Participants in the scheme and non-participants exhibited roughly comparable innovation activity before the introduction of the EU ETS, but they start diverging quickly after the new policy was put in place (see Figure 2).

To sum up, there is ample empirical evidence that climate change regulations, either directly or through their impact on energy prices, encourage the diffusion of environmentally-friendly technologies and drive innovation activity further up the technology supply chain, favouring R&D in low-carbon technologies. The impact on innovation appears both large and rapid. Thus, climate change regulations can help economies break away from a polluting economic trajectory and move to a low-carbon one.

Figure 2. Low-carbon innovation activity of EU ETS regulated companies compared with counterfactual scenario

Source: Calel & Dechezleprêtre, 2014. 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.

3 Low-carbon patents are defined based on the Cooperative Patent Classification "Y02" class, which covers "technologies or applications for mitigation against climate change. It includes: efficient combustion technologies (e.g. combined heat and power generation); renewable energy technologies, carbon capture and storage, efficient electricity distribution (e.g. smart grids); and energy storage (e.g. fuel cells). See Calel and Dechezleprêtre (2014) for a complete list of the sub-classes of low-carbon patents used in the paper.

2.2 Does innovation in low-carbon technologies crowd out R&D in other technologies?

It is reasonable to assume that the supply of researchers in the economy is fixed in the short run, so that at the macroeconomic level new R&D activity in one technology should almost completely crowd out innovation in another technological field. At the microeconomic level, companies can expand R&D activities by hiring more researchers, but even then, **there is empirical evidence that crowding-out does occur.** Hottenrott and Rexhaüser (2013) find that regulation-induced low-carbon-tech innovation crowds out R&D in other technologies, especially for small firms that are credit constrained. Popp and Newell (2012) use patent and R&D data to examine both the private and social opportunity costs of low-carbon R&D. Looking first at R&D spending across industries, they find that funds for energy R&D do not come from other sectors, but come from a redistribution of research funds in sectors that perform energy R&D. Moreover, taking a detailed look at low-carbon R&D in two sectors – alternative energy and automotive manufacturing – they find evidence that the patents most likely to be crowded-out by low-carbon research are innovations enhancing the productivity of fossil fuels, such as energy refining and exploration. This is in line with results by Aghion et al. (2016) which show that automobile companies react to increases in fuel prices by conducting more innovation in low-carbon cars (electric, hybrid and hydrogen) and less innovation in high-carbon (combustion engine) cars. These results are consistent with the notion that crowding-out reacts to market incentives. Hence as opportunities for alternative energy research become more profitable, research opportunities for traditional fossil fuels appear less appealing to firms.

Therefore, recent research suggests there is a crowding out effect and that low-carbon innovations tend to crowd out high-carbon innovations in the same sector. These results imply that **climate change policies play a crucial role in ensuring that low-carbon innovation activity comes at the expense of innovation in more polluting technologies rather than of other, potentially socially valuable, innovation.** Policies that change the relative price of low-carbon and high-carbon inputs, such as carbon markets or fuel taxes, can play this role effectively. Another implication is that the welfare impacts of induced low-carbon innovation will depend partly on the relative size of the social benefits coming from knowledge spillovers in low-carbon and high-carbon innovation. This question is addressed in the next section.

3. The impact of low-carbon innovation on profits, competitiveness and growth

A key question for policymakers is: what impact will climate change policies have on competitiveness and economic growth?

This chapter presents the evidence on the impact of low-carbon innovation on firms' profits. It also investigates the potential of low-carbon innovation to stimulate technological improvements in a broad range of sectors beyond what is typically regarded as the 'green' economy and, in doing so, be a driver of economic growth.

3.1 The impact of low-carbon innovation on firms' private profits

The ability of regulation-induced innovations in low-carbon technologies to improve firms' profitability depends on their impact on the productivity of labour, materials and energy. It has been argued that climate change regulations, in particular market-based instruments, can trigger innovation that may partially or more than fully offset these costs (Porter, 1991; Porter and Van der Linde, 1995).

Evidence can be found to support this statement to an extent. For example, Rexhauser and Rammer (2014) find that regulation-induced innovations which improve a firm's resource efficiency in terms of material or energy consumption have a positive impact on profitability, as measured by pre-tax profits over sales.

Lanoie et al. (2011) also find that regulation-induced, low-carbon innovation improves business performance, though not enough to offset the costs of complying with climate change regulations. They conclude that the net effect is negative—that is, the positive effect of innovation on business performance does not outweigh the negative effect of the regulation itself. These results suggest that **climate change regulation is costly, but less so than if one was to consider only the direct costs of the regulation itself, without the ability of innovation to mitigate those costs.**

3.2 The impact of low-carbon innovation on growth through knowledge spillovers

As discussed in section 2, climate change policies induce innovation in low-carbon technologies. By making polluting activities less profitable, climate change policies also reduce innovation activity in polluting technologies. Therefore, the potential consequences of climate policies on economic growth through their impact on innovation will be determined by the net effect of the increase in low-carbon and the reduction in high-carbon innovation. Will this effect be positive or negative?

It is well established in the economic literature that R&D activities provide not only private returns to inventors, but also returns to society which are not captured by inventors (Geroski, 1995). 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. This public knowledge may lead to additional innovations.[4] These knowledge spillovers provide benefits to the public as a whole, but not to the innovator. An obvious example of such a spillover is Android-based smart phones. Apple first launched the now dominant design of smart phones. However, other companies such as Google were also able to benefit from Apple's original R&D investments by copying or improving the original design.[5] Economists studying the returns to research consistently find that knowledge spillovers result in a large wedge between private and social rates of return to R&D.[6] Typical results include marginal social rates of return between 30 and 50 per cent. In comparison, estimates of private marginal rates of return on investments range from 7 to 15 per cent (Hall et al., 2010).

4 Intellectual property rights, such as patents, are designed to protect inventors from such copies. However, their effectiveness varies depending on the ease in which inventors may 'invent around' the patent by making minor modifications to an invention. See, for example, Levin et al. (1987).

