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Fiscal and regulatory instruments for clean technology development in the European Union

Antoine Dechezleprêtre (LSE)[a] & David Popp (Syracuse University and NBER)[b]

Key lessons for policymakers

- European countries currently emphasize technology deployment over direct R&D support. Current efforts on deployment should be augmented with additional R&D support.
- Given that there is no evidence that we have hit diminishing returns to energy R&D funding, we recommend an increase of public R&D funding for low carbon technologies. The IEA estimates that public R&D spending needs to at least double to achieve significant carbon emissions reductions.
- Increased funding should be gradual and consistent to avoid adjustment costs. A doubling of public R&D expenditures over 10 years corresponds to what was observed between 2001 and 2011 and thus seems achievable.
- To signal long-term commitments to energy R&D funding, we recommend directing 10% of the planned EU-ETS auctioned allowances revenues until 2025 to R&D funding. This would lead to the doubling of EU public R&D expenditures in 10 years suggested above.
- Public R&D efforts should focus on technologies central to any decarbonisation pathway and have a strong public good component, such as CCS, energy storage, smart grids, energy efficiency and infrastructure for electric vehicles.
- Because emissions standards and permits markets favour innovation in technologies that are closest to the market, public R&D efforts should in contrast support the development of technologies further from market that nonetheless have long term potential.

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Introduction

On 23 October 2014 European Union leaders adopted a commitment to reduce domestic greenhouse gas (GHG) emissions by 40% in 2030 relative to 1990. In 2012, GHG emissions were 19% lower than in 1990 at 4.5 Gt CO2eq. The additional reduction thus represents a significant challenge. In order to achieve this objective while meeting growing energy demand, significant changes in the mix of what existing technologies are used across Europe are needed. For this to happen at a reasonable cost for the economy requires decreasing the cost of clean technologies and developing new breakthrough technologies. This in turn depends upon investment in innovation activities. According to the last IPCC report, future investments in research, development and demonstration (RD&D) will be the determining factor for the cost of emissions reductions policies. For example, the unavailability of carbon capture and storage technologies would substantially increase the cost of any climate change policy[1]. The influence of technology on costs moreover increases with the ambition of the climate change mitigation goal (IPCC, 2014). 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 clean technologies. The cost of existing environment-friendly technologies, such as wind turbines and SO_2 scrubbers, needs to be brought down so that they can be deployed on a large scale, while fundamental research needs to advance on the frontiers of technologies such as smart grids or energy storage.

Yet, despite these pressing challenges, European companies in the electricity production sector – the largest GHG emissions emitter in Europe, with 33% of European emissions in 2012 – spend less than 1% of their turnover on innovation, against 10-15% in IT or pharmaceuticals (see Figure 1), suggesting that the incentives to conduct RD&D of new or enhanced low carbon technologies and their associated systems and processes might not be in place. This low intensity of R&D in the electricity production sector has been associated with high development costs, long development timescales, the homogeneity of the good produced and regulatory uncertainty. Importantly, the public sector does not

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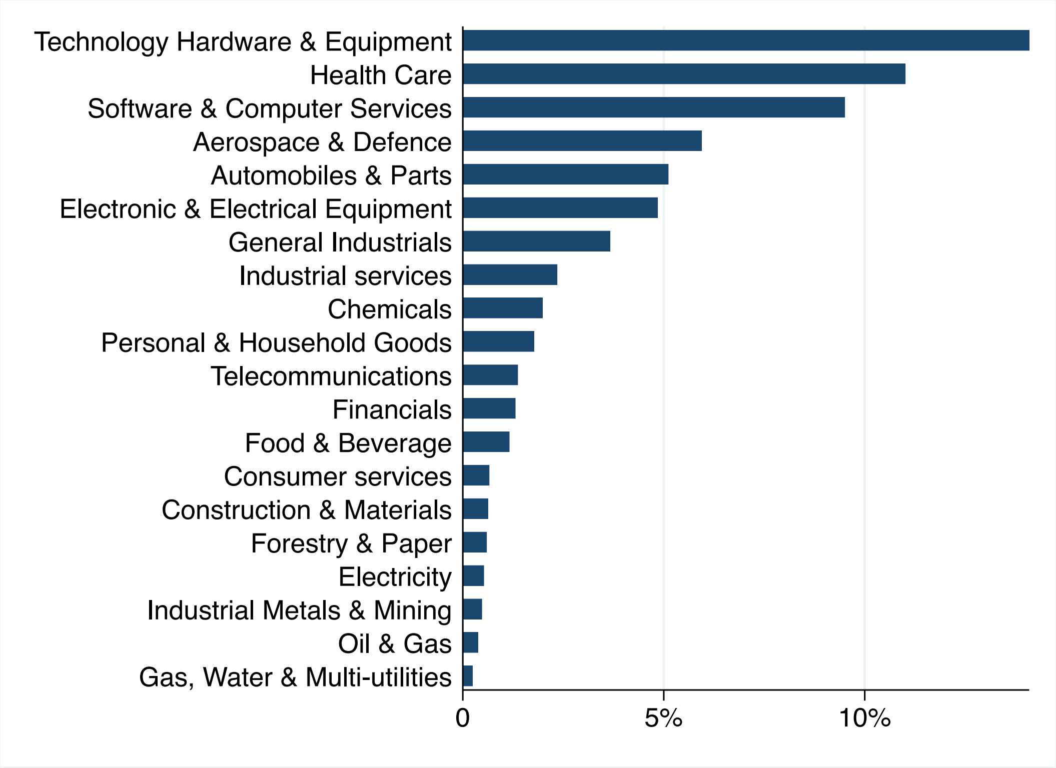
[1] Unavailability of CCS would increase the cost of a 450ppm CO2-eq policy by a factor of 1.5 to 3.5 and of a 550ppm CO2-eq policy by 20% to 70% (see Kriegler et al., 2014).

seem to make up for the lack of private investment: public R&D expenditures in the energy sector in Europe represent less than 0.1% of GDP in almost all European countries and account for less that 5% of total public R&D expenditures on average.

Figure 1 - R&D expenditure by top 1000 European companies in different sectors as % of sales, 2012



Source: EU Joint Research Centre on Industrial Investment and Innovation, R&D Scoreboard 2013

The objective of this policy note is to investigate whether the current level of public support to environment-friendly technologies is sufficient to allow European countries to respond to the multiple challenges posed by climate change and other environmental concerns and to discuss the policy interventions that might be needed in order to drive forward clean energy technology investments in Europe. We first lay out the justifications for government support to clean R&D activity at the various stages of technology development, discussing particular features of clean technologies that justify policy intervention. We present empirical evidence for the impact of various policies on the development of clean technologies and use this to identify what the appropriate policy mix should look like. We present an overview of policies currently in place to support the development of clean technologies across Europe and compare the current policy landscape to the appropriate policy portfolio. This comparison allows us to provide some practical steps for reform.

Our analysis shows that the current low price of carbon in Europe is a major barrier to clean technology development. The new commitments for 2030 as well as the planned Market Stability Reserve are steps in the right direction, but are unlikely to affect prices much in the next decade. Moreover, market-based policies such as the EU ETS favour technologies that are close to the market. The combination of low prices, political constraints on future emissions prices and well-known innovation market failures justify strong policies directly targeted at clean technology development. Thus we recommend a gradual increase of public R&D funding for low carbon technologies. The IEA has estimated that public R&D spending in OECD countries need to at least double to achieve significant carbon emissions reductions. If possible, commitments to fund R&D should have a long-term commitment (until at least 2030) just like carbon emission caps. Policy stability is important for companies, universities and other research stakeholders to make long-term predictions on innovation needs. Revenues from auctioned carbon permits could provide a source of sustained funding for low carbon R&D with the necessary long-term commitment. In fact, directing 10% of the planned auctioned allowances revenues until 2025 to R&D funding would lead to the doubling of EU public R&D expenditures suggested above in 10 years. With 30% of global innovation activity towards low-carbon technologies currently occurring in European countries[2], the EU cannot just rely on other countries such as Japan or the US to innovate and then transfer the technologies. Moreover, European countries have so far been clearly emphasizing technology deployment over direct R&D support. Yet, even as the costs of renewables begin to fall, technical barriers to deployment remain, suggesting that a greater emphasis on R&D is needed. In this respect, EU institutions and governments should focus their efforts on technologies that are central to any decarbonisation pathway and have a strong public good component: CCS, energy storage, smart grids, energy efficiency and infrastructure for electric vehicles. Since the incentives to subsidize R&D are much higher for Europe as a whole than for individual European countries, we call for a stronger involvement of European institutions in public R&D in

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[2] See OECD online Patent Statistics, "Patents in environment-related technologies" section, at https://stats.oecd.org/

clean technologies. Finally, our analysis suggests that in a context of high general public spending, regulatory instruments, such as technological standards, may become increasingly attractive, provided they are tied to direct R&D support for technologies that have longer term potential.

I. The case for government intervention to support clean technology development

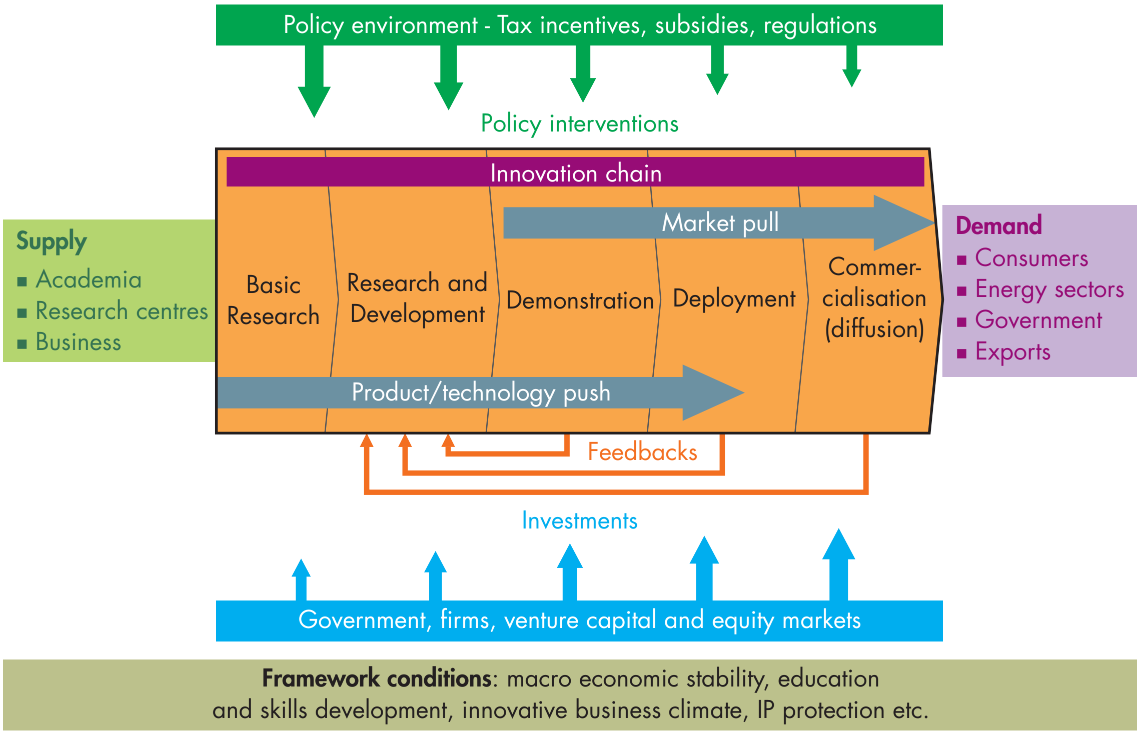
In this section we explain why economic theory justifies public support to technology development, and particularly so regarding technologies with an environmental benefit. For climate change, examples of such technologies include alternative energy sources, capturing methane gas from landfills, and carbon capture and sequestration. Technological development is understood as encompassing not only upstream R&D activity but also technology deployment all the way to large scale commercial diffusion. To consider the incentives (or lack thereof) that firms have to develop and deploy environmental technologies, it is useful to first consider the incentives faced for the development and deployment of new technologies in general.

