**Policy Brief**

# Encouraging Innovation that Protects Environmental Systems: Five Policy Proposals

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## Introduction

Innovation drives economic growth (Aghion and Howitt 1998) and enhances standards of living. However, the resulting economic growth also undermines the global environmental systems on which our economy and very civilization depend. While the concerns of Malthus (1798) thus far appear to have been misplaced—the number of humans on Earth and consumption per capita have simultaneously expanded since the industrial revolution—there is nevertheless undeniable pressure on air, water, food, and energy systems (Rockström et al. 2009; Steffen et al. 2015). These pressures, in turn, are affecting public health and human development (WHO 2014), threatening some of the gains in prosperity achieved as a result of innovation and jeopardizing the prosperity of future generations.

Yet innovation must also be harnessed to help *solve* our global environmental challenges. Thus the *direction* of innovation (Acemoglu et al. 2012; Aghion et al. 2016; Acemoglu et al. 2016) may be more important than the *pace* of innovation. Without cheaper forms of zero-carbon energy, transport, and agriculture, it will likely be impossible to meet the climate targets of the 2015 Paris Climate Agreement; and more innovation in high-carbon technologies may make matters worse. Moreover, the sixteen other "global goals" (i.e., the unanimously agreed-upon sustainable development goals [SDGs] that apply to all countries, rich

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and poor[1]) present humanity with a set of challenges and trade-offs that appear to be nearly impossible to meet without fundamental innovations to bring the costs of clean technologies below the costs of environmentally damaging technologies.

It is therefore critical to be able to distinguish between innovations that enhance global environmental systems and those that undermine them. This is not easy.[2] The consequences of new innovations are often complex and cut across multiple environmental and economic systems. For instance, the increasing push for electric vehicles as a way to reduce air pollution and greenhouse gas emissions potentially creates water problems and the prospect of disposing of more than 10 million tonnes of spent lithium-ion batteries that release toxic gases (Nedjalkov et al. 2016) if not carefully recycled.

The basic economic case for government support of innovation is simple. Without government intervention, markets undersupply innovative activity because firms do not capture all of the benefits. There are large spillovers associated with knowledge creation (Nelson 1959; Arrow 1962),[3] with the social marginal returns from research and development (R&D) typically estimated to be between 30 and 50 percent, which is sometimes more than double the private marginal rates of return (Hall, Mairesse, and Mohnen 2010). Moreover, innovations that are environmentally beneficial need not generate lower economic benefits than innovations that are environmentally harmful. Knowledge spillovers actually appear particularly high for environmental technologies, primarily because such innovations are newer: clean electricity technologies induce approximately 20 percent more knowledge spillovers than *average* innovations and 43 percent more than *dirty* electricity innovations (Dechezleprêtre, Martin, and Mohnen 2015).

Thus government policies have a vital role to play in shaping the direction, quality, and pace of innovations that affect the environment. Policy instruments can be aimed directly at inducing and accelerating the development and diffusion of new clean products, processes, or services. Such policies might encourage resource efficiency and environmental management or incentivize R&D (Dechezleprêtre, Martin, and Bassi 2016) in key sectors, including agriculture, energy, transport, and water. But the relevant policy set is much broader: correcting environmental externalities has been shown to create significant incentives for innovation, even though prices on pollution are not thought of as innovation policies *per se* (Dechezleprêtre and Popp 2017). In short, correcting market failures can impact the supply of and demand for innovation.

This article proposes and examines five key policies that governments can implement to support innovation that protects the natural environment. We focus on policy instruments that either aim to *directly* drive innovation (e.g., the provision of fiscal incentives and direct

[1]The SDGs aim to end poverty, protect the planet, and ensure prosperity for all and were adopted by world leaders at a United Nations (UN) summit in 2015, officially coming into force on January 1, 2016 (UN 2017).

[2]To illustrate, consider the 2017 U.S. Department of Energy budget, which includes $617.5 million for fossil fuel research and development (R&D) and $822.5 million for renewable energy R&D (Gallagher and Anadon 2017). Determining whether these allocations reflect government support for clean or dirty R&D is not straightforward. For example, while there are environmental concerns about the negative impacts of hydraulic fracturing (fracking) for natural gas, innovations in fracking methods have also helped natural gas surpass coal as the main fuel for U.S. electricity generation.

