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Promoting Clean Energy Innovation

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Meeting today's most ambitious climate policy goals, such as the European Union's plans to reduce emissions by 40 percent below 1990 levels by 2030 or California's goal to rely solely on zero-emission energy sources by 2045, requires replacing vast amounts of fossil fuel energy sources with alternative, carbon-free energy sources. While innovation over the past decades helped reduce the cost of wind and solar energy, many technical challenges remain, such as low-cost battery storage, both for intermittent energy sources and to bring down the cost of electric vehicles.

Well-designed climate and energy policies facilitate these technological advances. Regulatory pressures spur firms to develop new and better ways to improve environmental performance. Understanding how policy promotes clean energy innovation involves the study of what economists have termed "market failures," meaning that market forces alone will not lead to optimal allocation of resources. Two market failures are particularly relevant to energy and environmental technology:

- **The Economics of Pollution:** Because pollution is not priced by the market, firms and consumers have little incentive to reduce emissions without policy intervention. The market for technologies that reduce emissions will otherwise be limited, further slowing commercialization and reducing incentives to develop such technologies. Policies addressing these environmental externalities increase the potential market size for clean energy innovation, and are often referred to as *demand-pull* policies in the literature.
- **The Economics of Knowledge:** At the same time, the "public good" nature of knowledge creates spillovers that benefit the public as a whole, but not the innovator. Because they do not reap the rewards of these spillovers, potential innovators do less research than would otherwise be desirable, even if environmental policies to address externalities are in place. Science policy to support research performed in both the private and the public sectors helps bridge this gap. Examples include direct government funding of research projects and indirect support such as tax credits for private-sector research and development. Policies addressing knowledge market failures are often referred to as *technology-push* policies.

These two market failures could, in principle, be addressed separately. Since knowledge market failures apply generally across technologies, economy-wide policies affecting all types of innovation could address knowledge market failures, leaving it to environmental policy to "get the prices right" to encourage green innovation. A carbon tax exemplifies the economist's goal of "getting prices right" by putting a price on emissions related to climate change. However, recent evidence suggests that such broad policy strokes are not enough to promote clean energy innovation.

In addition to broad-based policies such as carbon taxes or cap-and-trade, which target all greenhouse gas emissions, governments use a variety of targeted policies to promote clean energy and reduce emissions. Examples include fuel economy standards for vehicles, renewable energy mandates, and tax incentives for purchasing rooftop solar photovoltaic equipment. Whether targeted or broad-based, policies to promote clean energy can be classified as *technology-neutral* or *technology-specific*. Technology-neutral policies provide broad mandates, but leave it to consumers and firms to decide how to comply. Examples include a carbon tax, which targets all emissions equally, as well as more focused policies such as renewable energy mandates. Such mandates require that utilities generate a set proportion of electricity from renewable energy, but do not dictate what types of renewable sources be used. Technology-specific policies stipulate the use of individual technologies. For example, tax credits for electric vehicles or rooftop solar energy are available only to consumers who purchase these products. Feed-in tariffs for solar energy in Germany were more than seven times higher than the feed-in tariffs for wind energy, thus encouraging investment in solar energy (OECD-EPAU 2013). Below, I review the evidence on how both broad-based and targeted policies shape the pace and direction of clean energy innovation, and I discuss the implications of this literature for climate and energy policy.[1]

INNOVATION FROM BROAD-BASED POLICIES

I first present evidence on innovation resulting from market forces such as higher energy prices or from broad-based policies. Most technological solutions to reduce climate emissions address the energy sector through one of two mechanisms: providing cleaner energy resources or improving energy efficiency. Understanding how the private sector will innovate on these technological areas *without* targeted support is important for understanding when targeted support will be most effective. Three key lessons emerge.

First, higher energy prices encourage innovation on alternative energy sources and on some energy efficiency technologies. Over the long term, a 10 percent increase in energy prices leads to a 3.5 percent rise in the number of US patents in 11 different alternative energy and energy efficiency technologies (Popp 2002). Most of the response occurs quickly after a change in energy prices, with an average lag between an energy

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[1] Popp (2019) provides a more extensive review of this literature.

price change and patenting activity of 3.71 years. Verdolini and Galeotti (2011) find similar results using a multi-country sample from 1975 to 2000. Similarly, when facing higher fuel prices, firms in the automotive industry produce more innovations on clean technologies, such as electric and hybrid cars, and less in fossil fuel technologies that improve internal combustion engines (Aghion et al. 2016). A 10 percent higher fuel price is associated with about 10 percent more low-emission energy patents and 7 percent fewer fossil fuel patents.

