THE HAMILTON PROJECT

POLICY PROPOSAL 2019-14 | OCTOBER 2019

Promoting Innovation for Low-Carbon Technologies

David Popp

MISSION STATEMENT

The Hamilton Project seeks to advance America's promise of opportunity, prosperity, and growth.

We believe that today's increasingly competitive global economy demands public policy ideas commensurate with the challenges of the 21st Century. The Project's economic strategy reflects a judgment that long-term prosperity is best achieved by fostering economic growth and broad participation in that growth, by enhancing individual economic security, and by embracing a role for effective government in making needed public investments.

Our strategy calls for combining public investment, a secure social safety net, and fiscal discipline. In that framework, the Project puts forward innovative proposals from leading economic thinkers — based on credible evidence and experience, not ideology or doctrine — to introduce new and effective policy options into the national debate.

The Project is named after Alexander Hamilton, the nation's first Treasury Secretary, who laid the foundation for the modern American economy. Hamilton stood for sound fiscal policy, believed that broad-based opportunity for advancement would drive American economic growth, and recognized that "prudent aids and encouragements on the part of government" are necessary to enhance and guide market forces. The guiding principles of the Project remain consistent with these views.

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BROOKINGS

Abstract

Despite remarkable progress made over the past decade, further innovation is necessary to achieve deep decarbonization of the U.S. economy. Economists consider carbon pricing, either through a carbon tax or an economy-wide cap-and-trade program, a key element of any policy strategy to reduce greenhouse gas (GHG) emissions. However, there is no comprehensive, national-level carbon pricing initiative now, and none is expected in the near future. Moreover, carbon pricing by itself is not enough to bring about breakthrough innovations needed for long-term emission reduction goals. Many remaining challenges involve technologies such as energy storage or improved electricity grid management that are difficult for the private sector to develop on its own. In this paper, I provide policy guidelines for promoting innovation on low-carbon energy technologies, and I review recent evidence on the effectiveness of multiple policy instruments. The proposal begins with advice for targeting government energy research and development (R&D) spending on long-term needs that are less likely to receive private sector support. It then continues with suggestions for targeted deployment policies that would foster clean energy innovation by focusing on technologies in the commercialization stage of innovation. I divide these targeted deployment policies into two categories: (1) those that address innovation market failures and thus complement broad-based carbon pricing, and (2) those likely to be more politically feasible than broad-based carbon pricing, but that could be removed should a sufficiently high carbon price be implemented. I then discuss guidelines for state and local governments.

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Introduction

Promoting innovation is an important part of environmental and energy policy. Regulatory pressures spur firms to develop new and better ways to improve environmental performance. Catalytic converters for automobiles, introduced as a response to U.S. air pollution regulations (Lee et al. 2010), led to dramatic reductions in air pollution in the developed world. As a result, forecasted costs of new environmental regulations often exceed actual costs (Harrington, Morgenstern, and Nelson 2000; Morgenstern 2015). Meeting climate policy goals currently under consideration, such as California's target of relying 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 has helped reduce the cost of wind and solar energy, many technical challenges remain, including low-cost battery storage, in order to make full use of intermittent energy sources and to bring down the cost of electric vehicles.

Economists consider carbon pricing, either through a carbon tax or economy-wide cap-and-trade program, to be a key element of any policy strategy to reduce greenhouse gas (GHG) emissions. However, comprehensive carbon pricing does not exist in the United States and is unlikely to be implemented in the near future. Although a patchwork programs target emissions at the state and regional levels, such as cap-and-trade policies in California or the Regional Greenhouse Gas Initiative in the Northeast, a direct national price on carbon has not been implemented. Even in heavily Democratic Washington State, voters have twice rejected referenda that would have made their state the first to tax GHG emissions. Moreover, carbon pricing by itself is not enough to bring about breakthrough innovations needed for long-term emission reduction goals.