[3]That is, there are positive externalities associated with knowledge creation because those that do not create the knowledge (or are not responsible for the innovation) can sometimes acquire that knowledge for free.

funds for innovative activities) or that *indirectly* induce innovation (e.g., regulations that make it costlier to operate in dirty sectors, thus inducing innovation in cleaner alternatives) of the environmentally friendly kind. Our aim here is not to identify a panacea for innovation policy but rather to provide broad guidance to policymakers and, whenever possible, to make specific recommendations for policy design based on the theoretical and empirical literature.

## Policy 1: Put a Price on Natural Capital

The most important policy for stimulating innovation that protects the environment is to put a price on unpriced, and increasingly scarce, natural capital. Natural capital—i.e., natural resources through which humans derive services and which sustain human life, such as water and geological formations—comprises approximately 2 percent of the wealth in Organization for Economic Cooperation and Development (OECD) countries and 20 percent or more of the wealth in developing economies (Hamilton and Hepburn 2017; World Bank 2017).

### Exhaustible Natural Capital

Much of the earth's natural capital is *exhaustible*, comprising oil, gas, subsoil minerals, and other assets. Markets for these minerals and fuels are fairly liquid and well-developed, with transparent prices. Concerns about the depletion of such natural capital—including "peak oil" worries—have come and gone in recent decades,[4] but the evidence suggests that the trend in reserve:production ratios is zero (Hepburn et al. 2017). The risk of exhausting these types of natural capital assets is very low because scarcity creates high prices, which leads to innovation, further exploration, reuse, and the development of substitutes. Indeed, many economists have long argued that the world is unlikely to "run out" of exhaustible resources due to market incentives and technological innovation (Tilton 1996). Claims regarding the depletion of exhaustible resources often do not adequately consider the impact of higher prices that result from exhausting easier-to-access and cheaper deposits. At a stroke, higher prices imply that minerals previously categorized as "resources" can be recategorized as "reserves" as they become economically extractable.

### Renewable Natural Capital

In contrast, the natural capital that is most "at risk"—i.e., where planetary boundaries could be or may already have been crossed—is *renewable* natural capital. This capital tends to be scarce because it is often incorrectly priced or has no price at all. Examples include many key systems that support life on earth—biodiversity, the ozone layer, land and water ecosystems.[5] The inadequate prices on these resources is a market failure that reduces the demand for innovation.

[4]See, e.g., Helm (2011) for a critique of the peak oil hypothesis and related policy.
[5]While the climate system is also a slowly renewing system, the capacity of Earth's carbon cycle to adjust for rapidly increasing atmospheric carbon dioxide concentrations without causing irreversible climate change suggests that it is better to consider the atmospheric space for carbon dioxide as an exhaustible resource (Allen et al. 2009).

## Tools for Correcting the Natural Capital Pricing Market Failure

How can these market failures be corrected? There is a well-known literature in environmental economics on the policy tools available (e.g., Goulder and Parry 2008). These tools include direct pricing (e.g., through taxation), trading, or command-and-control instruments that ban or limit certain activities or set technical standards. Implementing more stringent environmental regulations and policies makes it costlier to pollute and thus changes the relative costs and benefits of competing technologies. For example, a tax on carbon makes electricity generation from dirty fossil fuels such as coal more expensive than electricity generated from solar energy systems (Greenstone and Looney 2012). As the cost of carbon-emitting technologies and activities increases, there is a financial incentive to move away from dirty technologies and activities. This encourages a market in clean technologies to form, which encourages more innovation in environmentally friendly technologies and thus stimulates clean R&D (Baranzini et al. 2017). This hypothesis—known as the "induced innovation hypothesis"—suggests that policies that put appropriate prices on natural capital should be a major component of any policy portfolio aimed at redirecting technological change towards innovation for protecting the environment (Acemoglu et al. 2012; Aghion et al., 2016; Acemoglu et al., 2016; Fischer, Preonas, and Newell 2017).