Second, prices alone do not encourage sufficient energy efficiency innovation. There are incentives to develop and deploy energy efficient technologies even without climate policy in place, as improving energy efficiency not only reduces emissions, but also lowers costs. However, because reduced emissions are an external benefit, environmental market failures mean that individuals will not consider the social benefits of using technologies that reduce emissions, leading them to underinvest in energy efficient technologies. Thus, energy efficiency standards also help spur innovation. Using the relationship between fuel efficiency and vehicle characteristics to infer rates of technological progress, Knittel (2011) finds that fuel economy regulations have a positive effect on observed technological progress for cars, but not for trucks. The effect of energy prices on energy efficiency innovation is also limited by their saliency. While studies on the auto industry and on renewable energy find that higher energy prices spur innovation, energy prices are less effective for promoting innovation on home energy efficiency. Prices are particularly ineffective for inducing innovation on less visible technologies such as insulation that are installed by builders and are not easily modified. Instead, building code changes induce innovation for home energy efficiency (Noailly, 2012).

A third key lesson is that even the choice of broad-based policies focusing on overall emissions (e.g. a carbon tax) or on technology-neutral goals (e.g. renewable energy mandates) implicitly favors some technologies over others. Technology-neutral policies promote technologies closest to being competitive in the market without policy support. Johnstone et al.’s (2010) study of renewable energy innovation is an example. Because wind energy was the closest to being competitive with traditional energy sources at the time of this study, innovation in countries with mandates to provide alternative energy focused on wind. In contrast, direct investment incentives such as feed-in tariffs supported innovation in solar and waste-to-energy technologies. These technologies were less competitive with traditional energy technologies and required the guaranteed revenue from a feed-in tariff to compete.

These results suggest particular challenges to policymakers who wish to encourage long-term innovation for technologies that have yet to approach market competitiveness. Using technology-neutral policies that let markets “pick winners” leads to lower compliance costs in the short term, as firms choose the lowest-cost short-term strategy. However, the policy choice to let the market decide also implicitly “picks a winner.” Because firms will focus on those technologies closest to the market, broad-based market policies and technology-neutral targeted policies provide less incentive to develop technologies with longer-term research needs, such as offshore wind energy. Because no one technology will be fully able to meet all energy demands, complementary policies to promote the development of low-emission technologies further from the market are also needed. These policies will often target specific technologies.

WHEN SHOULD POLICY TARGET SPECIFIC TECHNOLOGIES?

Recent theoretical work suggests that other market failures may require governments to support specific technologies – particularly those furthest from the market. Such market failures include learning-by-doing, path dependency, and capital market failures (Acemoglu et al. 2016, Fischer et al. 2017, Lehmann and Söderholm 2018). Both learning-by-doing and path dependency justify technology-specific deployment policies such as feed-in tariffs or tax credits – most notably when the resulting cost reductions benefit not only early adopters, but also those who wait to adopt until costs fall (e.g. Lehmann and Söderholm 2018). However, the existing literature on learning-by-doing generally suggests that the benefits of learning-by-doing are not sufficient to justify current levels of deployment subsidies (e.g., Nemet 2012; Fischer et al. 2017; Tang 2018). Empirical evidence on path dependency is slim. Path dependency creates a market failure if switching costs make it difficult for firms previously investing in one type of technology to switch to profitable opportunities in another. While some recent studies find evidence of path dependency in energy innovation (e.g., Aghion et al. 2016; Stucki and Woerter 2017), none of these studies tests whether the observed path dependency results from high switching costs or are simply a reaction to better research opportunities. More research on the relationship between switching costs and path dependency is needed.

In contrast, the evidence on capital market failures for energy is limited but suggestive of such market failures. In an evaluation of the US Department of Energy Small Business Innovation Research (SBIR) program, Howell (2017) provides evidence that early financing helps overcome capital market failures in clean energy. SBIR grants improve the performance of new clean energy firms, but are ineffective for older technologies such as coal, natural gas, and biofuels. Similarly, Popp (2017) provides evidence that bringing new energy technologies to market takes longer in clean energy than in other fields (e.g., Branstattter and Ogura 2005; Finardi 2011), suggesting that the length of time necessary for commercialization of energy R&D creates a barrier to raising private sector financial support. Finally, both Mowrey et al. (2010) and Weyant (2011) argue that government research helps new energy technologies overcome roadblocks to commercialization. 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 et al. 2010). Palage et al. (2019a) find supporting evidence, showing that advanced biofuel patenting increases after investments in demonstration projects in EU countries. While more research is needed, the evidence to date suggests a need for policies that help bridge the gap between laboratory research and commercial success.