Clean energy innovation suffers from two broad classes of market failures. Carbon pricing directly addresses the first type of market failure: damages caused by carbon pollution that are not experienced by the polluter. But it does not address market failures affecting innovation itself. This second class of market failures includes knowledge spillovers that make it difficult for firms to realize the true social value of their inventions or increasing returns to scale in the energy sector that make energy capital intensive. Demonstrating commercial viability of a new energy production technology requires hundreds of millions of dollars, making it difficult for small start-up firms to enter the industry (Nanda, Younge, and Fleming 2015). Even if a sufficient carbon price existed, complementary policies would still be needed to address market failures such as these.

This paper provides policy guidelines for promoting innovation on low-carbon energy technologies. I discuss how both environmental and knowledge market failures affect clean energy innovation. Because separate policy instruments address different market failures, supporting clean energy innovation requires a portfolio of policy tools. I review recent evidence on the effectiveness of multiple policy instruments and provide policy guidelines for governments that want to promote clean energy innovation. The proposal begins with advice for targeting government energy research and development (R&D) spending on long-term needs that are less likely to receive private sector support. The proposal continues with suggestions for targeted deployment policies that foster clean energy innovation by focusing on technologies in the commercialization stage of innovation. I divide these policies into two categories: (1) those that address innovation market failures and thus complement broad-based carbon pricing and (2) those likely to be more politically feasible than broad-based carbon pricing, but that could be removed should the politics change.

The Challenge

Despite the decision to withdraw from the Paris Agreement, U.S. GHG emissions have been falling. As shown in figure 1, emission levels in 2017 were 13 percent lower than they were in 2005 (U.S. Environmental Protection Agency [EPA] 2018). Several technological advances helped make these reductions possible. Hydraulic fracturing lowered the price of natural gas to the point where natural gas, rather than coal, now generates the larger share of U.S. electricity (figure 2). Falling costs of wind and solar energy improved the competitiveness of these sources of electricity, leading to a rising share of energy coming from renewables. Because of decarbonization in the power sector, transportation—with 28.5 percent of GHG emissions in 2016—was responsible for a higher share of emissions than the electric power sector for the first time (EPA 2018).

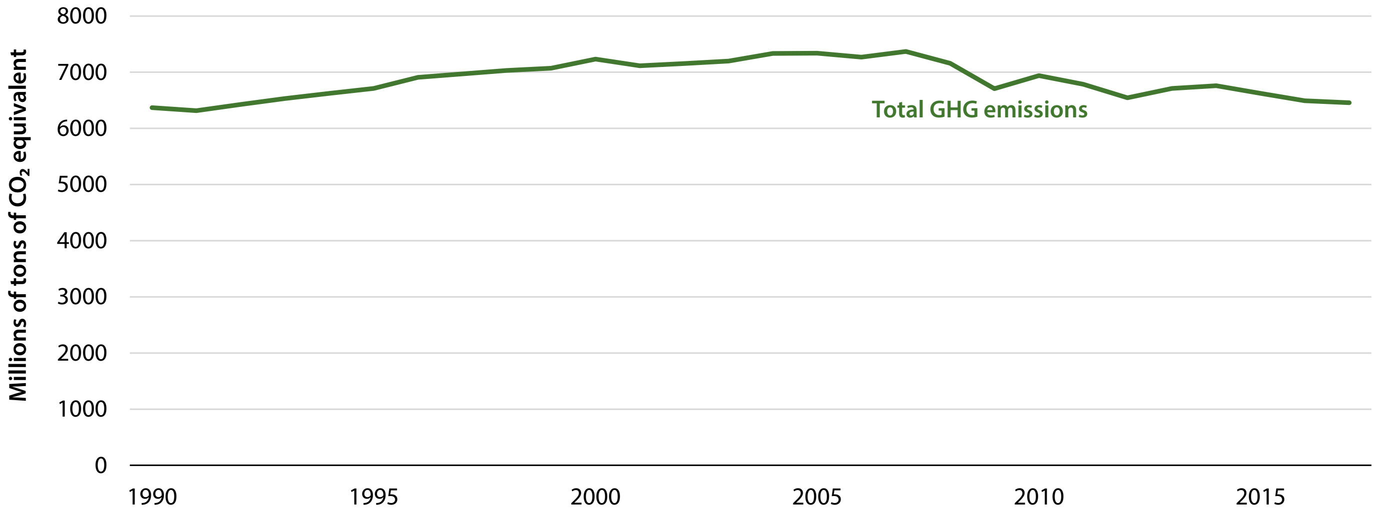
Despite these successes, meeting climate policy goals currently under consideration, such as California's target of relying solely on zero-emission energy sources by 2045 or the proposed Green New Deal's goal of achieving 100 percent zero-emission power sources in 10 years' time, will not be possible without further technological improvement. Many technical challenges remain, and the technological challenges of further reducing GHG emissions will be much greater than the challenges overcome so far (Cunliff 2018). 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 (International Renewable Energy Agency 2017). Within the transportation sector, electric vehicles may help reduce the environmental impact of driving, but will require better battery technology and new charging infrastructure.