## Evidence on the Induced Innovation Hypothesis

The induced innovation hypothesis—that more stringent environmental regulations and prices lead to greater R&D activity and innovation in environmentally friendly sectors—is widely supported by the theoretical and empirical literature (Hicks 1932; Acemoglu 2002; Acemoglu et al. 2016; Lanjouw and Mody, 1996; Jaffe and Palmer, 1997; Newell, Jaffe, and Stavins 1999; Popp 2002; Brunnermeier and Cohen 2003; Popp, Newell, and Jaffe 2010; Johnstone, Haščič, and Popp 2010; Ambec et al. 2013; Calel and Dechezleprêtre 2016). The empirical evidence indicates that the response to environmental regulation or prices is both large in magnitude and fast, typically occurring within 5 years.[6]

However, the literature indicates that the impact on innovation may vary depending on instrument choice. Market-based and flexible instruments such as emissions taxes or tradable allowances provide flexibility to firms to choose technical solutions that reduce compliance costs and can even enhance innovation and foster organizational change (Burtraw 2000). Putting a price on activities, such as carbon dioxide emissions, that damage natural capital can create stronger economic incentives for improving abatement technologies relative to setting standards (Jaffe and Stavins 1995). Importantly, however, market-based policies like carbon pricing must be credible to private sector firms over the long term to ensure sufficient demand for innovations once they are ready for the market (Helm, Hepburn, and Mash 2003; Newell 2010). There is evidence that performance standards can lead to more innovation than prescriptive standards (Lanoie et al. 2011). However, although market-based mechanisms—such as subsidies and taxes—are often found to be more effective in encouraging innovation than command-and-control regulations (Jaffe, Newell, and Stavins 2004), no clear evidence

[6]The response is even faster for regulation. For example, Popp (2006) finds that clean air regulations in the United States, Japan, and Germany have led to almost immediate innovation responses.

has emerged concerning which demand-side subsidies and policies have the greatest impact on innovation (Requate 2005). While the details remain to be worked through, the literature indicates that environmentally friendly innovation can be stimulated by policies that address environmental externalities.

### Evidence on the Direction of Innovation

Putting prices on natural capital that direct research efforts *towards* cleaner technology have the added benefit of directing innovation efforts *away* from dirtier technologies. For example, within the energy sector, as firms produce more patents for clean alternative energy, they also generate fewer patents enhancing the productivity of fossil fuels, such as energy refining and exploration (Popp and Newell 2012). Similarly, automobile companies react to increases in fuel prices by conducting more innovation on "clean" cars (electric, hybrid, and hydrogen) and less innovation on "dirty" (combustion engine) cars (Aghion *et al.* 2016). The potential impact of changing the direction of innovation is large. Gerlagh (2008) finds that the optimal carbon tax necessary to reduce emissions can be cut in half if one assumes that clean energy R&D replaces carbon-producing R&D rather than technology-neutral R&D. Thus, while it is important to acknowledge the impact of properly pricing environmental resources on the direction of innovation, governments could do even more to direct innovation away from dirtier technologies by also removing unnecessary subsidies on fossil fuels (see, e.g., Asmelash 2017).

## Policy 2: Support Environmentally Friendly R&D

Although the types of demand-side environmental regulations we have just discussed may encourage some early-stage innovations, such regulations tend to favor innovations in technologies that are already relatively close to market (Johnstone, Haščič, and Popp 2010; Popp 2010). This suggests that *timing* is important. That is, R&D support is necessary early in the innovation process to ensure the development of technologies that can subsequently be pushed closer to the market by demand-side support.

Sensible innovation policy for environmental protection should include subsidies for research (Acemoglu et al., 2012, 2016). In principle, government expenditures to support innovation should be equal to the size of knowledge spillovers (Goulder and Schneider 1999). Although it is notoriously difficult to measure spillovers and their effects on innovation decisions, several lines of analysis suggest that government spending on R&D for environmentally friendly technologies should be increased significantly relative to current levels (Nemet and Kammen 2007; Chan and Anadón 2016; Pless et al., in preparation).[7]

There are numerous ways to design and allocate government-funded R&D support. We describe and discuss evidence on the effectiveness of two common approaches—*indirect* fiscal incentives for R&D, such as tax credits, and *direct* funding, such as grants for R&D. We also consider the role of R&D conducted by government laboratories and research institutions.

[7]Popp (2016) shows that there is room to expand renewable energy R&D budgets but does not recommend a specific level of funding.

## Indirect Fiscal Incentives for R&D

Governments can subsidize private sector innovation through indirect fiscal incentives such as R&D tax credits. Such tax credits, which reduce corporate tax payable, are granted for corporate expenditure on activities that qualify (according to broad government definitions) as "research." Tax incentives have the advantages of not explicitly favoring specific technologies and being more predictable and reliable for financial planning (than funding that must be awarded through competitions) if implemented over the long term.[8] Fiscal incentives can also be used to target other broad objectives, if they are designed to provide more favorable credits for certain innovative activities (e.g., certain industries, collaborations, types of firms, or technologies). However, because they can make marginal projects profitable, tax credits often encourage firms to invest in innovation related to projects or technologies that are close to market and have high short-run returns rather than new technologies that are still far from market (Hall and van Reenen 2000).