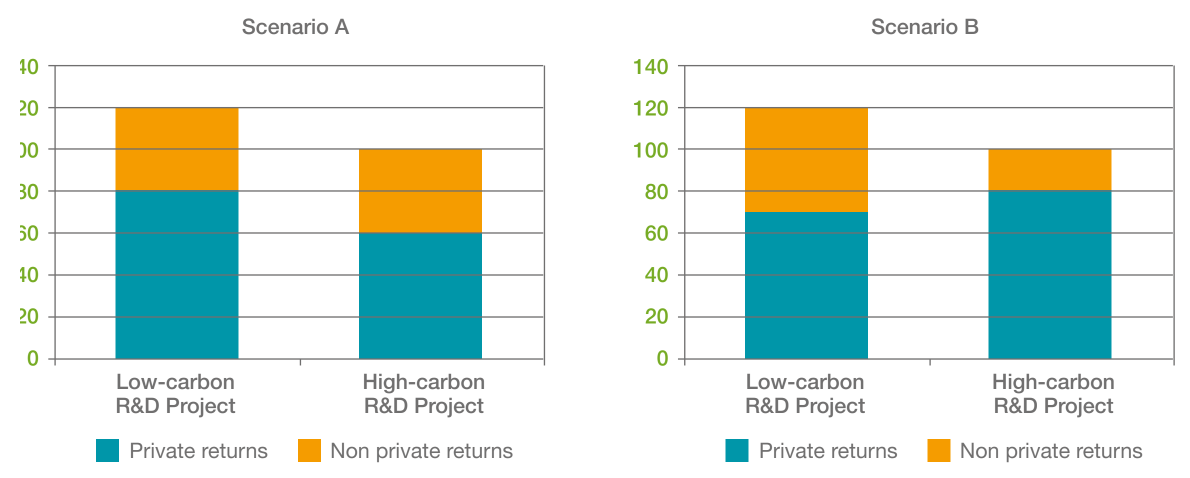
5 Sticking to energy, an example is the massive social benefits (and smaller emissions benefits) in the near term that are accruing due to the development of lithium ion technology. Note that private returns are harder to capture in sectors such as energy as, for example, a green electron is no more attractive than a high-carbon one to the end-user. By contrast, innovation can demonstrably improve the quality of a mobile phone and differentiate it from its competitors, allowing greater scope for returns to innovation to be captured.

6 Sticking to energy, an example is the massive social benefits (and smaller emissions benefits) in the near term that are accruing due to the development of lithium ion technology. Note that private returns are harder to capture in sectors such as energy as, for example, a low-carbon electron is no more attractive than a high-carbon one to the end-user. By contrast, innovation can demonstrably improve the quality of a mobile phone and differentiate it from its competitors, allowing greater scope for returns to innovation to be captured.

Since firms make investment decisions based on their private returns, the wedge between private and social rates of return suggests that **socially beneficial research opportunities are ignored by firms because they are unable to fully capture the rewards of such innovations.**[7] As a consequence, innovation in low-carbon technologies induced by climate change policies can increase welfare. However, this depends crucially on whether new R&D investments in low-carbon technologies come at the expense of innovation in other technologies.[8]

Consider two scenarios (A and B) that might present themselves to a firm deciding about its next R&D investment project, as illustrated in Figure 3. In both cases two R&D investment opportunities are compared: a low-carbon option and a high-carbon option.[9] In both cases the combined private and non-private return of the low-carbon project are higher. However, in scenario A combined returns are higher because of higher private returns. In scenario B non-private returns are higher, whereas private returns are lower for the low-carbon project. Now consider a climate policy that requires firms to invest in the low-carbon option. In scenario A this would not have an impact on growth or economic value, as the firm would already choose the low-carbon option in the absence of the regulation. The climate policy would not be necessary at all in this scenario, since the market would redirect the economy toward low-carbon technologies by itself. In scenario B the climate policy would be binding, as the private returns are lower in the low-carbon R&D project, and hence low-carbon innovation is only conducted in the presence of climate change policy. As a consequence of being forced to invest in the low-carbon R&D project, rather than in the high-carbon R&D project, the value of the firm would drop but the social economic value would increase.

Figure 3. Potential R&D investment scenarios in low-carbon and high-carbon technology



7 A central problem in the literature on spillovers is that firm performance is affected by two countervailing effects: a positive effect from knowledge spillovers and a negative effect from businesses stealing products from market rivals. Bloom et al. (2013) incorporate these two types of spillovers and show that technology spillovers quantitatively dominate, so that the gross social returns to R&D are at least twice as high as the private returns even when taking product rivalry into account.

8 For example, Popp (2004) estimates that, in case of no crowding-out (new R&D investments in low-carbon technologies come at the expense of investments in physical capital but not at the expense of other R&D activities), innovation induced by climate change policy increases welfare by 45 per cent compared to a situation without induced innovation activity. However, if one-half of new low-carbon R&D crowds out other R&D, induced innovation increases welfare by only 9 per cent, and if new low-carbon R&D fully crowds out other R&D, welfare gains decrease by 2 per cent.

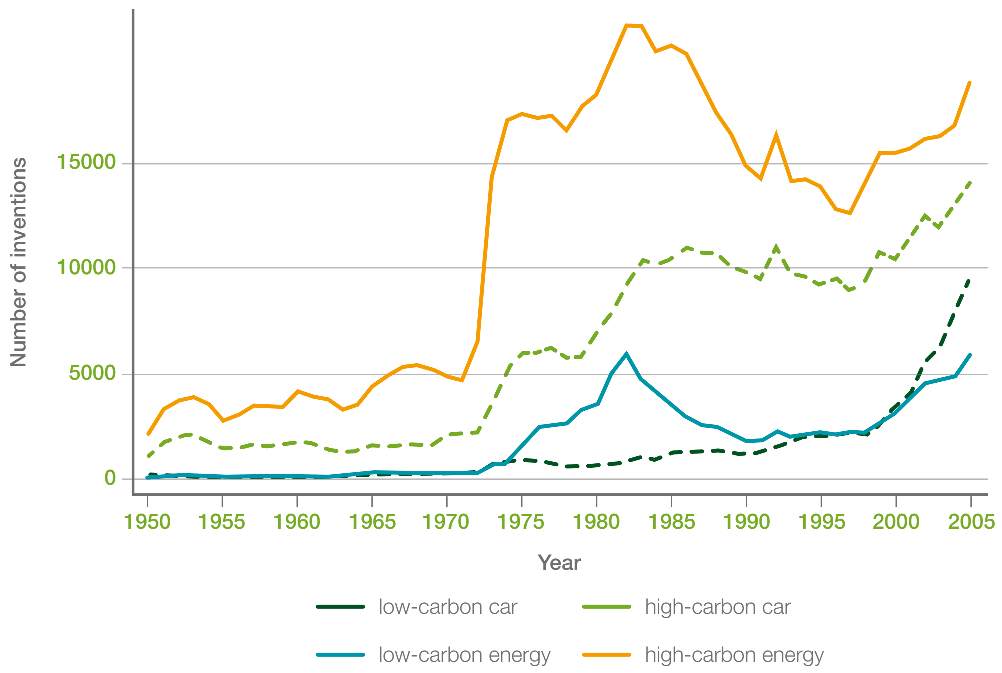
9 An example in the automobile sector would be an innovation in a new electric motor or an innovation to produce a larger vehicle, hence less energy efficient. The low-carbon or the high-carbon option could also be energy efficiency innovations on combustion engines. The key point is that one innovation is more carbon-intensive than the other.