THE EFFECTIVENESS OF GOVERNMENT R&D

The market failures above are addressed using policies that focus on deployment, which induce innovation by creating new markets for renewable energy. These policies do not address market failures affecting the supply of innovation. High social returns to R&D justify government research investment. However, this is true for all technologies, not just clean energy. Thus, an important question becomes whether spillovers from green innovation are larger, so that government R&D should play a larger role for cleaner technologies. Several recent papers use patent citations to study spillovers from energy innovations. Citations received by a patent indicate that the knowledge represented in the patent was utilized in a subsequent invention, providing evidence of potential knowledge spillovers. These studies generally provide support for a larger role for government-funded clean energy R&D, particularly for technologies that are still emerging. Both Dechezleprêtre et al. (2017) and Popp and Newell (2012) find that clean energy R&D generates large spillovers, comparable to spillovers in other emerging fields such as IT or nanotechnology. Noailly and Shestalova (2017) find similar results, but only for younger clean energy technologies. For emerging technologies such as energy storage, spillovers occur across technology domains, making it less likely that private sector inventors can capture the full benefits of these innovations.

The most important and most widely used policy addressing the supply side of clean energy innovation is government R&D funding. To study the effectiveness of public energy research, Popp (2016) links data on scientific publications to public energy R&D funding. The paper provides four key results. First, USD 1 million in additional government R&D funding leads to 1–2 additional publications, but with lags as long as ten years between initial funding and publication. Second, adjustment costs associated with large increases in research funding are of little concern at current levels of public energy R&D support. These results suggest that there is room to expand public R&D budgets for renewable energy, but that the impact of any such expansion may not be realized for several years. Third, factors found to influence private R&D activity in other papers, such as energy prices and policy, have little impact on publications, suggesting that current R&D funding efforts do appear to support different types of research than generated by the private sector. Finally, since the ultimate goal of government energy R&D funding is not an article, but rather a new technology, Popp uses citations from patents to scientific literature to link these articles to new energy patents. While public funding does lead to new articles, lags in both the creation of a new publication and the transfer of this knowledge to applied work mean that public R&D spending may take over a decade to go from a new article to a new patent.

The state of technology development also matters for government R&D effectiveness. Government R&D should focus on technologies furthest from the market. Costantini et al. (2015) compare patenting in conventional first-generation biofuels to patenting in more advanced second-generation biofuels. While technology-push policies do not induce innovation for more mature technologies (e.g. first-generation biofuels), they are important for fostering foster development in emerging, more advanced technologies. Thus, government support for clean energy R&D should focus on emerging technological areas such as energy storage, rather than more established technologies such as onshore wind energy.

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 US National Renewable Energy Laboratory). Such institutions have proven to be particularly valuable for promoting innovation in clean energy. Clean energy patents assigned to governments are more likely to be cited than clean energy patents from other institutions, signaling higher quality and highlighting the value of research performed at government institutions (Popp 2017). 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 linking basic and applied research. Collaborations across institutions also promote technology transfer. For clean energy technologies, both scientific articles and patents with authors from multiple types of institutions (e.g., universities and corporations) are cited more frequently, suggesting that collaborations across institutions enhance research quality (Popp 2017). These examples highlight the role of government R&D projects and laboratories in aiding the commercialization of new technologies, often referred to as "technology transfer."

Finally, it is important to remember that R&D subsidies address the supply of clean energy technology, but do not create demand for new technology. In a study of solar PV patent data from 13 European countries from 1978 to 2008, Palage et al. (2019b) find that public R&D support for solar PV innovation induces more private sector patenting when accompanied by a feed-in tariff. Their result emphasizes that public R&D can complement demand-pull polices to enhance innovation, but it is not a substitute for policies that create demand for clean technology.

INNOVATION IN A GLOBAL ECONOMY

Climate change is a global problem. Innovators partake in global markets and are influenced by regulation not only at home, but in other countries where they do business. Two recent studies compare the effect of domestic and foreign environmental policy for renewable energy. Dechezleprêtre and Glachant (2014) compare wind energy patents across OECD countries, using data from 1991 to 2008. Their observations are country pairs, as they look at both the source (i.e., where patents are filed from) and destination (i.e., where patents are granted) of invention. While both domestic and foreign demand-pull renewable policies positively affect renewable technology innovation, the marginal effect of policies implemented at home is 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. Both trade barriers and weak intellectual property rights dampen the influence of foreign policies on wind energy patenting in any given country. In a study of 15 OECD countries using patent data from 1978 to 2005, Peters et al. (2012) also find both domestic and foreign demand-pull policies (such as renewable portfolio standards or feed-in tariffs) are important for the development of solar PV technology. However, technology-push policies such as R&D subsidies increase only domestic innovation.