### Evidence on effectiveness: input additionality

Tax credits for R&D expenditures have become an increasingly popular policy tool, and many studies have examined the effectiveness of such incentives on firms' R&D expenditures, often referred to as "input additionality."[9] For example, in a study of nine OECD countries over a 19-year period, Bloom, Griffith, and van Reenen (2002) found that a 10 percent decrease in the cost of R&D due to tax credits stimulates a 1 percent increase in the level of R&D in the short run and a 10% increase in the long run. Lokshin and Mohnen (2012) study firms in The Netherlands and find evidence of additionality on average.[10]

### Evidence on effectiveness: output additionality

Although the most direct objective of these tax incentives is to increase business R&D expenditures (i.e., input additionality), the ultimate goal is to stimulate innovation, growth, and other productivity outputs (i.e., output additionality). There is growing evidence regarding the positive impact of R&D tax incentives on innovation outcomes. For example, Czarnitzki, Hanel, and Rosa (2011) studied Canadian firms from 1997 to 1999—when one-third of all firms and two-thirds of high-technology firms used R&D tax credits—and found evidence of innovation output effects. Most recently, Dechezleprêtre et al. (2016) identify causal evidence of the impacts of R&D tax incentives on some innovation outputs (quality-adjusted patents) in the U.K. Cappelen, Raknerud, and Rybalka (2008) provide further evidence of the impact of R&D incentives on innovation outcomes.

### Targeting incentives

It is important to keep in mind that R&D tax credits are usually available for all or most companies within an economy that are investing in innovation. This means that tax credits not only tend to incentivize R&D on marginal projects (i.e., those closest to market) rather than new

[8]Although tax incentives for R&D have been relatively stable in some regions, such as in the UK, they remain subject to repeal and uncertain in others.
[9]This is the marginal increase in firm R&D spending that results from additional R&D support.
[10]For further evidence on input additionality effects, see Duguet (2010) and Hægeland and Møen (2007), who study firms in France and Norway, respectively.

technologies, but also that they do not necessarily steer innovation systems towards environmentally friendly outcomes. However, policymakers can offer fiscal incentives that *do* target specific technologies or industries, such as technology-specific investment or production tax credits. For instance, France offers a 30 percent research tax credit for environmental investments up to €100 million (and 5 percent for eligible expenses exceeding €100 million) (KPMG International 2014).

## Direct Grants or Loans

Governments can also provide direct financial support for R&D through grants or loans, and there is growing empirical evidence regarding their impact on firms' innovation outcomes. For example, Jaffe and Le (2015) find that grants increased patenting by firms in the manufacturing and service sectors in New Zealand between 2005 and 2009 and receiving a grant nearly doubles the probability of a firm introducing a new good or service (although effects on process innovations are weaker). Although Jaffe and Le (2015) do not find differential effects for firms of different sizes, firms may indeed respond heterogeneously to grant support. For example, Bronzini and Iachini (2014) find that a grant program in northern Italy did not create additional firm investment in R&D on average, but that there was a substantial increase in investment by small firms. Furthermore, in a recent analysis of the U.S. Department of Energy's Small Business Innovation Research (SBIR) grant program, Howell (2017) showed that grants to small firms can have significant effects on measures of innovative, financial, and commercial success in such firms.

Direct grants and loans can be offered and targeted in various ways, such as through competitions or directed towards specific technologies or types of firms. One advantage of direct support is that resources can be targeted to areas where government intervention is particularly needed. However, it is difficult to identify projects that are guaranteed to produce successful outcomes given the great uncertainty associated with innovation. This suggests that a portfolio approach—i.e., providing support to numerous projects and technologies to reduce the overall funding risk—is likely to be most effective. Governments with deep pockets are in an excellent position to support a diversified portfolio of projects. For example, while the U.S. Department of Energy was criticized for its support of the failed Solyndra project, overall the loan guarantee program that supported Solyndra made money, as interest payments from successful projects outweighed losses from failed projects such as Solyndra (Eckhouse and Roston 2016).