Well-designed climate and energy policies can facilitate these technological advances. They are one reason that forecasted costs of new environmental regulations often exceed actual costs (Harrington, Morgenstern, and Nelson 2000; Morgenstern 2015). Moreover, promoting technological change is often a specific goal of environmental policy, such as through support mechanisms like feed-in tariffs that guarantee a minimum price for solar energy or by devoting a portion of funds from carbon taxes to energy R&D programs.

Figure 3 illustrates the importance of continued innovation. As part of a 2017 report (U.S. Department of Energy [DOE] 2017a) on the impact of clean energy technologies, the DOE

FIGURE 1.

U.S. Greenhouse Gas Emissions, 1990–2017

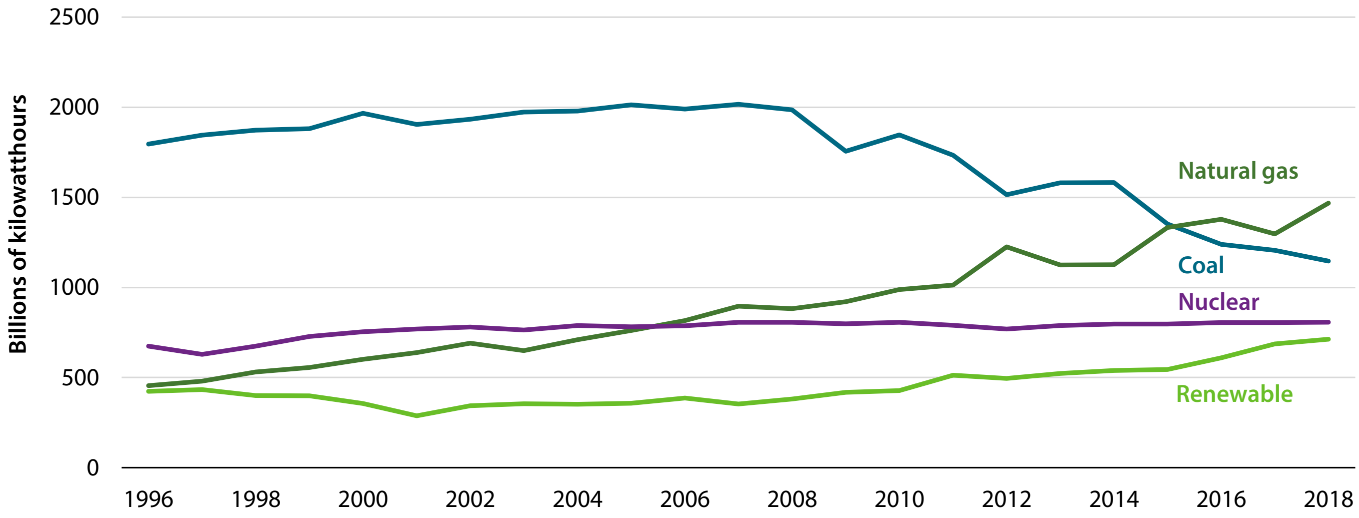


Source: Environmental Protection Agency (EPA) 2018; author's calculations.