An argument in favour of public intervention is therefore that **policy can help realise those societal benefits from innovation, or technology spillovers, that may not be triggered by private interest alone. Thus, higher spillovers for low-carbon technologies compared to high-carbon technologies can in theory generate positive growth effects from climate policies** if they are sufficiently high to compensate for the lower private value of low-carbon innovation.

Dechezleprêtre et al. (2014) measure knowledge spillovers coming from low-carbon and high-carbon patents using a global dataset of patent citations.[10] The analysis focuses on two sectors: transport and electricity production, which jointly account for the bulk of carbon emissions. In the electricity generation sector, low-carbon technologies cover renewable energy sources, while high-carbon technologies are those based on fossil fuels (mostly coal and gas). In the automotive sector, low-carbon technologies encompass electric, hybrid and hydrogen vehicles, while high-carbon technologies are associated to internal combustion and gasoline engines. Figure 4 reports the number of innovations in the different categories between 1950 and 2005.

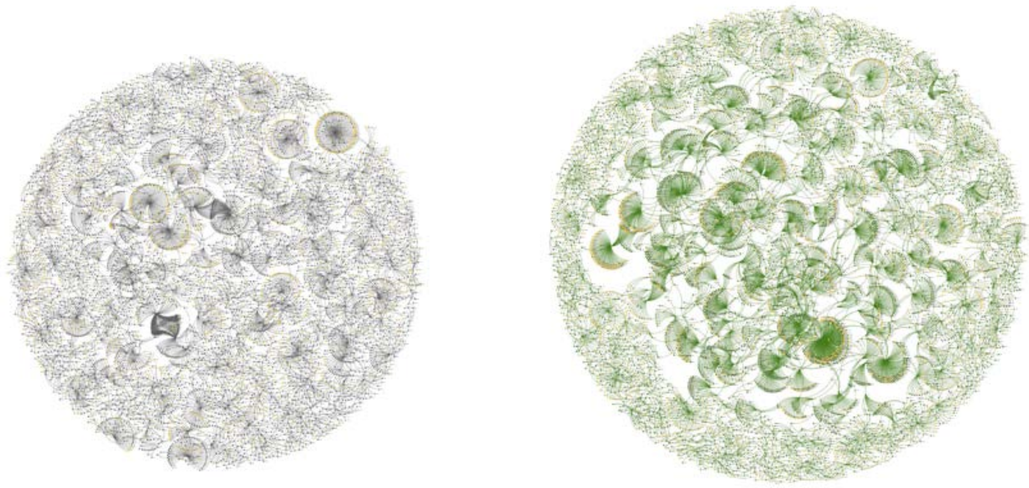
The key finding by Dechezleprêtre et al. (2014) is that **knowledge spillovers are much larger for low-carbon than for high-carbon technologies.** This is shown graphically in Figure 5 and confirmed by a large set of statistical analyses which account for a large number of potentially confounding factors, including the fact that low-carbon patents may have higher chance of being cited simply because there are fewer of them (see the full paper for details on these analyses).

Figure 4. Number of low-carbon and high-carbon innovations 1950-2005



10 Any innovator applying for a patent is required to reference all previous innovations – so called prior art – on which the new innovation is based. A citation indicates that the knowledge contained in the cited document has been useful in the development of the new knowledge laid out in the citing patent and thus represents a knowledge flow. For this reason, patent citations have been used frequently to measure knowledge spillovers.

Figure 5. Visualising spillovers from low-carbon and high-carbon technologies



Notes: The figure visualises all citations to a sample of 1000 high-carbon (left panel) and 1000 low-carbon (right panel) innovations. Each node represents an innovation (black=high-carbon innovation, green=low-carbon innovation, orange=other innovation), edges represent citations. The samples were drawn among innovations applying for patent protection in 1995. Interactive versions of these figures can be found online.[11]

While the main distinction in this analysis is between low-carbon and high-carbon technologies, there are many technologies within the high-carbon category that make fossil fuels more efficient. These can be viewed as another alternative to low-carbon (zero-carbon) technologies and are termed as 'grey'.[12] From a climate point of view these are helpful, but, as they rely on fossil fuels, they might not be sufficient to achieve a fully decarbonised economy and might also promote the lock-in of fossil fuel infrastructure (see Aghion et al., 2014). Comparing the intensity of spillovers between low-carbon and grey technologies, Dechezleprêtre et al. (2014) still find that **low-carbon technologies generate significantly larger spillovers than grey technologies. This means that R&D activities in zero-carbon technologies, such as electric and hydrogen cars or renewable energy technologies, should receive larger public support than R&D activities in energy-efficiency technologies.**

Although patent citations provide a measure of knowledge spillovers, they do not tell us anything about the associated economic value. If low-carbon citations reflect spillovers that are less economically valuable, finding higher citation counts would be of little economic relevance. However, Dechezleprêtre et al. (2014) look at the change of a firm's stock market value as they innovate (measured by patent applications) and find that, all else equal, a firm's value increases by more if they apply for a patent that cites a low-carbon patent rather than a high-carbon patent. In other words: **spillovers from low-carbon technologies are more economically valuable than spillovers from high-carbon technologies.** However, Dechezleprêtre et al. (2014) are not able to assess whether this economic gain is sufficient to offset the costs of regulation.

11 http://www.eeclab.org.uk/forcedirect_arx.html?tojson_dirlinks0_1995_15_1000_0.json
http://www.eeclab.org.uk/forcedirect_arx.html?tojson_dirlinks0_1995_15_1000_2.json

12 Note that since the data stops in 2005, fracking technologies are not included in the 'grey' category.

Where does the low-carbon advantage come from? One potential explanation is that low-carbon technologies are by and large new technology fields. New technology fields offer potentially high marginal private returns to first movers and might thus generate large knowledge spillovers. Dechezleprêtre et al. (2014) compare the spillovers from low-carbon and high-carbon technologies to a range of other emerging technologies, such as IT and biotechnologies. They find that the intensity of spillovers from low-carbon technologies is comparable to other emerging technologies (see Figure 6). Knowledge spillovers from high-carbon technologies are lagging behind.