Fabrizio et al. (2017) compare the effect of policy on domestic and foreign innovation for energy storage. Unlike the aforementioned papers, their sample includes patents from countries that do not directly regulate energy storage, as they combine data on energy storage policies in 11 OECD countries from 1990 to 2011 with data on energy storage patents from 61 countries during the same time frame. Demand-pull polices both promote domestic innovation and increase technology transfer coming into the country, measured as domestic patent applications filed for technologies that originally filed for patent protection elsewhere. Thus, increased innovation from environmental policy may come from abroad. In contrast, technology-push policies promote domestic innovation, but do not increase technology transfer.

Given the international nature of innovation, Stucki and Woerter (2017) ask whether technological followers might benefit from a “wait-and-see” strategy whereby they wait for knowledge spillovers to close the gap between themselves and technology leaders. By waiting, countries could avoid locking in early higher-cost green technology inventions. Focusing on the technology gap between technology leaders and other nations, they find that while knowledge spillovers from abroad enhance innovation in follower countries, they do not enable late movers to catch up to technology leaders. A wait-and-see strategy does not appear beneficial.

Finally, the global distribution of R&D expenditures is changing. By 2015, OECD nations’ share of global R&D fell to 65 percent. China alone performed 21 percent of global R&D. Only the US, with 26 percent, performed more (National Science Board 2018). As such, it is important to understand the drivers and impact of environmental R&D from emerging economies. In recent years, researchers have begun to assess environmental innovation in emerging economies, particularly in China.

Lam *et al.* (2017) use patent citation data to study the quality of wind innovation in China. During the 2000s, China dramatically increased the deployment of wind energy, so that by 2012 it had the most installed wind capacity of any country. Similarly, the number of Chinese wind energy patents awarded to domestic firms increased dramatically during this time period. However, few of these patents were of sufficient quality to be awarded protection abroad, and Chinese wind energy patents are cited less frequently than patents from other countries. Thus, while China’s wind energy innovation grew rapidly in the 2000s, its impact has yet to spread to other nations.

Given the dramatic increase in Chinese wind energy deployment, several studies use learning curves to look for evidence of technological progress. Tang and Popp (2016) consider the role of knowledge spillovers, using data on the projected costs of wind projects financed through the Clean Development Mechanism (CDM). Wind project developers benefit from their past experiences with both wind farm installation and wind power generation. More importantly, previous collaborative experience between a project developer and foreign turbine manufacturer leads to both the greatest reduction in project costs and the greatest improvement in productivity. Joint learning occurs between partners during interactions on wind farm installations, and the CDM helped achieve this goal by encouraging collaboration between project developers and foreign turbine manufacturers.

Hayashi et al. (2018) update the work of Tang and Popp using actual, rather than predicted, performance of CDM wind turbines. They find less evidence of learning when using actual performance data. Comparing the productivity of wind turbines in China and the US, Huenteler et al. (2018) offer several reasons for poor performance of wind energy in China, including delays in grid connection, curtailment of energy due to grid management, and suboptimal turbine selection and wind farm siting. These last features are locked in for the life of a wind farm, suggesting that it will take time to improve the overall performance of Chinese wind production.

CONCLUSIONS

Recent history provides many successful examples of environmental innovation. Better pollution control technologies, such as catalytic converters for automobiles, led to dramatic reductions in air pollution in the developed world. The costs of clean energy sources such as wind and solar power are now low enough to be competitive with fossil fuel sources, reducing emissions from the electric power sector. While private sector companies created many of these technologies, public support for their research was essential. This support comes in the form of both regulations to create demand for clean technology and public funding of the science underlying new green technologies.

Moving forward, the changing nature of technology suggests greater challenges lie ahead. Continued growth of intermittent renewable energy sources cannot continue without long-term energy storage solutions and smart grid technologies to integrate renewable generation into the grid (IRENA 2017). Breakthrough innovations are imperative if policymakers aim to reduce carbon emissions to near zero in the long term. For example, as the share of electricity generated by intermittent renewable power grows, managing the electric grid becomes more complicated. Advances in energy storage would greatly improve grid management. Energy storage breakthroughs leading to better batteries would also make electric vehicles more attractive to consumers by both reducing costs and increasing vehicle range. Because advances in energy storage could have spillover effects to multiple sectors, public sector R&D is likely to play a more important role in coming years. Similarly, innovation for public infrastructure, such as charging stations for electric vehicles, will also be needed. An important next step for both researchers and policymakers is to better understand the potential role of private vs. public sector innovation in a changing technological environment.

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