A. The main stages in technology development

Technological change is a complex process, encompassing both the creation of new ideas (e.g. invention and innovation) as well of the diffusion and adoption of new technologies throughout the economy. Throughout this process, feedbacks between the various stages of technological change exist (see Figure 2). For example, experience acquired during the commercialization process usually influences subsequent product innovation. Yet, at each stage, incentives, in the form of prices or regulations, affect the development and adoption of new technologies. These multiple feedbacks in the innovation chain imply that if the right incentives are not in place at a given stage (in particular through public policies, as we will see below), this will have an effect on all stages.

Importantly, successful innovation requires an ecosystem, made of the private sector (entrepreneurs, technology firms, capital), academia (research universities, technical training schools) and multiple government institutions (to ensure regulation, policy and public funding). While not all European countries may individually possess a fully-functioning innovation ecosystem, the European Union as a whole does possess all the ingredients necessary to carry out successful technological change, although some of the stages of technology development may be less relevant for some countries than for others. For example, it might be relevant for small or lower income countries to focus on the diffusion stages of technological development and leave earlier stages to more advanced economies.

Figure 2 – The main stages of technological development



Source: IEA (2008), adopted and modified from Grubb (2004).

B. The rationale for government intervention to support innovation in clean technologies

At all three stages of technological development, market forces provide insufficient incentives for investment in either the development or diffusion of environmentally-friendly technologies. Economists point to two principal market failures as the explanations for underinvestment in environmental R&D. These market failures provide the motivation for government policy designed to increase such research.

A first market failure, which compounds innovation activity at all stages of clean technological change, is the traditional problem of environmental externalities. When pollution can be emitted freely, firms and consumers lack incentives to invest in the use of emissions - reducing and other environmentally friendly technologies. Thus, without appropriate policy interventions, the market for technologies that reduce emissions will be limited, reducing incentives to diffuse such technologies and hence to develop them in the first place. This underinvestment extends to technologies with both private and public benefits, such as energy efficient technologies that reduce a firm's costs as well as reducing the resulting emissions from energy consumption, The market failure problem simply means that individuals do not consider the social benefits of using technologies that reduce emissions, so that firms underinvest in energy efficient technologies. It is important to note that innovation activities are driven primarily by expectations about future environmental regulations and the uncertainty surrounding future policies represents a clear barrier to technology development.

The second market failure[3] pertaining to clean technology development is the public goods nature of knowledge (see, for example, Geroski 1995), which impedes technological change at the R&D stage. 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, or even to copies of the current innovations.[4] These knowledge *spillovers* provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of research activity. Economists studying the returns to research consistently find that knowledge spillovers result in a wedge between private and social rates return to R&D[5]. Typical results

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[3] This section draws heavily on Jaffe (2012).

[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] Examples of such studies include Mansfield (1977, 1996), Pakes (1985), Jaffe (1986), Griliches (1992), Hall (1996), and Jones and Williams (1998). These studies typically construct a pool of "external" R&D available to a firm by weighting other firms' R&D by geographical or technological distance, and identify the effect of this external knowledge pool of firms' productivity.

include marginal social rates of return between 30 and 50 percent. In comparison, estimates of private marginal rates of return on investments range from 7 to 15 percent (Hall et al., 2010). Since firms make investment decisions based on their private returns, the wedge between private and social rates of return suggests socially beneficial research opportunities are being ignored by firms because they are unable to fully capture the rewards of such innovations.[6] Recent evidence further shows that knowledge spillovers are particularly high for clean technologies, suggesting that the wedge between private and social rates of return in environmental technologies might be particularly high.

Box 1 – Knowledge spillovers from clean technologies

Dechezleprêtre et al. (2013) investigates the magnitude of knowledge spillovers from clean technologies in the electricity production and the transportation sectors and has found evidence that clean patents generate larger knowledge spillovers than the dirty technologies they replace. The magnitude of knowledge spillovers in clean technologies is comparable to that found in other emerging technological fields such as IT or nanotechnology. This means that underinvestment in innovation due to knowledge externalities might be particularly high for clean technologies (see Figure 3). Moreover, while knowledge spillovers often have a strong local component, Dechezleprêtre et al. (2013) show that spillovers are highly prevalent across European Union countries. While globally 50% of knowledge spillovers in clean technologies occur within the country of the inventor, this share is much smaller for many small open European countries: 25% for France, 17% for the UK, 10% for the Netherlands. For Europe as a whole, however, (ie considering Europe as a single entity) 61% of spillovers occur domestically. As such, coordination of European Union research policy is theoretically justified and 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

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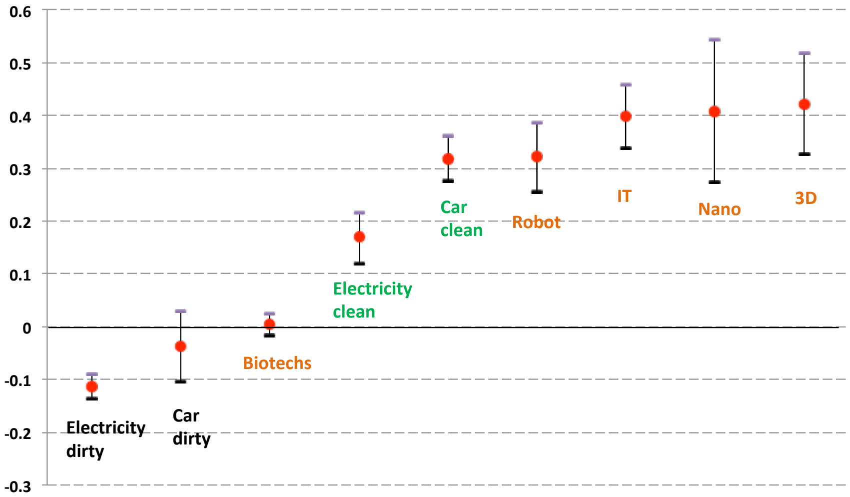
[6] A central problem in the spillovers literature is that firm performance is affected by two countervailing "spillovers": a positive effect from knowledge spillovers and a negative business stealing effects from product market rivals. Bloom et al. (2013) incorporate these two types of spillovers and 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.

the federal government rather than by individual states.

Figure 3: Knowledge spillovers from clean, dirty and other emerging fields



Note: the y-axis measures the difference in the intensity of knowledge spillovers, as measured by patent citations, between various technologies and the average innovation patented in the economy. For example clean electricity technologies induce about 20% spillovers than the average innovation.

A related market failure associated with technological change is learning-by-doing. It has been empirically demonstrated that production costs tend to decrease as the volume of production increases (Arrow, 1962). Learning curve studies typically find faster learning for younger technologies, with estimates of learning rate revolving around 15-20% (so that production costs decrease by 15-20% for a doubling of production) for alternative energy sources such as wind and solar energy (McDonald and Schrattenholzer, 2001). Hence, the early producers of a technology generate knowledge *through the production process* (and not through R&D activity). The extent to which this is a market failure depends on whether the benefits of learning spill over to other producers. For example, Nemet (2012) finds evidence of learning spillovers in California wind farms. This learning effect provides an incentive for producers to wait until the production costs have decreased. Similarly, there is evidence that product improvements often happen through producer-user relationships. This uncertainty over the benefits of a new technology, which resolves itself only through supply chain exchanges, creates an incentive for companies to wait until the technology has been developed by someone else (a ‘second mover advantage’) even in the absence of knowledge spillovers.

The combination of the environmental market failure and the knowledge market failure creates the famous ‘double externality problem’ whereby investment in clean R&D is doubly underprovided by the market, making policies to support clean technology development all the more necessary. However, the literature has identified many other market failures and barriers that mean that left to its own devices, the private sector will tend to underinvest in clean technologies at pre-commercial stages of development. In particular, even if problems associated with incomplete appropriability of the returns to R&D are solved, it may still be difficult or costly to finance such investments using capital from sources external to the firm. Information about the potential of a new technology is held by the innovator, creating a fundamental asymmetry of information that pushes investors to favour projects with least uncertain and short-term benefits (Hall and Lerner, 2010). These imperfections in the market for capital decrease the incentives for financing technological development. Similarly, lock-in and path dependency of previous investments due to long-lived capital (like power plants), market power, network effects and dominant designs impede technology development. These additional market failures help explaining what has become known as the “technology valley of death” (see Grubb (2013) for a extensive presentation of the issue).

Of course, there is a wide variety of clean technologies and different sets of market failures apply to different technologies. For example, knowledge market failures are highest in technologies that are newer, like solar PV, and have wide applications across the board, like energy storage, while they are much smaller in magnitude in mature technologies such as hydro power (Dechezleprêtre et al., 2013). Hence, the case for policy support is stronger for the former types of technologies than for the latter.

II. Policies to support clean technology development

The combination of environmental externalities and knowledge market failures suggests two possible avenues through which policy can encourage the development of environment-friendly technologies: correcting the environmental externality and/or correcting knowledge market failures. Because knowledge market failures apply generally across technologies, policies addressing knowledge market failures may be general, addressing the problem in the economy as a whole. Examples include patent protection, R&D tax credits, and funding for generic basic research. Such policies focus on the overall rate of innovation – how much innovative activity takes place. In contrast, policies aimed specifically at the environment focus on the direction of innovation. Although the latter group of policies includes policies regulating externalities, such as a carbon tax or cap-and-trade system, it also includes environmental and energy policies using more general R&D policy mechanisms with a specific focus on the environment, such as targeted government subsidies for the adoption of alternative energy and targeted funding for basic and applied research. As we'll discuss below, such policies may be justified by differences in the returns to different types of R&D, or by evidence of behavioural anomalies that limit the diffusion of energy technologies.