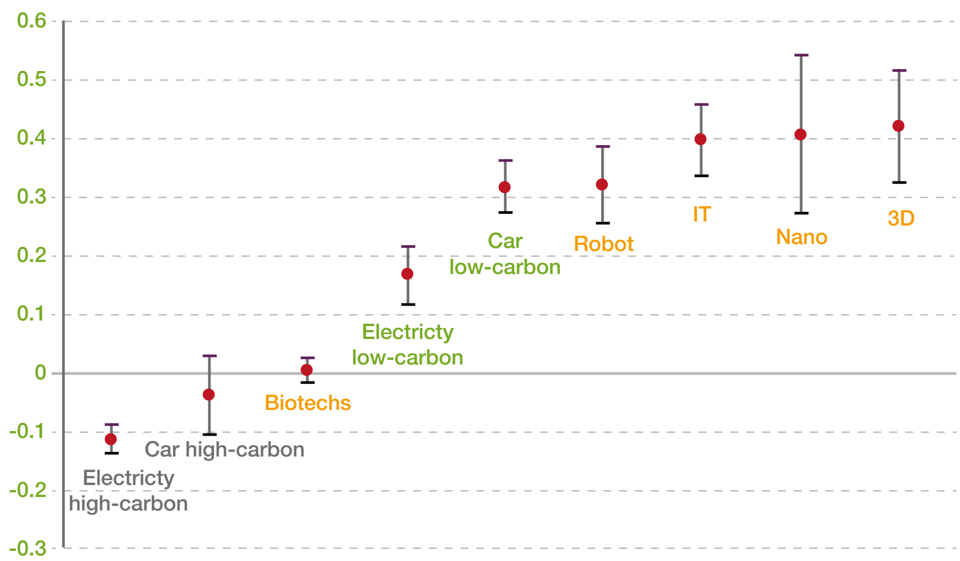
To sum up, while environmental policies are unlikely to be beneficial for companies facing new regulatory costs, they can have economy-wide benefits through increased innovation spillovers. An important implication of this finding is that **seeking only 'win-win' solutions with no losers would risk leaving many socially beneficial policies off the table.**

3.3 Capturing the benefits of innovation locally

Currently most climate policy is unilateral and some countries, for example those in the European Union, are imposing more stringent policies than others. This raises concerns that climate policies can harm the competitiveness of those countries and induce firms to relocate.

The evidence on competitiveness impacts from unilateral climate change policy is mixed, with empirical analysis indicating that existing policies have small effects on companies' performance and relocation (or 'carbon leakage'), at least in most sectors (for a review of the most recent literature see Bassi & Zenghelis, 2015; Dechezleprêtre & Sato, 2015).

Figure 6. Low-carbon and high-carbon spillovers versus other emerging fields

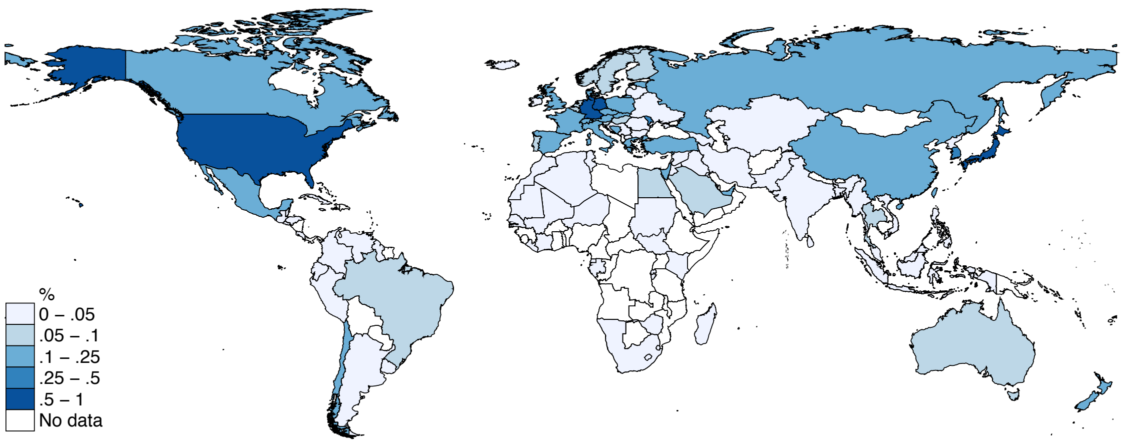


Note: The figure compares the intensity of knowledge spillovers (as measured by patent citations) in a number of technologies, compared to the average patented technology. The y-axis represents the percentage difference in the intensity of knowledge spillovers. For example, a value of 0.2 means that the technology induces 20% more knowledge spillovers than the average patented technology. Red dots are point estimates; the black lines show 95% confidence intervals. Source: Dechezleprêtre et al. (2014)

If there are sufficiently strong localised spillovers, such negative effects on economic outcomes could potentially be offset. Hence, the incentives to adopt climate change policies are much higher when local knowledge spillovers from low-carbon technologies are factored in.

Dechezleprêtre et al. (2014) examine this by looking separately at spillovers that occur within the same country where the original innovation emerged and spillovers elsewhere. They find that **low-carbon innovations generate knowledge spillovers both locally and across borders, with a somewhat larger advantage for local benefits.** Hence, this provides a potential channel for positive home country effects from unilateral policies. Moreover, they find that on average, 52 per cent of spillovers in low-carbon technologies patented since the year 2000 occur within the inventor's country. This proportion of local spillovers depends on the size and the openness of the economy: 61 per cent for Japan, 59 per cent for the US, 44 per cent for Germany but 28 per cent for France, 15 per cent for the UK and 10 per cent for the Netherlands (see Figure 7). For the European Union as a whole (i.e. considering Europe as a single entity), 61 per cent of knowledge spillovers occur domestically. These numbers all suggest that **the local benefits from induced low-carbon innovation are far greater than the local benefits of carbon emissions reductions alone,** since the benefits of avoided climate change are essentially equally shared among all countries around the world.