## R&D in Government Laboratories and Research Institutes

Governments support research not only by providing financial support to private firms and universities, but also through performing research in government laboratories and research institutes (e.g., the U.S. National Renewable Energy Laboratory). Such institutions have proven to be particularly valuable for promoting innovation in clean energy. For example, Popp (2017) finds that clean energy patents assigned to governments are more likely to be cited than clean energy patents from other institutions, signaling patent quality and highlighting the high value of research performed at government institutions. Moreover, government articles on clean energy technology are more likely to be cited by patents than similar articles from any other institution, including universities. This suggests that clean energy research performed at government institutions plays an important role in linking basic and applied research.

The high value of government-conducted research on clean energy is different from what is found in other sectors, where university research tends to produce the most highly cited output (e.g., Jaffe and Trajtenberg 1996; Trajtenberg, Henderson, and Jaffe 1997). Why might government research be more important for energy than other sectors? Both Mowrey, Nelson, and Martin (2010) and Weyant (2011) find that government research helps new energy technologies overcome roadblocks to commercialization. For instance, significant energy innovations typically have disproportionately large capital expenses, leaving a role for collaboration with the public sector to provide support for both initial project development and demonstration projects. Such demonstration projects can promote further learning (Mowrey, Nelson, and Martin 2010). For example, advances in wind turbines were aided by U.S. Department of Energy–sponsored innovation on multiple turbine components, which complemented private sector efforts and allowed for feedback between public and private sector researchers (Norberg-Bohm 2000).

## Policy 3: Judiciously Support Early-Stage Deployment

While economists tend to focus on government support for R&D, as discussed under policy 2, there are at least two situations in which support for early-stage deployment of specific technologies is also warranted.

First, there are often deployment-related market failures that even correct natural capital prices and R&D support will not address. These include first-of-a-kind costs incurred by the first mover in a new technology. Followers gain the benefit of the lessons learned by the leader, including technical experience, training of personnel (who can be subsequently hired), financial structures and better-educated banks, and improved legal and market arrangements. The result is that without government support to address market failures associated with the diffusion of new technologies, socially valuable deployment might occur too slowly, or not at all (Jaffe, Newell, and Stavins 2005).

Second, there is a "second-best" argument for deployment support. Fischer, Preonas, and Newell (2017) show that while technology-specific deployment policies such as renewable energy mandates are less cost effective than technology-neutral policies, they also result in less redistribution, making them more feasible politically. If government has been unable to correct natural capital prices, perhaps for political reasons—such that the "demand pull" is weak or R&D externalities cannot be internalized and thus the "supply push" is also too weak—deployment support for environmentally friendly innovations might be able to compensate. These types of interventions may be particularly important to avoid crossing a particular planetary boundary where there is little time left for more economically efficient policies to be enacted. In the case of climate change, for instance, there is growing evidence that there is little, if any, time remaining to meet globally agreed-upon goals (Pfeiffer et al. 2016; McGlade and Ekins, 2015) and thus more intervention may be needed.

Should deployment support be technology neutral? The use of *technology-neutral* policies—a standard recommendation of economists—focuses attention on the lowest-cost alternative to meet policy goals, which implicitly favors cheaper technologies. If all environmental externalities have been internalized, the cheapest technology is more likely to be an environmentally beneficial technology, assuming no difference in maturity. Because it is very hard, or indeed impossible, for policy to account for all environmental externalities, policymakers should be aware of the *direction* of innovation they are implicitly choosing with a technology-neutral policy. If this direction threatens to cross a so-called "planetary boundary", policies that are more *technology specific* should be considered.

How specific should such support be? In general, no more specific than is required. Consider a renewable energy target aimed at reducing local air pollution, contributing to energy security, and meeting climate objectives. Several policies could be implemented to achieve the target. A "renewable portfolio standard" would leave it to market forces to determine which renewable sources are deployed to meet the target. The renewable energy that is currently cheapest is more likely to be selected, even if this may not be optimal in the long run (Way et al. 2017). However, no one technology will be fully able to meet all future clean energy demands. Thus complementary policies to promote the development of low-emission technologies that are further from the market are needed. Direct deployment subsidies can be targeted to drive the adoption of specific technologies. For example, the California Solar Initiative has successfully deployed solar, and there would be 53 percent fewer solar installations in the region had there been no subsidies (Hughes and Podolefsky 2015). Similarly, feed-in tariffs, which provide payments for generating renewable power, may target specific energy sources. Feed-in tariffs for solar energy in Germany were more than seven times higher than the feed-in tariffs for wind energy at certain times (OECD-EPAU 2013). As a result, innovation efforts in Germany focused on solar, whereas efforts in countries using renewable portfolio standards have tended to favor wind technology (Johnstone, Haščič, and Popp 2010). In short, it remains unclear whether support should be highly specific: on the one hand, it is often successful for the specific technology chosen, but on the other hand, this may not be a cost-optimal use of public funds and can exclude other promising technologies.