A. Addressing the environmental externality

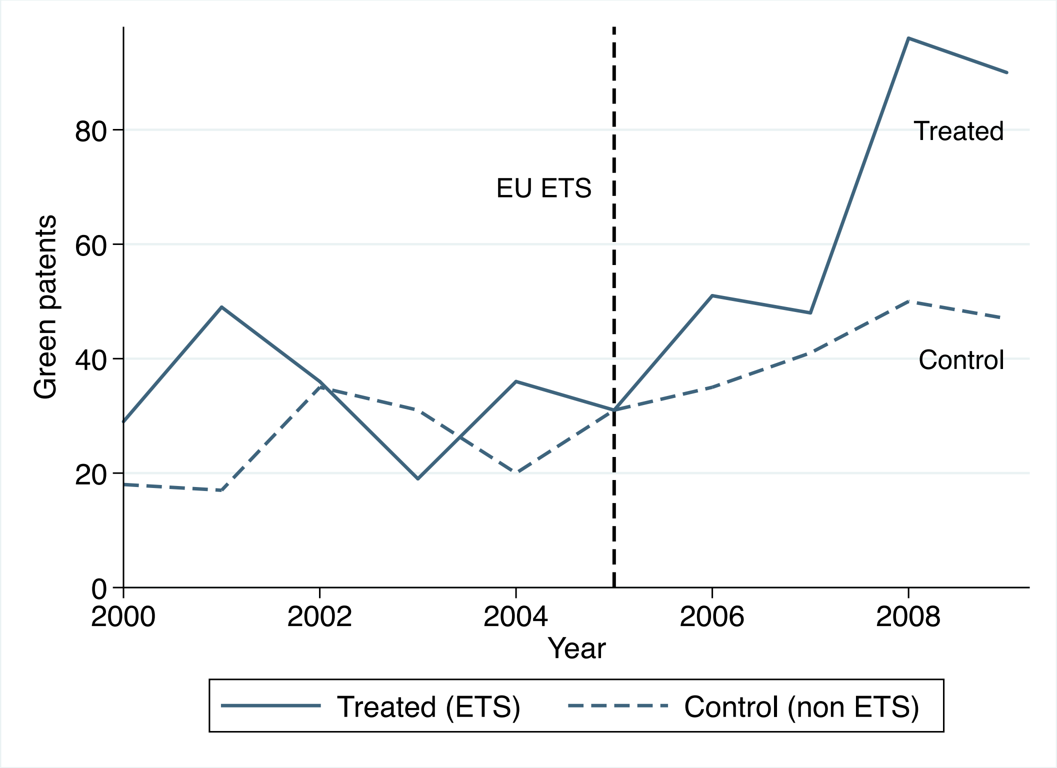
The effects of environmental policy on environmental innovation

The existence of environmental externalities requires public policies that force economic agents to "internalize" the benefits of protecting the environment. Environmental policy tools are usually grouped in two categories: market instruments, which establish a price on the externality (for example, a tax on carbon emissions or a cap-and-trade system), and command-and-control instruments, which impose limits on emissions of pollutants or require adoption of particular technical standards. By making polluting emissions costly, both types of environmental policies change the relative costs and benefits of competing technologies. For example, carbon taxes make coal relatively more expensive than natural gas. Renewable energy portfolio standards make alternative energy sources more attractive relative to carbon-based energy. Thus, policies that force agents to internalize environmental externalities encourage the *diffusion* of environmentally-friendly technologies. In fact, studies addressing adoption of environmental technologies find that regulations dominate all other firm-specific factors in explaining the gradual diffusion of new technologies. Examples include Kerr and Newell (2003) on the removal of lead from gasoline in the United States, 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 NO_X pollution control technologies at power-plants.

Environmental regulation also encourages innovation. Because R&D is a profit-motivated investment activity, innovation responds to the change in the expected diffusion of technologies induced by environmental regulations by developing cleaner technologies. This notion of induced innovation (Acemoglu, 2002; Acemoglu et al., 2012; Hicks, 1932) provides the theoretical background for the vast empirical literature on the effect of policy and prices on environmental innovation. This literature – recently surveyed in Popp et al. (2010), Popp (2010), and Ambec et al. (2013) – supports the conjectures of the induced innovation hypothesis and provides evidence on the magnitude of the effects. These studies, highlighted in Box 2, show that both stricter environmental policies and higher energy prices encourage additional innovation on clean technologies, and that the innovative response to policy happens quickly. For example, much of the innovative response to higher energy prices occurs within five years or less. When looking at the innovative response to environmental regulation, rather than energy prices, the response time is even faster. Popp (2006a) finds an almost immediate innovative response to the passage of clean air regulations in the US, Japan, and Germany. Similarly, Figure 4, taken from Calel and Dechezleprêtre (2014), shows how the EU ETS has increased innovation activity in low-carbon technologies among regulated companies. The figure plots the patenting activity of firms regulated under the EU ETS with that of a control group of unregulated but similar firms selected through matching techniques. The control group represents what would have happened, had the EU ETS not been implemented. Regulated and unregulated companies exhibit roughly comparable innovation activity before the introduction of the EU ETS, but they start diverging quickly after the new policy is put in place.

Figure 4 – Low carbon innovation activity of EU ETS regulated companies compared with counterfactual scenario



Source: Calel & Dechezleprêtre, 2014

To sum up, there is ample empirical evidence that environmental regulations, by encouraging the diffusion of environmentally-friendly technologies, affect innovation activity further up the technology supply chain, favouring R&D in clean technologies and discouraging it in conventional (polluting) technologies. The impact on innovation appears both large and rapid. Thus, environmental regulations can help economies break away from a polluting economic trajectory and move to a 'cleaner' one.

Box 2 – Induced innovation from environmental policy

Early studies of induced innovation from environmental policy made use of pollution abatement control expenditures (PACE) to proxy for environmental regulatory stringency. Examples include Lanjouw and Mody (1996), Jaffe and Palmer (1997), and Brunnermeier and Cohen (2003). Each finds a significant correlation within industries over time between PACE and innovative activity. Renewable energy policies, which require the adoption of renewable energy technologies to generate electricity, have also been shown to incentivize innovation. 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 (2013) show that every 100 MW of new wind power capacity installed in OECD countries induces 3 new patented innovations globally.

Other studies examine the effect of changing energy prices on innovation, providing evidence on how innovation will react to higher energy prices resulting from regulation. Newell *et al*. (1999) show that the energy efficiency of home appliances available for sale changed in response to energy prices between 1958 and 1993. Suggesting the role that policy-induced technological change may play as climate policy moves forward, they find that energy efficiency in 1993 would have been about one-quarter to one-half lower in air conditioners and gas water heaters if energy prices had stayed at their 1973 levels, rather than following their historical path. Both Popp (2002) and Verdolini and Galeotti (2011) find similar estimates of the elasticity of energy patenting activity with respect to energy prices for alternative energy and energy efficiency technologies, with a 10% increase in energy prices raises energy patenting in the long-run by 3.5-4%. Aghion et al. (2012) examine innovation activity by around 3,000 firms in the car industry and show that firms tend to innovate more in clean technologies (ie, electric, hybrid and hydrogen cars) and less in dirty technologies (ie internal combustion engines) when they face higher fuel prices. A 10% higher fuel price is associated with about 10% more clean patents and 7% less dirty patents.

What instruments work best?

Studies on induced innovation provide some insight as to the pace of environmental innovation. Also important, however, is the nature of policies used to stimulate innovation. Policymakers have a range of policy instruments available to regulate environmental quality. Command-and-control regulations direct a specific level of performance. For instance, performance standard sets a uniform control target for firms (such as pounds of sulfur dioxide emissions per million BTUs of fuel burned), 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 U.S. SO_2 market or the European Union's Emission Trading System for carbon.

Historically, economists have argued that market-based policies provide greater incentives for innovation. Market-based policies provide rewards for continuous improvement in environmental quality, whereas command-and-control policies penalize polluters who do not meet the standard, but do not reward those who do better than mandated (Magat, 1978; Milliman and Prince, 1989). However, more recent research suggest that the effects are more nuanced. For example, standards can be of use when behavioural anomalies result lead consumers paying little attention to the benefits of energy efficiency, as illustrated in box 3. Similarly, in a recent review, Vollebergh and van der Werf (2014) show that although standards are often viewed by economists as rigid and cost-inefficient command-and-control policy instruments, 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. However, these policy signals must be clear, or unintended consequences may result. See box 4 for an example.

Box 3 – The energy efficiency paradox

A priori, energy efficiency and fuel-saving technologies should diffuse even without the aid of policy, as they do provide cost-saving benefits to the user. However, to the extent that fuel prices do not capture the external costs of energy use, such as carbon emissions, energy prices alone will not encourage a socially optimal level of adoption for energy efficiency technologies.

However, an important puzzle in the literature on energy technology diffusion is the notion that seemingly cost-effective energy-efficient technologies diffuse slowly, suggesting what has become to be known as an “energy efficiency paradox.” To the extent that diffusion is limited by other market failures, policy measures that simply increase the economic incentive to adopt environmentally-friendly technologies will be insufficient. In addition, policies focused directly on the correction of adoption market failures can be justified.

Several researchers have examined this energy efficiency 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 in landlord/tenant relationships (Levinson and Niemann, 2004), and uncertainty over future costs (Anderson and Newell, 2004).

In addition to market failures, more recent research addresses potential behavioural anomalies that may affect diffusion of energy efficient technology. This research combines psychology and economics, and notes cases where observed behaviour differs from what traditional economic models predict. Gillingham and Palmer (2014) provide a review of studies on behavioural economics and energy efficiency and provide several examples of how behavioural economics can inform policy. For example, how choices are framed influences consumer decisions, suggesting that proper labelling of energy efficient technologies matters. Inattention to future costs may cause consumers to undervalue energy efficiency (Allcott et al., 2014). However, Houde (2014) finds that while Energy Star labelling has positive net benefits, it also crowds out other energy-saving activity. Attention to social norms, such as providing information on the energy consumption of neighbours, can increase energy conservation (e.g. Allcott, 2011; Schultz et al., 2008). Similarly, Sallee (2014) argues that, given the time necessary to learn about the value of energy efficiency, in many cases it is rational for consumers to devote little attention to it. Such behavioural anomalies provide support for policies such as product labelling or minimum performance standards that reduce the burdens on consumers to seek out energy efficient product.

Box 4 – Policy signals and innovation on SO_2 scrubbers

Examples from the U.S. market for sulphur dioxide (SO_2) permits show the importance of clear policy signals to direct innovation. Popp (2003) compares innovation on SO_2 controls before and after the 1990 Clean Air Act (CAA) instituted permit trading. Before this Act, new plants were required to install a flue gas desulfurization (FGD) unit capable of removing 90 percent of SO_2. As a result, the innovations that occurred before the 1990 CAA focused on reducing the cost of FGD units, rather than on improving their environmental performance. After passage of the 1990 CAA, the nature of innovation changed, with a greater focus on improving the ability of FGD units to remove SO_2 from a plant's emissions. Similarly, Taylor *et al*. (2003) note that the scrubber requirement led to a reduction in patents on pre-combustion techniques for reducing SO_2 emissions, such as cleaner coal.

Moreover, even among market-based policies, differences between policies matter. Johnstone *et al*. (2010) compare price-based policies to promote renewable energy, such as tax credits and feed-in tariffs[7], to quantity-based policies such as renewable energy mandates. Quantity-based policies, such as renewable energy certificates, favor development of wind energy, as wind has the lowest cost and is closest to being competitive with traditional energy sources. As such, when faced with a mandate to provide alternative energy, firms focus their innovative efforts on the technology that is closest to market. In contrast, direct investment incentives are effective in supporting innovation in solar and waste-to-energy technologies, which are further from being competitive with traditional energy technologies.

These results suggest particular challenges to policy makers who wish to encourage long-run innovation for technologies that have yet to near market competitiveness. Economists generally recommend using broad-based environmental policies, such as emission fees, and letting the market "pick winners." This leads to lower compliance costs in the short-run, as firms choose the most effective short-term strategy. However, this research suggests complications for the long-run. Because firms will focus on those technologies closest to market, market-based policy incentives do not provide as much incentive for research on longer-term needs. This suggests a trade-off: directed policies such as investment tax credits or technology mandates more effectively encourage the deployment of more expensive emerging technologies that are not yet cost-effective. However, this raises the costs of compliance, as firms are forced to use technologies that are not cost-effective. One possible solution here is to use broad, market-based policies to ensure short-run compliance at low costs, and use support for the research and development process to support research on emerging technologies. Thus, the focus is

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

on continued improvement for emerging technologies, rather than on deployment of them.

Finally, the perceived stability of the policy is also important. Long-term regulatory consistency is crucial for new technology development (Held et al., 2009). In the presence of regulatory uncertainty market-based instruments may do a poor job at incentivizing R&D, and regulatory instruments may work better. For example, Butler and Neuhoff (2008) show how German feed-in tariffs stimulated overall investment quantity more than UK renewable energy quotas because FIT reduced risks associated with future revenues from the project investment, therefore making it possible to lower the cost of project financing. Similarly, the prices established by market-based policies must be sufficient to encourage innovation. Calel and Dechezleprêtre (2014) show that the effect of the EU ETS on innovation activity was concentrated at the beginning of the System's second phase, which saw a significant increase in the price of carbon on the market at about €30/tonne CO_2. This suggests that the current level of carbon prices in the EU ETS might not be providing strong incentives for technology development.