Figure 7. Proportion of local spillovers from low-carbon technologies by country

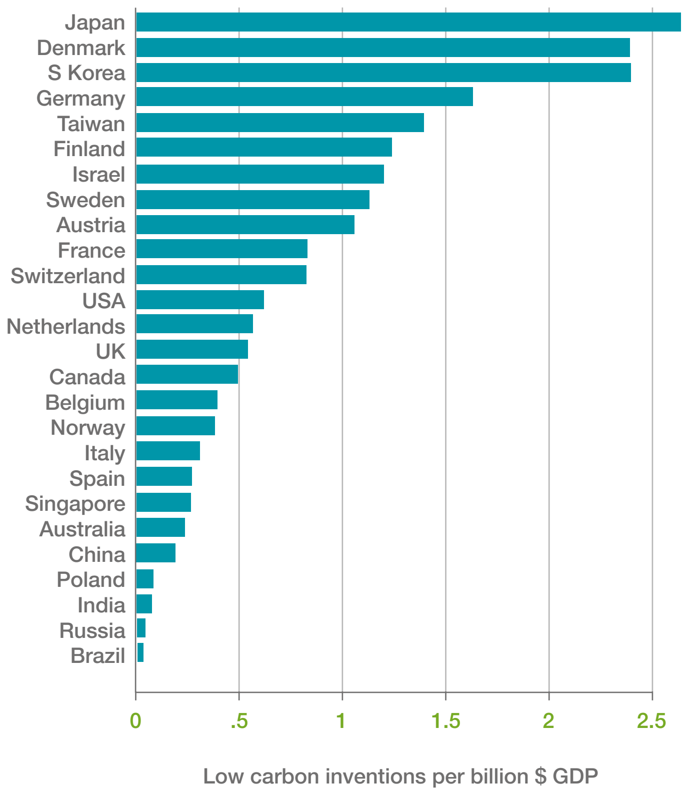


4 How to best incentivise low-carbon innovation?

As explained above, innovation in low-carbon technologies is not only key to any long-term decarbonisation scenario, it can also lower or even offset the costs of climate change policies. From a policy perspective, the question then becomes: which policy combination will provide the best incentive for new low-carbon technology development?

A quick look at the performance of countries with respect to low-carbon innovation as measured by patent data (see Figure 8) reveals striking differences that have been linked to differences in the policy environment (Dechezleprêtre et al., 2011). For example, Germany appears to reap the benefits of its novel Fraunhofer system, which fosters strong and fruitful partnerships between researchers, industry and government (see box 1). The ranking of countries by the number of low-carbon inventions per billion dollars in Figure 8 shows that amongst European Union Member States, Germany and the Scandinavian countries are at the forefront in the innovation scale. The UK is approximately midway in the ranking, ahead of countries such as Belgium, Norway, Italy, Spain and Poland, but behind France, the Netherlands and others.

Figure 8. Number of low-carbon inventions per bn US$ GDP 2010-2014



Source: Source: authors' own calculations from the Patstat database. Only high-value patents taken out in at least two patent offices in the world are included. Real GDP at chained PPPs in billion 2005 US$ is from the Penn World Table. We group five years to mitigate the effect of annual fluctuations.

Box 1: Fraunhofer-Gesellschaft – the importance of applied R&D in commercialising solar PV technologies

Germany has created the largest network of applied research institutes in Europe, known as the Fraunhofer-Gesellschaft (or the Fraunhofer Institute). It is comprised of 67 different institutes that cluster advanced scientific and engineering expertise in different technological fields. A significant percentage of the funding for each institute is provided by industry, creating incentives for collaborative learning that leverages the advanced research capabilities of the institutes with the engineering capabilities and facilities of the industrial firms.

The Fraunhofer Institute also provides information and policy advice to the German government with regards to developments in the technological landscape and the viability of different technological options. The Fraunhofer Institute for Solar Energy Systems is especially important in supporting high-level solar PV innovation for the solar PV industry – particularly in helping domestic semi-conductor companies retool and sell the equipment used for crystalline PV factories. This Institute also holds the world record for the most efficient silicon solar cells (in lab settings). Fraunhofer's engineering and economics research also provides technical and policy assistance in managing electricity market and grid instability caused by sudden increases to the renewable energy generation feed into the German electricity grid.

4.1 Optimal public R&D funding

In 2011, the last year for which comprehensive public R&D data reported to the IEA is available, OECD governments spent around €14 billion (£10.25 billion at current exchange rate) to support research in climate change mitigation technologies (see Figure 9). This represents 0.03 per cent of the GDP of these countries on average, although there is variation across countries (see Figure 10). Public climate change-related R&D expenditures in OECD countries have increased significantly since 2000. However, in 2011 they were still below what they were in the early 1980s after the second oil shock. Moreover, after a sudden increase in 2009 corresponding to recovery programmes that followed the recession (and in particular the American Recovery and Reinvestment Act of 2009), public R&D funding fell by 20 per cent in the next year.

Figure 9. Public R&D expenditures in climate change mitigation technologies in OECD countries, 1974-2011