## Policy 4: Support Collaborative R&D Arrangements

Successful innovation depends on a firm's ability to integrate external information, knowledge, and technologies into its own innovation process (Cassiman and Veugelers 2002). Some external information and knowledge can be transferred through cooperative arrangements that enable collaborations across firms, between the public and private sectors, or between academia and national laboratories and other sectors of the economy. Such collaborations can bring together complementary skills and resources, either between firms or across the innovation spectrum. For instance, universities and national laboratories provide industry with access to cutting-edge research, while researchers benefit from accessing industrial and business development expertise. Other benefits include reduced transaction costs, technology risks, and R&D costs. In this section we discuss evidence concerning the impacts of collaboration on innovation and how governments can support collaborative R&D.

### Impacts of Collaboration on Innovation

Networks that result from R&D cooperation can help transfer knowledge and drive innovation (Powell, Koput, and Smith-Derr 1996). There is also emerging evidence that collaborative research can produce higher-quality research output, which in turn can translate into innovation. For example, in a study of papers and patents, Wuchty, Jones, and Uzzi (2007) show that teams of researchers tend to produce more highly cited and higher impact outputs than individuals. Popp (2017) finds that for alternative energy technologies, both scientific articles and patents with authors from multiple types of institutions (e.g., university and corporations) are cited more frequently, suggesting that collaborations may have positive impacts on research quality.[11] Furthermore, in a study of government-sponsored research consortia in Japan, Branstetter and Sakakibara (2002) found that consortia research outcomes are positively associated with the level of potential R&D spillovers within the consortium and that consortia focusing on basic research are most effective.[12]

### Supporting Collaborative R&D

Government policies can be used to promote or enhance collaborative R&D. For example, the National Science Foundation's Industry/University Cooperative Research Program (I/UCRP) supports collaborations between universities and industry to tackle engineering challenges. Public funding can also increase the propensity to engage in R&D cooperation agreements, as long as sufficient budgetary support is provided (Segarra-Blasco and Arauzo-Carod 2008). Some countries—such as Belgium, Denmark, Italy, Spain, France, and others—do this by providing R&D tax credits to companies collaborating with a research institute or university (Stepp and Atkinson 2011).

One example of a successful partnership between numerous actors in the U.S. energy sector is the Innovation Incubator ($IN^2$), which supports commercialization of clean energy technologies. $IN^2$ was launched by Wells Fargo and Company and the National Renewable Energy Laboratory (NREL), bringing together external industry stakeholders, research institutes, universities, and industry labs. This partnership is unique because it supports early-stage, middle-stage, and later-stage companies, providing support for accelerated enterprise growth over time (Adams et al. 2016).

## Policy 5: Reduce Barriers to Private Sector Financing

One common constraint on innovation is costly external financing, which discourages private sector investment in R&D (Bond, Harhoff, and van Reenen 2005). Private sector financing for environmentally friendly technologies includes the conventional menu of financing options. Early-stage private financing is often equity based, with angel and seed finance (increasingly including crowdfunding methods) being suitable for embryonic ideas, venture capital being suitable for early-stage technologies, and private equity being suitable for the scale-up phase. Once technologies reach a degree of maturity, debt-based financial options come into play—corporate finance, project finance, green bonds, and other crowd-based financing platforms.

[11]While it could be the case that these collaborations simply expose research to a larger group of people, these results occur even when ignoring self-citations made by the same research organizations, suggesting that this is not the case.

[12]Other studies showing that cooperation is positively associated with increases in firms' research productivity include Veugelers (1997) and Branstetter and Sakakibara (1998).

While it is not the role of government policy to provide private finance to firms, policymakers can carefully monitor the ability of the financial "ecosystem" to provide access to private sector funds for environmentally friendly innovation. By reducing barriers to these various forms of private finance, governments can help to facilitate the later stages of the innovation process. Options include creating tax schemes that target these later stages of innovation (such as the venture capital trusts in the U.K.) and providing patient capital (i.e., capital that does not require a very fast payback period) through low-interest loans.