The cross-border effects of environmental policies

The European Union is composed of 28 countries, most of which are small and highly connected to their neighbours through trade relationships. Therefore, the impact of environmental policies across borders is of key importance for these countries. Two recent empirical papers look at this issue. Dechezleprêtre and Glachant (2014) study the effect of both domestic and foreign policies for the promotion of wind innovation. While both promote innovation activity, they find the marginal effect of policies implemented at home to be 12 times higher. However, since the foreign market is much larger than the domestic market across the sampled countries, the overall impact of foreign policies is on average *twice as large* as the overall impact of domestic policies on innovation. In other words, wind power policies induce twice as much innovation abroad than domestically .[8] Similarly, Peters *et al.* (2012) find that both domestic and foreign demand-pull policies are important for the development of solar PV technology. However, the overall impact of foreign countries is smaller than in the case of wind

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[8] These results are valid on average across OECD countries but presumably differ with the size of the domestic economy.

power, perhaps because barriers to international technology diffusion are larger in solar power.

These results provide a strong case for designing environmental policies jointly at the European level rather than at the Member State level. Indeed, the cross-country innovation spillovers might be viewed negatively from a narrow national perspective but are strongly positive from a global (or European) perspective.

These results also constitute an incentive for Europe to push for strengthening of environmental regulation globally as this will encourage innovation in Europe by increasing the demand for clean technologies globally.

B. Addressing the innovation market failures

The existence of knowledge market failures provides a rationale for public support to innovation. Note that there is no reason a priori to implement R&D policies targeted specifically at clean technologies. Positive externalities in knowledge production may be addressed by generic instruments, such as intellectual property rights protection and tax rebates for research and development activities that apply to all industries equally (Schneider and Goulder, 1997). Yet, in theory, public R&D expenditures and subsidies to private R&D activities should reflect the size of the external spillovers from the research (Goulder and Schneider, 1999). Consequently, the optimal level of subsidies for clean R&D crucially depends on the magnitude of knowledge spillovers from clean technologies. The recent results from Dechezleprêtre et al. (2013) who show that spillovers from clean technologies are particularly large suggest that specific support for clean innovation that goes beyond standard policies in place to internalize knowledge externalities is justified. As illustrated above, optimal subsidies for clean technologies are at least 20% to 30% higher than for the average innovation.

Public R&D

Even when environmental regulations that encourage eco-innovation are in place, private firms will focus research efforts on technologies that are closest to market. One of the particular problems faced with many climate-friendly innovations is the long-time frame from the initial invention to successful market deployment. Consider, for instance, the case of solar energy. Despite research efforts that began during the energy crises of the 1970s, solar is still only cost competitive in niche markets, such as remote off-grid locations. This leaves a role for government-sponsored R&D to fill in the gaps, particularly in the case of climate change, where a diversified energy portfolio will be necessary to meet currently proposed emission reduction targets.

Government investment in R&D plays several roles. First, government R&D can help to compensate for underinvestment by private firms. Unlike firms, the government is in position to consider social returns when making investment decisions. In addition, government R&D tends to have different objectives than private R&D. Government support is particularly important for basic R&D, as long-term payoffs, greater uncertainty, and the lack of a finished product at the end all make it difficult for private firms to appropriate the returns of basic R&D. Thus, the nature of government R&D is important. For example, Popp (2002) finds that government energy R&D served as a substitute for private energy R&D during the 1970s, but as a complement to private energy R&D afterwards. One explanation given for the change in impact is the changing nature of energy R&D. During the 1970s, much government R&D funding went to applied projects such as the effort to produce synfuels. Beginning with the Reagan administration, government R&D shifted towards a focus on more basic applications. To avoid duplicating, and potentially crowding-out, private research efforts, government R&D support should focus on basic research or on applied research whose benefits are difficult to capture through market activity. For instance, improved electricity transmission systems benefit all technologies, and will typically not reap great rewards for the innovator. Applied technologies whose costs are still high, such as solar photovoltaics, will also see less private investment, as firms focus on projects with greater short-term payoffs. In cases such as these, public R&D efforts will be important. The uncertain nature of long-term research also makes government R&D valuable. In a situation where failure is more likely than success, but the successes will have great social value, government can bear the costs of a diversified R&D portfolio more easily than any one private firm. Consider, for example, the U.S. National Research Council's review of energy efficiency and fossil energy research at DOE over the last two decades (National Research Council, 2001). Using both estimates of overall return and case studies, they concluded that there were only a handful of programs that proved highly valuable. Their estimates of returns suggest, however, that the benefits of these successes justified the overall portfolio investment. These uncertain returns also suggest that government research portfolios should be diversified, rather than trying to pick winning technologies at early stages of development.

IP systems

As stated in the previous section, competitive markets under-incentivize innovation because of the public-good nature of ideas (Arrow, 1962; Nelson, 1959). Intellectual property (IP) rights, such as patents and copyrights, aim to incentivize innovation by allowing firms to capture a higher share of the returns to their research investments. Successful patent applicants are provided a temporary monopoly, lasting twenty years from the initial application date in the main patent offices (US, Europe, Japan…), in return for disclosing information on the innovation in the patent document, which is part of the public record. By granting this market power, IPR helps to mitigate potential losses from knowledge spillovers and encourage innovation. It is also supposed to help other inventors since innovation activity is cumulative in nature. Evidence shows that patents are effective in encouraging innovation in countries with high economic development, which would generally include all European economies, but that sectors that develop environmental technologies are not critically dependent on patent protection (see Box 5).

Box 5 - Intellectual property rights, innovation and technology diffusion

Whether patents are effective in encouraging innovation is the subject of a vast literature. Economic theory does not provide a clear prediction in this respect, and empirical studies provide mixed findings. For example Moser (2005) constructs a dataset of 15,000 innovations from a number of European countries that were displayed at two international fairs during the 19th century, and finds that the level of innovative activity in these countries was unaffected by the presence of a patent system. Park and Ginarte (1997) use data on 60 countries from 1960-1990 and an index of the strength of IP rights and find that the strength of IP rights is positively associated with R&D investment, but only in countries with above-median income (among which all European countries can be found) and not for the less-developed countries. Qian (2007) also finds that patent protection stimulates domestic innovation only in countries with higher levels of economic development, educational attainment, and economic freedom. Additionally, there appears to be an optimal level of intellectual property rights regulation above which further enhancement reduces innovative activities.

Note that the above studies focus on the effects of patents on innovation throughout the entire economy. An important finding from the empirical literature is that some sectors are more likely than others to react to patents by increasing innovation, because some products are more prone to imitation and more easily codified in a patent document. These include the pharmaceutical, biotechnology, medical instrument and chemical sectors. In other sectors, patents are not perceived as an important means to protect innovation (Cohen et al., 2000). This has implications for environmental technologies, which for the vast majority do not belong to the sectors most dependent on patent protection.

Nonetheless, patents may be useful to address the imperfection in capital markets stemming from the asymmetry of information about the technology between the inventor and potential funders. Patents may be useful signals to investors that a startup firm has valuable assets even in the absence of a current profit stream. For example, Haeussler et al. (2009) find that European patent applications (but not grants) serve as an important signal to VC investors in German and British biotechnology firms. Similarly, Dechezleprêtre (2013) finds that programmes to fast-track green patent applications have been particularly successful among start-up companies currently raising capital, for which a granted patent represent a valuable asset.

The impact of patenting on the diffusion of climate change related technologies has recently become a subject of significant debate. It is certainly true that, *conditional on an innovation having taken place*, one would expect technology diffusion to be slower when IPR is in place, because monopoly power implies that the price of clean technologies will be higher. The role of demand for clean technologies cannot be overstated, however, and is consistent with results found elsewhere. In an oft-cited study on the role of intellectual property on pharmaceuticals, Attaran and Gillespie-White (2001) ask whether patents constrain access to AIDS treatments in Africa. They find that, even in African countries where patent protection is possible, few AIDS drugs are patented as the markets for such drugs are too small to be of interest to multinational pharmaceutical companies. Rather than patents, they conclude that a lack of income, national regulatory requirements, and insufficient international aid are the main barriers to the spread of AIDS treatments in Africa. Similarly, with green technologies, one would expect demand (or the lack thereof) for clean technologies to be a primary constraint on international technology diffusion. The strengthening of environmental regulation across Europe is an important pre-condition to the diffusion of eco-innovations. Calls to weaken IPR for eco-innovations would likely have little impact on their diffusion.

Support to private R&D

Another way for governments to help firms internalize the knowledge externalities associated with innovation is to directly subsidize firms for their innovation activities, through technology prizes, research grants (such as the public R&D funding discussed earlier) or R&D tax credits. In theory, subsidies to private R&D activities should reflect the size of the external spillovers from the research (Goulder and Schneider, 1999). Evidence on the effectiveness of R&D tax credits is mixed. Bloom et al. (2002) find evidence that tax incentives are effective in increasing R&D intensity. They estimate that a 10% fall in the cost of R&D stimulates a 1% rise in the level of R&D in the short-run, and a 10% rise in R&D in the long-run. More recently, Duguet (2010) and Czarnitzki et al. (2011) also find evidence that R&D tax credits lead to additional innovation output. Lokshin and Mohnen (2012) find that small firms (below 200 employees) have a larger cost elasticity of R&D than larger firms. One caveat is that the studies mentioned all study R&D subsidies or tax credits more generally, rather than R&D tax credits designed to promote renewables. Compared to direct public funding of R&D, firms applying for R&D tax credits retain control over the type of R&D projects they pursue. Thus, while tax credits may make marginal projects profitable, firms will still focus on projects with the greatest short-run returns (David et al., 2000). As such, tax credits may not be the best policy tool to promote new technologies that are not close to the market.

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

C. The problem of crowding-out non-clean innovation

An important question for the macroeconomic impact of policies supporting clean technologies is whether policy-induced innovation activities in clean technologies come at the expense of innovation in other technologies. This question of crowding out is raised in two recent simulations of climate policy. Using the ENTICE model, Popp (2004) begins with a base case that assumes one-half of new energy R&D crowds out other R&D. In this case, induced innovation increases welfare by 9%. Assuming no crowding out increases the welfare gains from induced innovation to as much as 45%, while assuming full crowding of R&D reduces welfare gains to as little as 2%. Gerlagh (2008) extends this work by separately modeling the choice of carbon-energy producing R&D, carbon-energy saving R&D, and neutral R&D. In such a case, it is carbon-producing R&D, rather than neutral R&D, that is crowded out by induced carbon-energy saving R&D. As a result, the impact of induced technological change is larger, with optimal carbon taxes falling by a factor of 2.

Thus, an important question is what types of R&D are replaced by an increased focus on clean technologies. Recent research, highlighted in box 6, suggests that there is evidence for a crowding out effect, but that clean innovations tend to crowd out dirty innovations in the same sector. These results imply that the complementarity between technology policies and environmental policies is key to make sure that that clean innovation activity comes at the expense of innovation in dirty technologies and not of other socially valuable innovation.

It also suggests that any policy effort to accelerate innovation in clean technologies include a component to train new scientists and technical workers in order to increase the supply of qualified scientists in the long run. As an example, consider the experience of the U.S. National Institutes of Health (NIH), which supports biomedical research in the U.S. The NIH budget has traditionally grown at a slow, steady pace. However, between 1998-2003, annual NIH spending nearly doubled, from $14 billion to $27 billion.