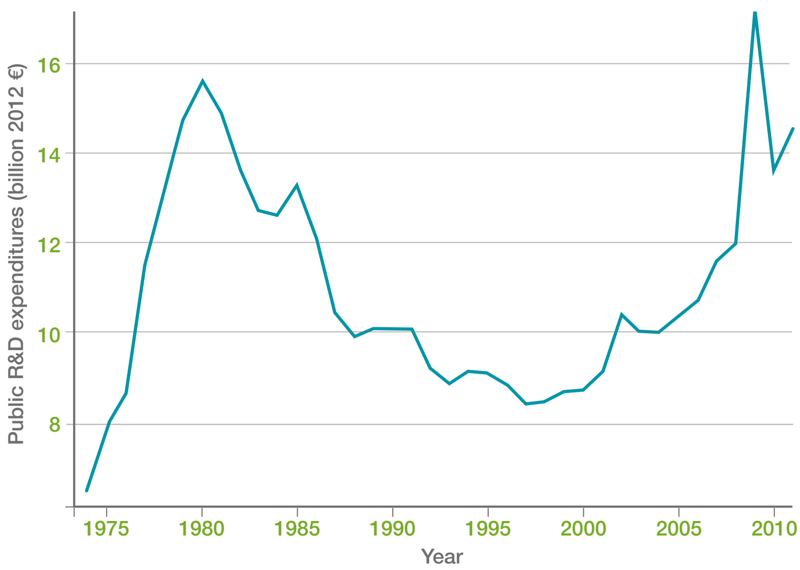
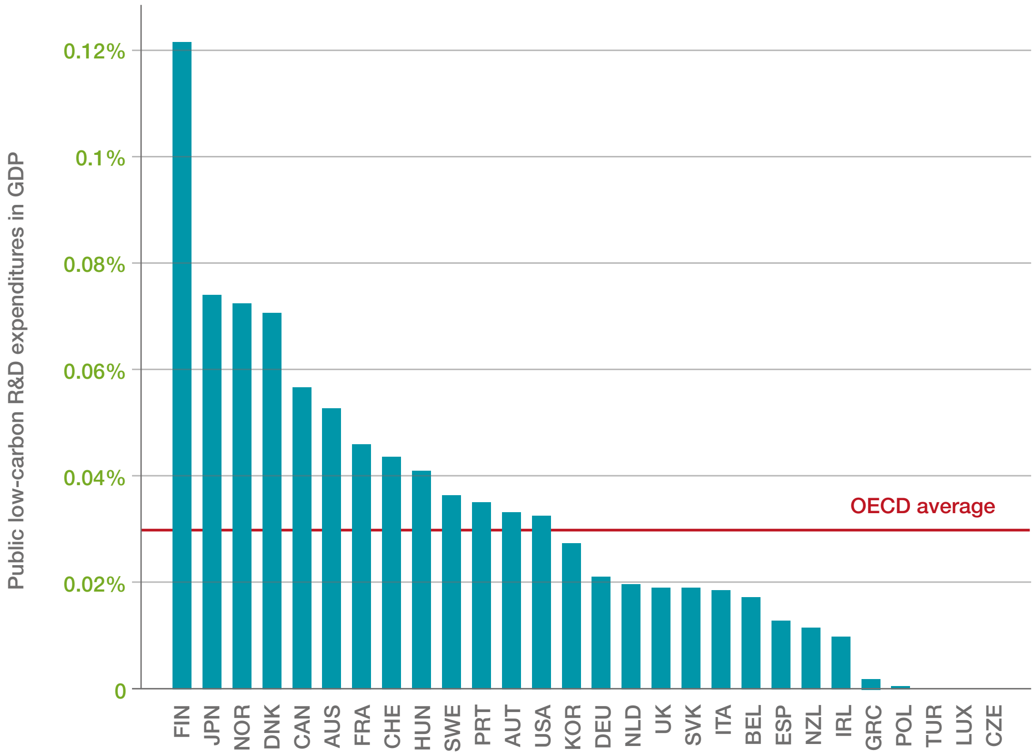


Figure 10. Public R&D expenditures in climate change mitigation technologies as share of GDP (2011)



Determining how much government R&D money to spend on low-carbon innovation is an important question for policymakers. Here, economics provides less of an answer, as estimating the potential benefits from new R&D spending is a difficult task and engineers are better suited than economists to determine which projects are most deserving from a technical standpoint. However, given the need for a diversified energy 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 for funding are likely to come from other sources, such as the current pool of scientists and engineering personnel available to work on low-carbon projects, and how quickly it can be expanded. That is, the spending limits come not from the number of deserving projects, but rather the limits of the existing research infrastructure.

Recent papers show that the optimal climate policy heavily relies on research subsidies. For example, Acemoglu et al. (2014) suggest that 90 per cent of all R&D expenditures in low-carbon technologies should be funded by the government during a couple of decades, so that the productivity of low-carbon technologies quickly catches up with that of high-carbon technologies.

Recent IEA estimates suggest that achieving global energy and climate change ambitions consistent with a 50 per cent reduction of energy-related carbon dioxide emissions in 2050 with respect to 2007 (the 2010 BLUE Map scenario) would require a two to fivefold increase in public R&D spending (IEA, 2010). The gap between current public R&D and the funding needed is particularly large in low-carbon transportation, CCS, smart grids and energy efficiency in industry (IEA, 2010).

However, growth in low-carbon R&D budgets should be slow and steady, allowing time for the development of young researchers in the field. In Europe, a doubling of public R&D expenditures over 10 years (from €4bn to €8bn a year) corresponds to what was observed between 2001 and 2011 and thus seems achievable. Experience from the US National Institutes of Health (NIH), for instance, shows that rapidly doubling and subsequently decreasing budget on the bio-medical sciences between 1998 and 2007 led to high adjustment costs (linked with hiring new staff, buying new equipment, and so on), a career crisis (young persons trained during the upsurge in spending had to compete with a larger supply of young biomedical researchers after the upsurge when there were fewer research opportunities than when they were attracted to the field) and wasteful uses of resources (Freeman and Van Reenen, 2009).

It is also important that any policy effort to accelerate innovation in low-carbon technologies includes a component to train new scientists and technical workers, in order to increase the supply of qualified scientists in the long run. In this respect, the 2009 spike in R&D funding in the US and elsewhere can be counterproductive. What is needed is a slow but sustained growth in public R&D funding over the next decade. Commitments to fund R&D should have a long-term component (until at least 2030) just like carbon emission caps. So while it is welcome that countries such as the UK have committed to doubling public funding for low-carbon R&D by 2020 as part of 'Mission Innovation'[13]; countries should be encouraged to set public R&D targets as far ahead as 2030. Targets would vary between countries and may need to be set within a range, but such long-term targets would reduce public funding spikes and associated adjustment costs, and ultimately could reduce the overall cost of decarbonisation.

To provide such a long-term commitment, revenues from auctioned carbon permits in the many carbon markets that now exist around the world could provide a source of sustained funding for low carbon R&D. For example, to fund a doubling of public R&D in Europe over the next decade, it would be enough to allocate 10 per cent of the revenues from auctioned emissions allowances (assuming an average carbon price of €11/tonne) to low-carbon innovation (Dechezleprêtre and Popp, 2015).[14]

4.2 Types of policy instruments

Studies on induced innovation provide robust evidence on the effectiveness of public policy as a driver of low-carbon innovation (as discussed in Chapter 2). Also important, however, is the nature of policies used to stimulate innovation. Policymakers have a range of instruments available to regulate environmental quality. Command-and-control regulations can help achieve a specific level of performance. For instance, performance standards sets a uniform control target for firms (such as pounds of sulphur dioxide emissions per million BTUs of fuel burnt), but do not dictate how this target is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation, such as requiring that a percentage of electricity be generated using renewable sources. Market-based policies establish a price for emissions, either directly through the use of fees, such as a carbon tax, or indirectly through the use of permits that can be bought and sold among firms, such as in the US sulphur dioxide market or the EU ETS for carbon.