Furthermore, direct grants can help alleviate barriers to finance. Recent research on small firms in the United States shows that grants to small firms increase a firm's chance of receiving private venture capital investment from 10 percent to 19 percent and nearly doubles the probability of firm survival and successful exit (Howell 2017). The implication for policy is that reallocating support from larger, later-stage grants to more numerous small, early-stage grants to younger firms may achieve better outcomes (Howell 2017) and help smaller firms move new ideas from the initial research stage to technology commercialization.[13]

## Summary and Conclusions

This article has presented and discussed the evidence concerning five policies that governments could use to support environmentally beneficial innovation. We would argue that such policies should be considered in any portfolio of innovation policies aimed at protecting global environmental systems, especially given the urgency of addressing additional pressures on sustainability from climate change risks. Based on our review of these policies and some of the evidence regarding their effectiveness, we recommend that innovation policy prioritize the following actions:

- **Price natural capital properly:** This includes implementing more stringent environmental regulations and policies that address environmental externalities and interventions that increase the prices of dirty products, processes, and services.
- **Support environmentally friendly R&D and innovation and discourage environmentally harmful innovation:** This includes providing R&D tax credits and grants in order to reduce the cost to private sector firms of investing in R&D that promotes sustainability. Government laboratories and research institutes can also be supported to complement private sector R&D, particularly for large capital-intensive research projects. Similarly, removing unnecessary subsidies on fossil fuels will discourage innovation that is environmentally harmful.
- **Support early-stage deployment of clean technologies:** This is especially important when there are additional market failures (e.g., learning spillovers, first-of-a-kind costs) or when the economically optimal interventions under policies 1 and 2 are not possible or will not address the urgency implied by planetary boundaries.
- **Support collaborative R&D:** This entails targeting financial support for R&D activities that specifically bring together multiple entities—such as private sector firms, universities, and national laboratories—to capitalize on complementary skills and resources.

[13]For another example of the impacts of direct subsidy programs to small business, see Lerner (2000).

- **Reduce barriers to external financing:** This includes policies such as corporate tax relief that rewards investments in clean innovation activities and helps high-risk companies raise funds not only for early-stage R&D but also for companies engaged in the later stages of innovation.

This list of policy recommendations is not intended to be exhaustive. We considered several other policies and government interventions aimed at promoting innovative activity and outputs, but these did not make it into our top five list. These policies include creating intellectual property and patent laws that protect environmentally friendly innovators and do not stifle innovation, setting migration and employment policies that make it easier to hire and retain talent across borders, and implementing technology performance standards that require operational improvements.

As we have discussed, the policies we have focused on here are already implemented—in various combinations and forms—in many countries around the world, although with varying degrees of success. It is therefore important for policymakers to consider evidence-based best practices and policy designs in the context of their policy objectives. For example, when considering policy options for pricing natural capital, a wide array of instruments is available. The theoretical literature evaluating their effectiveness suggests that market-based instruments provide stronger incentives for innovation relative to mandates for specific technologies or performance standards and that auctioned emissions permits and emissions taxes more effectively encourage innovation than freely allocated permits (Dechezleprêtre and Popp 2017; Milliman and Prince 1989; Fischer, Parry, and Pizer 2003; Parry, Pizer, and Fischer 2003), but the empirical evidence is less conclusive in regards to ranking.[14] Similarly, when providing support for R&D, policymakers should assess whether tax credits or direct grants are most appropriate for achieving their objectives, and also consider whether they can target specific types of innovative activity.

Ultimately the appropriate mix of policies for driving innovation depends on the policy, economic, and social context and the relative intensity of market failures therein—particularly those related to knowledge and environmental spillovers. Although the literature concerning the effectiveness of the policy tools discussed here is growing, more research is needed on the effectiveness of innovation policy, in particular identifying mechanisms that can promote environmentally friendly innovations rather than environmentally harmful innovations, understanding how these policies impact innovation outcomes (i.e., output additionality), and considering how innovation policies interact.

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[14]For instance, innovation activity actually decreased when permit trading replaced command-and-control regulation under the 1990 U.S. Clean Air Act Amendments, but became more focused on reducing emissions rather than just lowering compliance costs (Popp 2003).

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