Adjusted for inflation, this represents a 76% in just five years, and was nearly twice as high as the increase for the entire decade before. This rapid increase resulted in high adjustment costs. New post-doctorate researchers needed to be brought in to support research projects. Managing a larger budget entails administrative costs for NIH. Moreover, after this rapid doubling, research funds were cut, so that real NIH spending was 6.6% lower in 2007 than in 2004. This created a career crisis for the same post-doctorate researchers supported by the earlier doubling of support, as there was more competition for funds to start their own research projects. Moreover, scientists spent more time writing grant proposals. Because the probability of funding for any one proposal falls as the NIH budget falls, researchers submitted multiple proposals in the hope that one would succeed (Freeman and Van Reenen, 2009). This NIH experience suggests that growth in clean R&D budgets should be slow and steady, allowing time for the development of young researchers in the field. The training of new scientists through graduate and post-graduate grants should be an important component of the overall public research funding approach.

Box 6 – Crowding-out non-clean innovation

A few empirical papers have addressed the question of crowding-out of environmental R&D. Gray and Shadbegian (1998) find that more stringent air and water regulations had a positive impact on paper mills' technological choice in the US, but that the increased investment on abatement technologies came at the cost of other types of productivity-improving innovation. Hottenrott and Rexhaüser (2013) find that regulation-induced environmental innovation crowds out R&D in other technologies, especially for small firm that are credit constrained. Popp and Newell (2012) use patent and R&D data to examine both the private and social opportunity costs of climate 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 may come from a redistribution of research funds in sectors that are likely to perform energy R&D. Given this, they link firm-level patent and financial data to take a detailed look at climate R&D in two sectors – alternative energy and automotive manufacturing – asking whether an increase in alternative energy patents leads to a decrease in other types of patenting activity. They find evidence of crowding out. Interestingly, the patents most likely to be crowded out by alternative energy research are innovations enhancing the productivity of fossil fuels, such as energy refining and exploration. This is consistent with the notion that any apparent crowding out reacts to market incentives – as opportunities for alternative energy research become more profitable, research opportunities for traditional fossil fuels appear less appealing to firms. This is also in line with the result by Aghion et al (2012) which shows that automobile companies react to increases in fuel prices by conducting more innovation in "clean" cars (electric, hybrid and hydrogen) and less innovation in "dirty" (combustion engine) cars. Thus, while evidence of crowding out exists, those studies that are able to detail the types of R&D crowded out suggest that it is dirty R&D that is reduced to make way for policy-induced clean R&D.

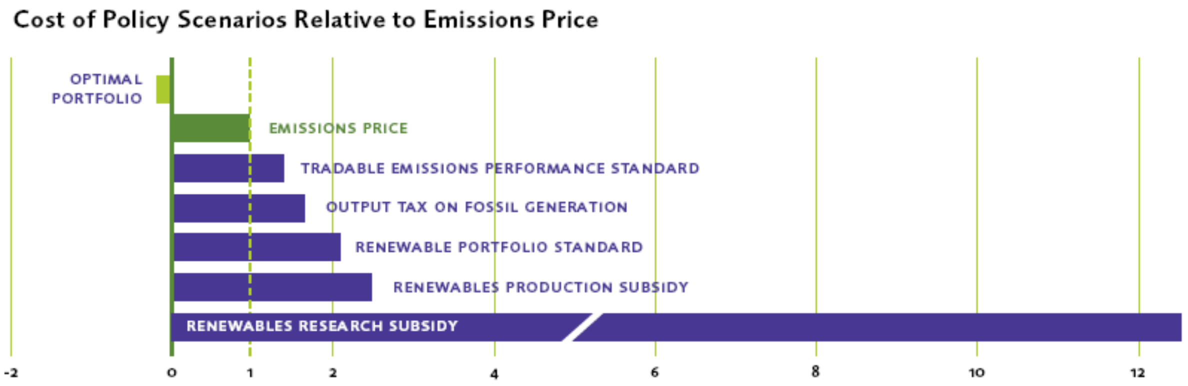
D. The appropriate policy mix

Combining instruments

The presence of several market failures requires the implementation of several policy instruments. Technology policies alone are irrelevant: if no carbon pricing is in place to create a market demand for technologies like CCS, no R&D will be conducted even with large research subsidies in place. Similarly, environmental policy cannot supplant the need for technology policy. Indeed, studies evaluating the effectiveness of these various policy options find that environmental and technology policies work best in tandem. Although technology policy can help facilitate the creation of new environmentally friendly technologies, it provides little incentive to adopt these technologies. For example, Popp (2006b) considers the long-run welfare gains from both an optimally designed carbon tax (one equating the marginal benefits of carbon reductions with the marginal costs of such reductions) and optimally designed R&D subsidies. While combining both policies yields the largest welfare gain, a policy using only the carbon tax achieves 95% of the welfare gains of the combined policy, whereas a policy using only the optimal R&D subsidy attains just 11% of the welfare gains of the combined policy in his model. While this model is a stylized representation of the global economy, and thus ignored barriers to diffusion such as those discussed in box 3, it does highlight the key lesson that developing new clean technologies without providing incentives to use them will not be sufficient.

Fischer & Newell (2008) use a micro approach to study a broader set of policies, including those encouraging technology adoption, to assess policies for reducing CO_2 emissions and promoting innovation and diffusion of renewable energy. Although the relative cost of individual policies in achieving emission reductions depends on parameter values and the emission target, in a numerical application to the U.S. electricity sector, they find the ranking is roughly as follows: (a) emission pricing (b) emission performance standard, (c) fossil power tax, (d) renewables share requirement, (e) renewables subsidy, and (f) R&D subsidy.[9] Nonetheless, an optimal portfolio of policies—including emission pricing and R&D—achieves emission reductions at significantly lower cost than any single policy (see Figure 5). The benefits from more R&D are even able to compensate for the cost of the carbon tax. Gerlagh and van der Zwaan (2006) find an emission performance standard to be the cheapest policy for achieving various carbon stabilization goals. They note that the ordering of policies depends on the assumed returns to scale of renewable energy technologies. Fischer & Newell (2008) assume greater decreasing returns to renewable energy, due to the scarcity of appropriate sites for new renewable sources. Thus, an important question raised by Gerlagh and van der Zwaan (2006) is whether the cost savings from innovation will be sufficient to overcome decreasing returns to scale for renewable energy resulting from limited space for new solar and wind installations.

Figure 5 – Cost of climate change policy under different policy scenarios



Source: Fischer, C. and R.G. Newell. 2008. Environmental and Technology Policies for Climate Mitigation, *Journal of Environmental Economics and Management*

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[9] Note that the analysis is confined to the power sector—presumably an economy-wide carbon price would be a lot more cost effective relative to other policies like renewable subsidies.

What is the optimal policy mix between technology-push and demand-pull? The answer to this question depends on the relative intensity of market failures associated with technology development, mainly knowledge spillovers and learning-by-doing. Recent papers attempt to disentangle the separate contributions of R&D and experience by estimating two-factor learning curves for environmental technologies. These two-factor curves model cost reductions as a function of both experience (learning-by-doing, or LBD) and R&D (learning-by-searching, or LBS). Söderholm and Sundqvist (2007) find LBD rates around 5 percent, and LBS rates around 15 percent, suggesting that R&D, rather than learning-by-doing, contributes more to cost reductions. However, these results are very sensitive to the model specification, illustrating the difficulty of sorting through the various channels through which costs may fall over time. Nemet (2006) uses simulation techniques to decompose cost reductions for PV cells into seven categories. Plant size (e.g. returns to scale), efficiency improvements, and lower silicon costs explain the majority of cost reductions. Notably, most of the major improvements in efficiency come from universities, where traditional learning by doing through production experience would not be a factor. Learning from experience (e.g. through increased yield of PV cells) plays a much smaller role, accounting for just 10 percent of the cost decreases in Nemet's sample.

Fischer, Newell & Preonas (2013) model the US energy system and determine the optimal distribution of public spending between R&D support and deployment under various scenarios. They find that the ratio of deployment spending to R&D spending does not exceed one for wind energy in almost all scenarios. With extreme assumptions on learning-by-doing this ratio goes to 6.5. The ratio of public spending on deployment to R&D exceeds one for solar energy but not by much. The ratio reaches 10-to-1 under the "high learning-by-doing" scenario. As one can see, the optimal policy mix varies across clean technologies, depending on their degree of maturity. The relative importance of market pull vis-à-vis technology push decreases, as one moves from technologies close to market competitiveness towards highly immature ones (Grubb, 2004).

Acemoglu et al. (2014) develop a model of endogenous growth with clean and dirty technologies and characterize the optimal climate change policy. They show that the transition to clean technology is slow when dirty technologies are initially more advanced. They find that the optimal policy includes a very aggressive research subsidy for clean technology. With a 1% social discount rate, the optimal carbon tax is fairly low, (representing 16% of the turnover of the carbon emitting sector), while research directed at clean technologies receives a 61% government subsidy (meaning that for every dollar of R&D spending, there is a 61 cents subsidy). With a social discount rate of 0.1%, carbon taxes are raised to 44%, but clean research subsidies are even more aggressive, at 95%. Moreover they show that relying only on carbon taxes and not on research subsidies leads to large welfare losses. This is in line with the result by Acemoglu et al. (2012), which shows that optimal policy involves both carbon taxes and research subsidies, so that excessive use of carbon taxes can be avoided.

Optimal public R&D funding

An important question for policy makers is how much government R&D money to spend on environment-friendly innovation. Here, however, economics provides less of an answer. Cost-benefit analysis provides a useful tool for ex-post evaluation of R&D spending, but estimating the potential benefits from new R&D spending is more difficult. Engineers are better suited to determine which projects are most deserving from a technical standpoint. 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, as suggested above, economic analysis suggests that the constraints for funding are likely to come from other sources, such as what is the pool of scientist and engineering personnel currently available to work on energy projects, and how quickly can we grow this pool. That is, the limits to how much we can spend come not from the number of deserving projects, but rather limits of the existing research infrastructure. It is worth pointing out, however, than recent models of climate policy show that the optimal policy heavily relies on research subsidies. For example, Acemoglu et al. (2014) suggest that 90% of all R&D expenditures in clean technologies should be funded by the government during a couple of decades, so that the productivity of clean technologies quickly catches up with that of dirty technologies. Moreover, recent IEA estimates suggest that achieving global energy and climate change ambitions consistent with a 50% reduction of energy-related CO2 emissions in 2050 with respect to 2007 (the 2010 BLUE Map scenario) would require a twofold to fivefold increase in public RD&D spending (IEA, 2010).

As regards what sorts of technologies should be priority for funding, European governments should focus on technologies have a strong public good component but are central to any decarbonisation pathway. The goal is to avoid providing public support for research that the private sector would otherwise do on their own. This could include projects supporting long-term research needs where the payoff occurs farther into the future, as well as infrastructure that has a public goods component. Examples include carbon capture and storage, energy storage, smart grids, energy efficiency and infrastructures for electric vehicles.