Historically, economists have argued that market-based policies provide greater incentives for innovation, while command-and-control measures (such as performance or technology standards) can be too rigid and cost inefficient. **Market-based policies provide rewards for continuous improvement in environmental quality,** whereas command-and-control policies penalise polluters who do not meet the standard, but do not reward those who do better than mandated (Magat, 1978; Milliman and Prince, 1989).

13 Mission Innovation is a global initiative to accelerate public and private clean energy innovation to address climate change, make clean energy affordable to consumers, and create green jobs and commercial opportunities. Through the initiative, 20 countries representing 80 per cent of global clean energy research and development (R&D) budgets are committing to double their respective R&D investments over five years.

14 To efficiently allocate public spending, one would need to equate the marginal social benefit of projects with the marginal social cost of revenue raising methods, and there is no reason why green R&D and emissions permits would meet this except by coincidence. However, from a political economy point of view, hypothecation could help securing buy-in and credibility.

However, recent research suggests that the effects are more nuanced. For example, **standards can be of use in case of anomalies in the behavioural response to market-based instruments.** A typical example is the 'energy efficiency paradox', where seemingly cost-effective energy-efficient technologies diffuse slowly, even if they provide cost-saving benefits to the users. Several researchers have examined this paradox, offering explanations including: consumers using high discount rates (Train, 1985); credit-constrained consumers caring more about up-front costs than lifetime cost savings (Jaffe and Stavins, 1994); agency problems such as landlord/tenant relationships (Levinson and Niemann, 2004); and uncertainty over future costs (Anderson and Newell, 2004).

To the extent that diffusion is limited by other market failures, market-based instruments that simply increase the economic incentive to adopt environmentally-friendly technologies will be insufficient. Additional command-and-control policies focused directly on the correction of market failures and other government/institution failure can therefore be needed. In a recent review, Vollebergh and Van der Werf (2014) show that, in appropriate conditions, **standards are key complements to market-based instruments.** For example, to promote the development of electric vehicles, charging stations must be in place. However, the private sector has little incentive to provide charging stations without existing demand from electric vehicles. In the case of such network externalities, clear technology standards provide guidance to firms as to the expected future direction of technology. These policy signals must be clear, to avoid unintended consequences.

Among market-based policies, differences between policies also matter. Johnstone et al. (2010) compare quantity-based policies, such as renewable energy certificates, to price-based policies to promote renewable energy, such as tax credits and feed-in tariffs.[15] Quantity-based policies tend to favour the development of lowest cost technologies which are closest to being competitive with traditional energy sources, such as onshore wind energy. This leads to lower compliance costs in the short-run, as firms choose the most effective short-term strategy. However, since firms focus on those technologies closest to market, quantity-based incentives do not provide as much incentive for research on longer-term needs. By contrast, price-based incentives that differentiate between technologies (for example feed-in tariffs that differ across types of renewable energy technologies) can be more effective in supporting innovation in emerging technologies which are further from being competitive with traditional energy sources, such as marine energy. However, this raises the costs of regulation, as firms are forced to use technologies that are not cost-effective.

The perceived stability of the policy is also important. Since expectations over future prices determine innovation, long-term regulatory consistency is crucial for new technology development (Held et al., 2009). For example, Butler and Neuhoff (2008) show how German feed-in tariffs stimulated overall investment quantity more than UK renewable energy quotas because the guaranteed revenues associated with feed-in tariff reduced risks from the project investment.

Similarly, the price signal established by market-based policies must be sufficient to encourage innovation, else other measures may be required. Calel and Dechezleprêtre (2014) show that the effect of the EU ETS on innovation activity was concentrated at the beginning of the scheme's second phase, which saw a significant increase in the price of carbon on the market (permit prices rose to approximately €30 per tonne of carbon dioxide) and an expectation that prices would remain at a high level in the foreseeable future. This suggests that the current level of carbon prices in the EU ETS combined with expectations of a low price in the next decade might be too low to provide sufficient incentives for technology development (Dechezleprêtre and Popp, 2015).

15 Feed-in tariffs, used in various European countries, guarantee renewable energy producers a minimum price for the electricity they produce.

One possible solution to overcome this is to **use a portfolio of policies – including carbon markets, taxes, targets, feed-in tariffs, etc. – to ensure short-run compliance at low costs, as well as providing public funding to low-carbon R&D that supports emerging technologies.**

4.3 Direct R&D funding vs demand-pull policies

While it is impossible to provide an 'optimal' policy mix between R&D and deployment, recent evidence also indicates that **many countries, in particular in Europe, have put a strong emphasis on deployment policies compared with direct R&D support.**

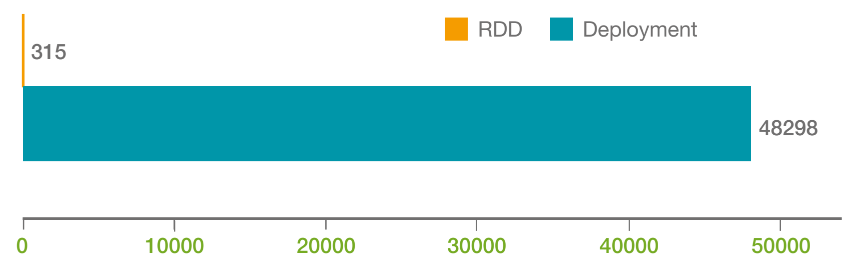
A study by Zachmann et al. (2014) shows that the six largest European countries spent €315 million in 2010 to support R&D in wind and solar power. The cost to society implied by the deployment of wind and solar technologies[16] that same year represented €48,300 million (see Figure 11).

According to Fischer, Newell & Preonas (2013) the optimal ratio of deployment spending to R&D spending does not exceed one for wind energy. With extreme assumptions on learning-by-doing this ratio goes to 6.5-to-1. 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 optimal policy mix varies across low-carbon technologies, depending on their degree of maturity.

The relative importance of market 'pull' vis-à-vis technology 'push' decreases as technologies mature (Grubb, 2004). However, the public spending ratio in European countries for deployment vs R&D of 150-to-1 (see Figure 11) seems completely disconnected from the most optimistic assumptions on the rate of learning-by-doing which usually serves as the main justification for deployment policies. It appears, then, that European countries have been emphasising technology deployment through feed-in tariffs for renewable energy production, over direct R&D support.