III. Current policies for clean technology development in Europe

A. Policies targeting environmental externalities

The European Union Emissions Trading System is Europe's flagship policy to address climate change. Beginning with an overall cap on EU carbon emissions, the EU sets a national CO2 emissions limit for each country. From this, the EU specifies economic activities (such as burning of fuel or production of cement) that participate in trading of carbon permits[10]. As a result the EU ETS covers around 45% of the EU's greenhouse gas emissions. As with any environmental policy, the effect of the EU-ETS on innovation depends on the strength of the policy. Indeed, Calel and Dechezleprêtre (2014) show that the large positive impact of the EU ETS on low-carbon innovation coincided with the time at which carbon prices were highest at around 25-35€/tonne. Unfortunately, the EU ETS has been plagued from the beginning by overallocation of permits (or the lack of a price stability mechanism). In addition, the economic downturn and the resulting contraction of production reduced industrial carbon emissions. As a result, permit prices are far below the level required to provide meaningful incentives for companies to invest in low carbon technology development, with the price of futures on the European carbon market now at a record low (around 5€/tonne, see Figure 6),

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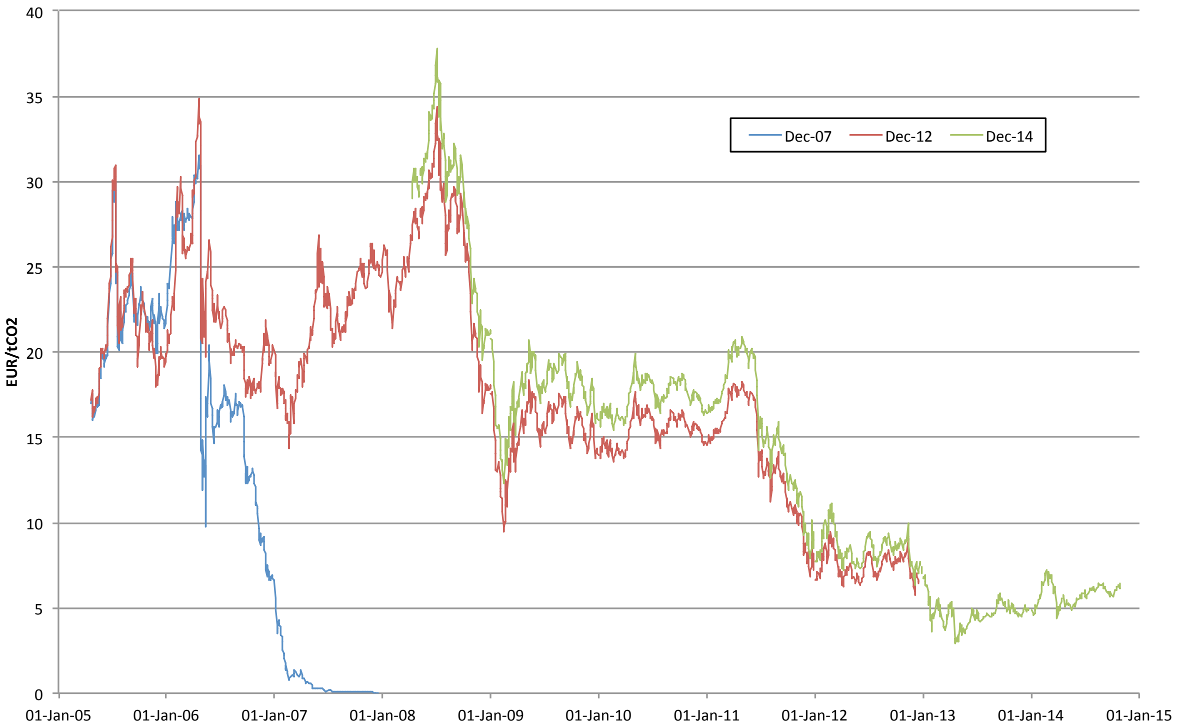
[10] Activity-specific size criteria then determine which installations are included in the EU ETS. For instance, only combustion installations with a yearly thermal input exceeding 20 MWh are covered. In the absence of data on non-regulated installations it is not possible to determine fraction of emissions is produced by installations with input less than 20 MWh.

Figure 6 – EUA Futures prices 2005-2014



Source: Intercontinental Exchange

According to recent analysis by Thomson Reuters Point Carbon[11], the European carbon market is likely to remain oversupplied with allowances for many years to come, despite the recent commitment to reduce greenhouse gas emissions by 40 percent in 2030 because of the accumulated oversupply in the market, which is expected to be in the order of 2.5 Gt in 2020. As a consequence, carbon prices are expected to remain low, at an average of €13/tonne between 2015 and 2020 and an average of €24/tonne from 2021 to 2030.

Thus, carbon prices are likely to remain at a low level for the next decade or so, and are unlikely to provide companies with strong incentives to conduct low-carbon R&D at the scale needed, especially since the EU ETS covers less than half of Europe's emissions. Thus, policies to augment low carbon prices will be necessary to spur innovation during the next decade. For example the UK introduced in 2013 a carbon price floor (CPF)

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[11] See http://www.commodities-now.com/reports/environmental-markets/18188-carbon-price-to-average-13-t-in-next-five-years.html

starting at around £16 per tonne of C02 and projected to reach £30 per tonne of C02 in 2020. The CPF is made up of the price of CO2 from the EU ETS and the carbon price support (CPS) rate per tCO2, which ensures that the minimal price paid by power generator does not go below the CPF. The carbon price support rates for 2013-14 is £4.94/t, rising to £9.55/t in 2014-15 and £18.08/t in 2015-1016. The CPF is explicitly designed to provide an incentive to invest in low-carbon power generation. Of course, the UK carbon price floor is environmentally ineffective, unless other European countries adopt similar policies or the ETS is supplemented by a price floor. At present, this is highly unlikely.

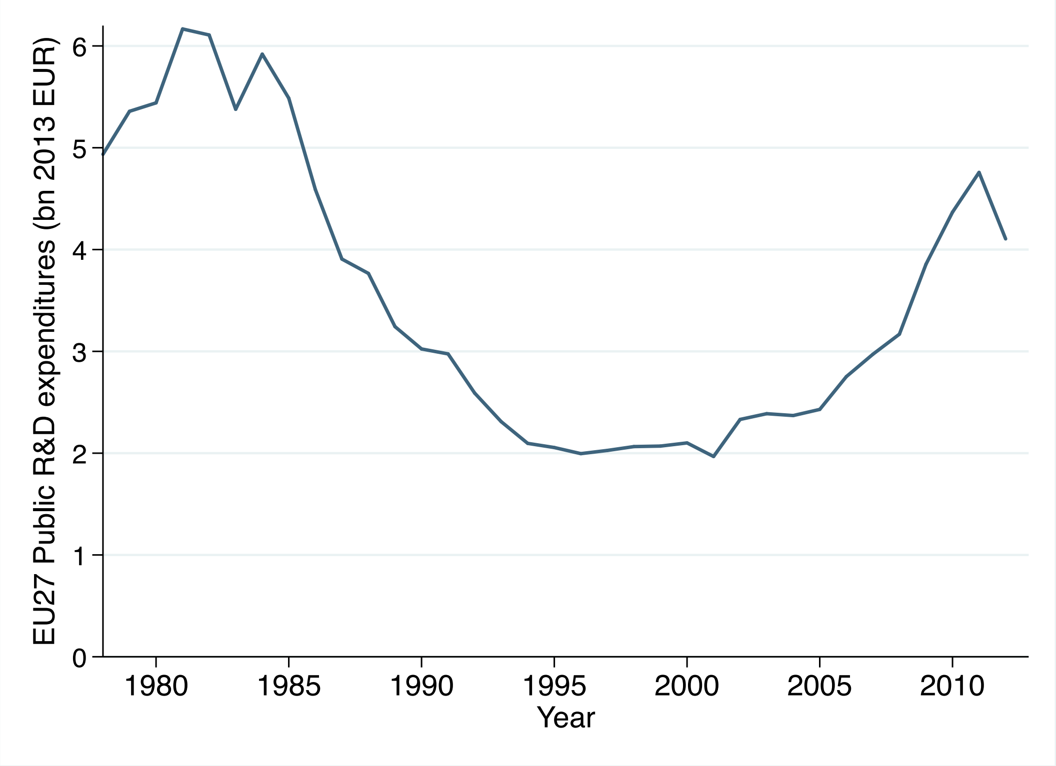
B. Technology policies

Public R&D support

Public R&D spending plays a particularly important role in the energy sector. In 2011, the last year for which both private and public energy R&D data are available, European industry spent around €7 billion on energy R&D according to the EU Joint Research Centre on Industrial Investment and Innovation R&D Scoreboard 2013 (European Commission, 2013), while European governments spent around €4 billion, according to IEA public R&D data. Although public energy-related R&D expenditures in European countries have increased significantly since 2005, after having stagnated at around €2bn/year for almost a decade, they are still 30% below what they were in the early 1980s after the second oil shock. Moreover, while public R&D grew at an average annual rate of 8% between 2001 and 2011, it has seemingly started to decrease recently, perhaps as a consequence of falling energy prices which makes the value of future energy savings smaller (see Figure 7). Energy-related expenditures account for 4% of total government R&D in Europe, compared to over 10% in 198. Meanwhile, environment-related expenditures account for 2.5% of total government R&D. However, there are important differences across countries, with France and Germany spending around 8% of their public R&D budgets on energy and environment issues, while the figure is only 4% in the UK (see Figure 8). Overall, energy and environment appear to lag behind other research priorities such as health, space exploration or defence (Figure 9).

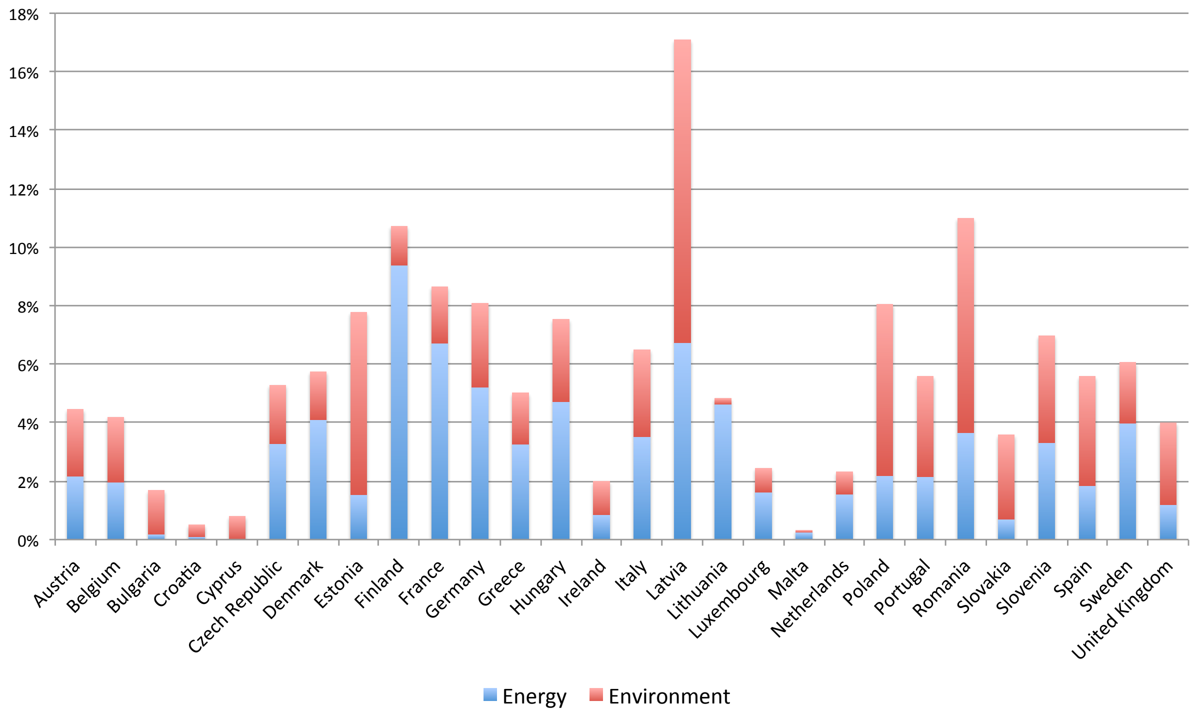
Public R&D expenditures in the energy sector in Europe represent less than 0.1% of GDP in almost all European countries (see Figure 10).

Figure 7 - EU 27 public R&D spending in energy technologies (billion euros)



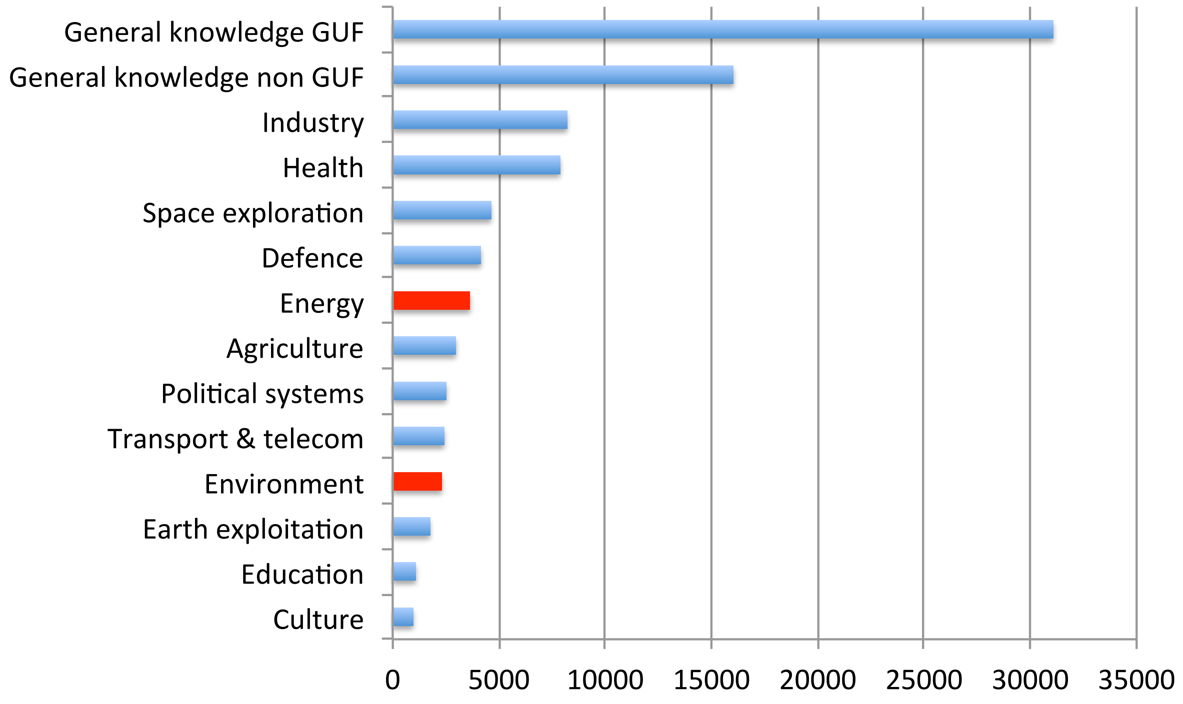
Source: IEA

Figure 8 – Share of public R&D expenditures towards energy and environment across EU28 countries (2013)



Source: Eurostat

Figure 9 – Distribution of public R&D expenditures in Europe across socio-economic objectives (2013)



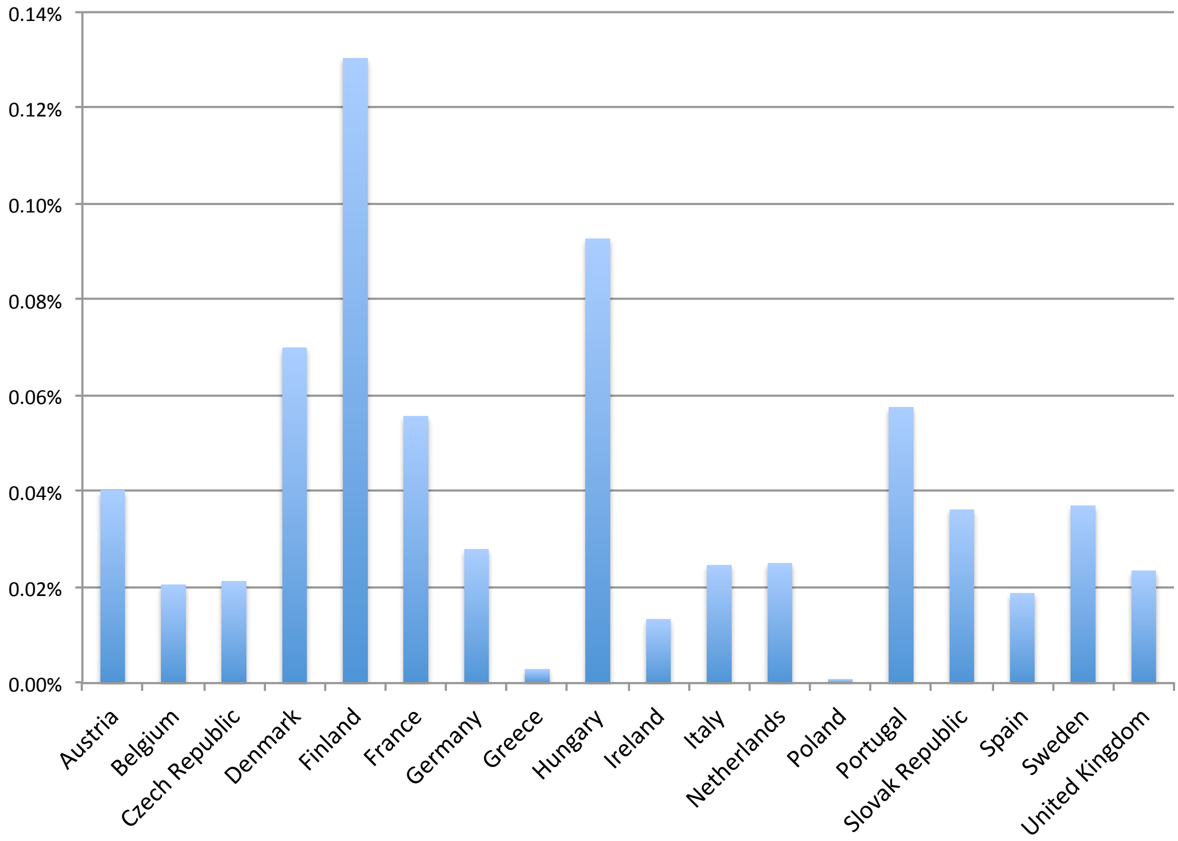
Source: Eurostat

Note: GUF= General University Funds. General knowledge non GUF stands for "General advancement of knowledge: R&D financed from other sources than GUF"

Environment relates to pollution control and includes Atmosphere and climate protection; Protecting the air; Solid wastes; Water protection; Soil and phreatic water protection; Noise and vibrations; The protection of species and their habitats; Protecting against natural hazards; Radioactive pollution.

Energy covers the production, storage, transportation, distribution and usage of any type of energy and processes designed to increase efficiency in the production and distribution of energy. It includes Energy efficiency; The capture and storage of CO2; Sources of renewable energies; Nuclear fission and fusion; Hydrogen and gas.

Figure 10 – Public R&D expenditures on energy as a share of GDP (2011)



Source: IEA

Of the €4.7 billion of public expenditure in 2011, 30% went to energy efficiency, 25% to renewable energy (with biofuel, solar and wind energy respectively accounting for 9%, 7.5% and 4% of the total), 22% to nuclear energy R&D, 10% to energy storage and 6% to fossil fuels (including €123 million for CCS). €90 million (less than 2%) were spent on electric cars, including batteries, motors and infrastructure.

Importantly, the vast majority of public funding for clean energy technologies in Europe comes from national governments. European institutions play only a marginal role. For example, the estimated public (EU and national) RD&D investments dedicated to six technologies covered by the EU Strategic Energy Technology Plan[12] in 2010 reached €2.26 billion, out of which, €2.02 billion were national funds and €0.24 billion (or 11%) were EU funds. A possible consequence of the primary involvement of national governments is the relatively low efforts dedicated to technologies that are further away from the market and have a very strong public good component, such as electricity grids and carbon capture and storage. For example, in 2010, public R&D investments in wind and PV were around €900 million each, while for electricity grids and carbon capture and storage (CCS) they were €323 and €400 million respectively (see Figure 11). Yet, the financing needs of technology development, as described in the SET-Plan roadmaps (European Commission, 2009), have been established at €1-1.5 billion per year for CCS. Thus R&D support for CCS may be lower than what is socially desirable, especially given the potential for European CCS technologies to be deployed in China and other large industrializing countries.

True, the European Union has limited funding available to support clean technology development, with its budget capped at 1.05% of the EU-27's Gross National Income. However, an interesting source of additional funding comes from the revenues from auctioned carbon permits. The European Union created the NER300 programme, which was funded from the sale of 300 million emission allowances from the New Entrants' Reserve (NER) set up for the third phase of the EU ETS. The aim of the programme is to fund innovative demonstration projects in CCS and renewable energy. The allowances were sold on the carbon market and the money raised — €2.1 bn EUR — is being made available to projects as they operate. As part of their deliberations on the EU's Framework for Climate and Energy 2020-2030, European leaders recently mandated the creation of a successor programme to NER300, "NER400", which would be initially endowed with 400 million carbon allowances. The new programme would raise over €9 bn on the assumption of a carbon price of €23/tonne.

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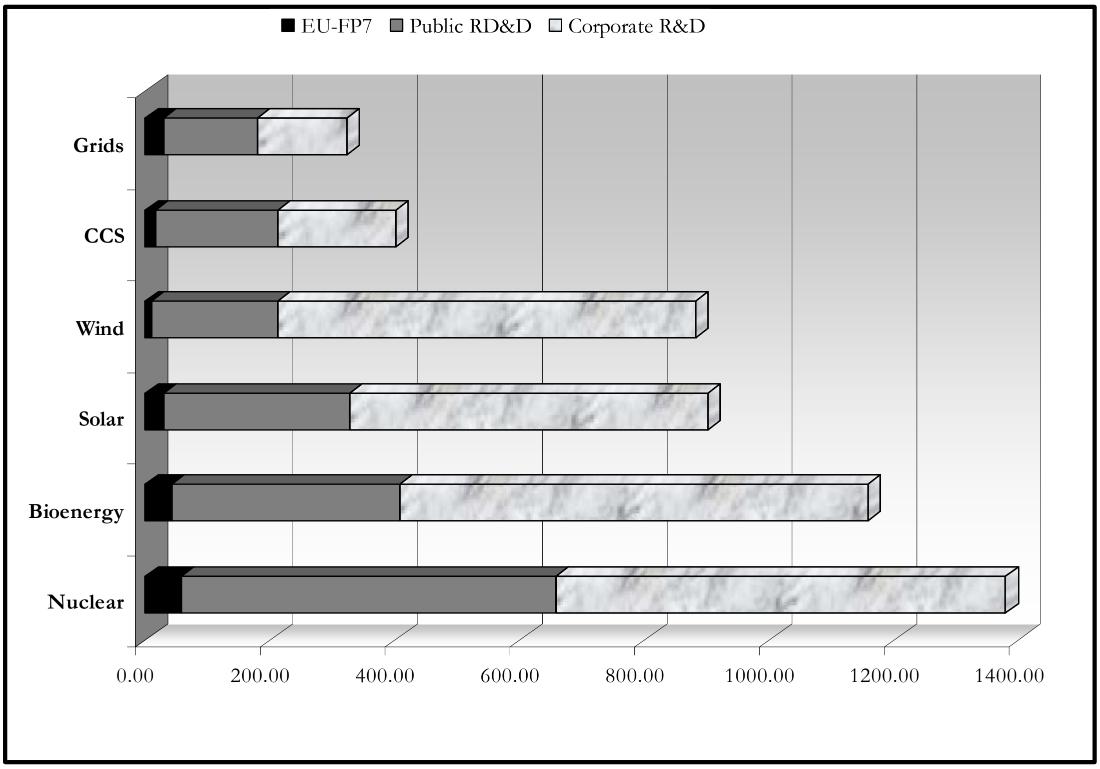
[12] Since 2008, the EU Strategic Energy Technology Plan (SET-Plan) aims to accelerate energy technology development and deployment across Europe. The implementation of the SET-Plan has led to the establishment of large scale programs, called European Industrial Initiatives (EIIs), which bring together industry, the research community, the Member States and the European Commission in risk-sharing partnerships aiming at the rapid development of key energy technologies at the European level. Six technologies have been identified as the focal points of the first EIIs: wind, solar (photovoltaics and concentrated solar power), electricity grids, bioenergy, carbon capture and storage, fuel cells and hydrogen and nuclear fission.