This suggests that **current efforts on deployment should be augmented with additional R&D support, such that the marginal euro spent on low-carbon technologies should go to R&D rather than deployment.** From a political point of view, an additional advantage of direct support to R&D over demand-pull instruments such as feed-in tariffs is that, although feed-in tariffs incentivise innovation activity since the return from, for example a wind farm, depends on electricity production related to the performance of wind turbines, direct support to R&D is by definition targeted at domestic manufacturers while feed-in tariffs may encourage innovation activity mostly in foreign countries, as shown by Dechezleprêtre and Glachant (2014).

Figure 11. Public support to R&D vs deployment in wind and solar energy in the six largest European economies in 2010 (million euros)



Source: Zachman et al., 2014

16 Net deployment costs are calculated as the difference between the deployment costs and the net present value of the future electricity generated, so it does not only include direct support (e.g. loans, tax credits), but it also places a value on support mechanisms such as feed-in tariffs and RPS.

5. Conclusion

It is widely recognised that innovation is essential for the development of new low-carbon technologies and the improvement of existing technologies. As such, it is key to any carbon emissions mitigation scenario.

There is ample empirical evidence that climate change policies induce innovation in low-carbon technologies. The impact on innovation appears both large and rapid. Thus, climate change regulations can help economies break away from a polluting economic trajectory and move to a low-carbon one.

The public goods nature of knowledge implies that socially beneficial research opportunities are ignored by firms because they are unable to fully capture the rewards of such innovations. Consequently, too little innovation is carried out in the economy compared to a socially optimal situation. Hence, **innovation in low-carbon technologies induced by climate change policies can increase welfare.**

However, this depends on whether new research and development (R&D) investments in low-carbon technologies come at the expense of innovation in other technologies. Empirical evidence suggests that some degree of crowding-out does occur. However, low-carbon innovations tend to crowd out high-carbon innovations in the same sector. **A crucial role for climate change policies is to make sure that low-carbon innovation activity comes at the expense of innovation in polluting technologies and not of other socially valuable innovation.** Policies that change the relative price of low-carbon and high-carbon inputs, such as carbon markets or fuel taxes, can play this role effectively.

Another implication is that the welfare impacts of induced low-carbon innovation depend on the relative size of social benefits coming from knowledge spillovers in low-carbon and high-carbon innovation. Recent evidence shows that **low-carbon innovations induce larger economic benefits, in terms of knowledge spillovers, than the high-carbon technologies they replace.** This supports the idea that directed technological change could help offset the costs of climate change regulations or even encourage economic growth.

Moreover, knowledge spillovers from low-carbon technologies are mostly local. Hence, the incentives to adopt climate change policies are much higher when local knowledge spillovers from low-carbon technologies are factored in.

How, then, to encourage the development of new low-carbon technologies? Quantity-based instruments, such as renewable energy mandates, tend to favour innovation in technologies that are closest to the market. **Public support to R&D is thus necessary to support the development of technologies that are further from market but nonetheless have long-term potential.**

Currently, R&D support has been disproportionately low compared to deployment support, especially in Europe. There is a strong argument therefore to increase the size of public R&D support. The IEA estimates that achieving a 50 per cent reduction of energy-related carbon dioxide emissions between by 2050 requires at least a doubling of public R&D spending. As a matter of comparison, in Europe such an increase in public R&D funding over the next decade represents only 10 per cent of the planned revenues from auctioning of allowances on the EU ETS.

Increased investment in low-carbon R&D should be slow and sustained. While it is welcome that countries such as the UK have committed to doubling public funding for low-carbon R&D by 2020 as part of 'Mission Innovation'; **countries should be encouraged to set public R&D targets as far ahead as 2030.** Targets would vary between countries and may need to be set within a range, but such long-term targets would reduce public funding spikes and associated adjustment costs, and ultimately could reduce the overall cost of decarbonisation.

Box 2: Key findings for the European Union

– The European Union Emissions Trading System (EU ETS) has proven effective in stimulating low-carbon innovation and firms' response happened quickly after its introduction. The effect on innovation was particularly strong in the second phase when the price of emissions allowances was about €30 per tonne, while incentives were less visible when the price decreased. Should the planned reform of the EU ETS result in a stronger carbon price, this could have significant benefits in terms of increased innovation.

– Environmental policy can effectively redirect R&D investments from high-carbon technology towards low-carbon technology. Well-designed, credible climate-related policies have the ability to shape a low-carbon future for important economic sectors like the automobile and the energy sector.

– Coordination of European Union research policy is theoretically justified and European institutions should fund R&D. While globally 50 per cent of knowledge spillovers in low-carbon technologies occur within the country of the inventor, this share is much smaller for European countries with small or open economies: 25 per cent for France, 17 per cent for the UK, 10 per cent for the Netherlands. For Europe as a whole, however, (i.e. considering Europe as a single entity) 61 per cent of spillovers occur domestically. As such, there is a strong case for European institutions – such as the European Research Executive Agency, the European Research Council or the Innovation and Networks Executive Agency – to fund R&D, just like public R&D in the US is funded by the federal government rather than by individual states.

– There is scope for increasing investment in several Member States if the European Union is keen to strengthen its competitive advantage on low-carbon innovation. Ranking European Member States by the number of low-carbon inventions per billion US dollars of GDP shows that Germany and the Scandinavian countries are at the forefront of innovation. The UK is approximately midway in the ranking, ahead of countries such as Belgium, Norway, Italy, Spain and Poland, but behind France, the Netherlands and others.

– Growth in public R&D funding is achievable. In Europe, a doubling of public R&D expenditures over 10 years corresponds to what was observed between 2001 and 2011 and thus seems achievable. The amount necessary to fund this growth in public R&D funding in Europe over the next decade represents only **10 per cent of the expected revenues from auctioned emissions allowances** assuming an average carbon price of €11/tonne (Dechezleprêtre and Popp, 2015).

– Additional direct support for R&D is vital to meet emissions reduction targets cost effectively. In the past years European member states have put a strong emphasis on deployment policies, especially through feed-in tariffs for renewable energy. This has resulted in a strong imbalance between deployment and R&D measures across the European Union, with deployment policy outweighing direct R&D support by 150 to 1. While there is no agreement of what the optimal mix between R&D and deployment spending should be, the European ratio appears completely disconnected from the ratio suggested in the literature, which even under extreme assumptions should not go beyond 10 to 1. **This suggests that current efforts on deployment should be augmented with additional direct support to R&D activities such that the marginal Euro spent on clean technologies should go to R&D rather than deployment.**

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