The NER programmes are interesting in that the auctioned carbon permits provide a source of sustained revenues that can be used for R&D support, even though the price of permits is uncertain and volatile. In contrast, temporary support programmes to R&D are unlikely to be useful since, as explained above, R&D is by nature a long-term activity that necessitates some guarantee of sustained support. For example in 2009 the European Commission implemented the European Energy Programme for Recovery (EEPR), which dedicated €4 billion to co-finance projects in the fields of gas and electricity infrastructure (€2.5 billlion), offshore wind (€565 million) and CCS (€1 billion). To our knowledge all funded CCS projects have since then been abandoned because of the low carbon price on the market, suggesting that temporary R&D support programmes are of little help and can even be counterproductive if they divert resources away from sustained R&D efforts.

Figure 11 - Estimate of public and corporate R&D by technology and source for the 6 SET Plan technologies (2010)



Source : European Commission

Along the NER programmes, national governments can use auctioning revenues to support public R&D. Under the revised EU ETS Directive, at least 50 % of auctioning revenues should be used by Member States for climate and energy related purposes. Under the Monitoring Mechanism Regulation, Member States are requested to report annually on the amounts and use of the revenues generated. In 2013, the total auctioning revenues for EU countries reached € 3.6 billion. From this, around € 3 billion have been used for climate and energy related purposes according to the European Commission, of which only €256 million (or 7%) have been dedicated to research (European Commission, 2014). Between 2015 and 2020, around 6 billion allowances should be auctioned, or 1 billion per year on average. Thus, auctioning represents a potentially significant source of revenues to increase public R&D. For example, directing 10% of the planned auctioned allowances revenues until 2025 to R&D funding would lead to a doubling of EU public R&D expenditures in 10 years, similar to the one observed between 2000 and 2010.

Support to private research

Many European countries have policies to subsidize private R&D expenditures. For example in France companies can deduct 30% of all R&D expenditures from profit taxes.[13] Most of these policies are technology-neutral, with a few exceptions. For example, Belgium has introduced a tax deduction of up to 15.5 percent of investments in R&D fixed assets if they have an environmental benefit.

At the European level, some policies are in place to facilitate access to finance for innovative firms. In particular the European Commission and the European Investment Bank Group (EIB) have launched 'InnovFin – EU Finance for Innovators' which includes guarantees for intermediaries that lend to SMEs, direct loans to enterprises and advisory services. This scheme is expected to support up to €48 billion of final R&I investments.[14] The scheme is not targeted at any technology in particular, but is assuring financial support to the renewable energy and energy efficiency sectors.

Intellectual property rights

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[13] In 2011 this represented 5 billion euros in tax credits, i.e. 1.1% of the government budget and 0.2% of GDP.

[14] http://setis.ec.europa.eu/energy-research/content/eu-and-eib-group-jointly-provide-eur-48-billion-ri-investment-support

Europe has a well functioning patenting system. The European Patent Office makes it easier for applicants to file a patent across all European countries. Yet because of legal and translation costs, the cost of filing a patent in Europe is still relatively high. In the early 2000s, filing a patent cost around €5,000 in Japan, €10,000 in the US and €30,000 at the European Patent Office (Roland Berger Market Research, 2005). Since January 2014, applicants can apply for a "unitary patent" across Europe which ensures uniform protection for an invention in 25 Member States (all EU Member States except Italy and Spain). The implementation of this new EU Patenting System is expected to substantially decrease patenting costs for innovators.

It is important to keep in mind that, as shown in the previous section, patents are likely to provide useful incentives for innovation in European developed economies, but not so much in many sectors where environmental technologies are actually being developed. Hence, changes in IP rights (either strengthening or weakening) would be unlikely to induce significant changes in innovation activity except in a handful of sectors, including for example biotechnology. However, programmes to accelerate the examination of patents in clean technologies can be useful in helping start-up companies raise capital. Because proving that a patent application does cover a "green" technology is difficult, we do not however recommend restricting fast-track programmes to green patents only, but instead recommend they be open to all patent applications.

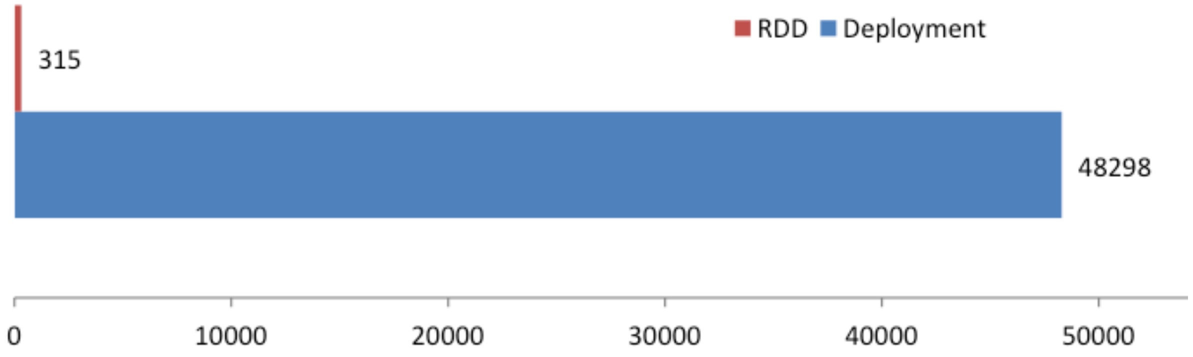
Deployment policies

As of 2011, every EU country has implemented at least one of the major support instruments towards renewable energy deployment (feed-in tariffs, feed-in premiums, tender schemes or quota obligations). Amongst the major support instruments, feed-in tariffs schemes are clearly dominant, with 85% of countries implementing it in 2010 (Kitzing et al., 2012). Almost all countries have also implemented at least one supplementary support scheme: investment grants, fiscal measures (tax incentives, etc) or financing support (loans etc). Amongst the supplementary support instruments, investment grants dominate.

Recent evidence indicates that European countries have put a strong emphasis on deployment policies compared with direct R&D support. A study by Zachmann et al (2014) shows that the top 6 European countries spent 315 M€ in 2010 to support R&D

in wind and solar power. The cost to society implied by the deployment of wind and solar technologies[15] that same year represented 48,300 M€ (see Figure 12).

Figure 12: Public support to RDD vs deployment in wind and solar energy in the top 6 European countries (2010)



Source: Zachman et al 2014

Conclusion

Technological advances will play a crucial role in efforts to stabilize atmospheric greenhouse gas concentration. As this paper demonstrates, well-designed climate policy can help shape the development of environment-friendly technologies. These policies must address multiple market failures pertaining to the environmental externalities of greenhouse gas emissions, knowledge spillovers, learning-by-doing, imperfections in capital markets and other barriers. This requires a menu of policy options. Simply providing R&D support is not sufficient, as without environmental policy, there is little incentive to adopt clean technologies. At the same time, while broad-based environmental policies such as a carbon tax or cap-and-trade scheme provide an overall framework for emission reductions, this review suggests that other market failures remain important. Private firms will focus on technologies most likely to generate short-term profits. For instance, carbon taxes are likely to promote wind energy at the expense

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[15] 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.

of solar, as wind is currently the most cost-effective renewable option. Similarly, because improving electricity transmission efficiency systems benefits all technologies, private innovators are likely able to capture only a small portion of the social benefits of such innovation. “Leaving it to the market" also picks a winner - markets will emphasize the lowest cost technology, which might prevent the development of a broader portfolio of technologies. Long-term benefits, spillovers, and uncertain R&D returns all suggest a role for public R&D support, either through direct financing or targeted policy incentives. Finally, once technologies are available, additional policy support is needed to encourage diffusion. As the research on the energy efficiency paradox shows, even energy innovations with relatively short payback periods diffuse slowly. This suggests that simply getting the prices right through policies such as a carbon tax will not be sufficient.

As our review demonstrates, the European Union and national governments have adopted a set of policies to address these various market failures and lift the barriers to the development of clean technologies. These policies include the EU ETS, public R&D expenditures, support to private R&D and to start-up companies, a well-functioning IP system and a range of policies to encourage the deployment of renewable energy technologies. While these policies are encouraging and go in the right direction, we suspect that the very low price of carbon on the EU ETS, which is projected to remain so for another decade, along with its partial coverage, is a major barrier to clean technology development in Europe. The new commitments for 2030 as well as the Market Stability Reserve are steps in the right direction but didn't have any influence on the price so far because of the vast amount of allowances currently on the market. Combined with the presence of innovation market failures and political constraints on high emissions prices, this justifies stronger policies targeted directly at technology development. Here we propose a series of reforms to the current policy landscape that could enhance clean innovation activities in Europe and help European countries tackle the challenges posed by climate change and other environmental issues.

Some practical, recommended steps for reform

(1) While it is impossible to provide an "optimal" policy mix between R&D and deployment, it appears that European countries have been emphasizing technology

deployment, in particular 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 in line with the recommendations below the marginal euro spent on clean technologies should go to R&D rather than deployment.

(2) Given the scale of the climate change problem (and other environmental issues), the amount of money spent on R&D in clean technologies seems small, especially when compared with other equally important sectors such as health or defence. Public energy-related R&D expenditures in European countries are still 30% below what they were in the early 1980s and have decreased recently. There is no evidence that we've hit diminishing returns to energy R&D funding, so at this point it is macroeconomic constraints on available funding that limit increases. The IEA estimates that public RD&D spending need to at least double to achieve significant carbon emissions reductions. Thus, we recommend an increase of public R&D funding for low carbon technologies.

(3) This increase in funding needs to be gradual, however, because the supply of researchers in the society is fixed in the short run and expanding research in clean technologies involves training new scientists to avoid crowding out other socially valuable R&D. Ephemeral increases in clean R&D funding, like the 2009 EEPR programme, can be counterproductive as they divert resources away from steady research programmes. A sustained 8% annual increase in funding leading to a doubling of public R&D expenditures in 10 years corresponds to what was observed between 2001 and 2011 and thus seems achievable.

(4) We think that commitments to fund R&D should have a long-term component (until at least 2030) just like carbon emission caps. Policy stability is important for companies, universities and other research stakeholders to make long-term predictions on innovation needs. To provide a long-term commitment, revenues from auctioned carbon permits could provide a source of sustained funding for low carbon R&D. Directing 10% of the planned auctioned allowances revenues until 2025 to R&D funding would lead to the doubling of EU public R&D expenditures in 10 years suggested above.

The EU seems to be in a better position than individual European governments to make such long-term R&D commitments.

(5) EU institutions and governments should focus their efforts on technologies that are central to any decarbonisation pathway and have a strong public good component: CCS, energy storage, smart grids, energy efficiency and infrastructure for electric vehicles. Compared to wind and solar power, these technologies have received relatively less support.

(6) The low price of carbon on the market, combined with uncertainty over future policies, may make regulatory instruments, such as technological standards, attractive. However, because standards – just like emissions permits markets – are likely to favour technologies that are closest to the market, they too should be used in combination with direct R&D support for technologies that have longer term potential.

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