Note: Data shows the sum of greenhouse gas emissions for all economic sectors as defined by the EPA.

FIGURE 2.

U.S. Electricity Generation by Fuel Source, 1996–2018

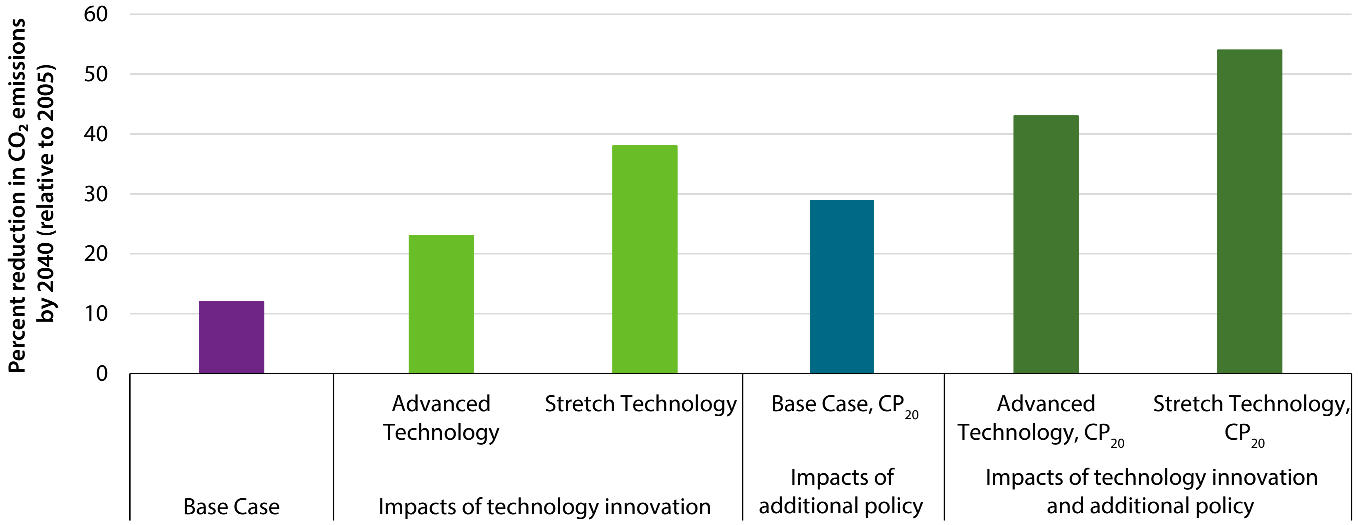


Source: U.S. Energy Information Administration (EIA) 2019; author's calculations.

Note: "Renewable" includes conventional hydropower, wind, wood biomass, waste biomass, geothermal, and solar.

FIGURE 3.

Projected Carbon Dioxide Emissions Reduction in 2040 under Various Technology Scenarios



Source: DOE 2017a.

Note: The figure shows carbon dioxide (CO_2) emissions under various assumptions about technology and policy, as calculated by the DOE. The Base Case projects what would occur under a business-as-usual scenario in which no new technologies emerge and policies remain the same. The Advanced Technology and Stretch Technology scenarios (light green) show the potential of new technology. The Advanced Technology scenario assumes current DOE energy program technological goals are met. The Stretch Technology scenario includes technological improvements from additional R&D pledged as part of Mission Innovation, in which more than 20 countries pledged to double energy R&D investments by 2020. To illustrate the potential effects of carbon pricing, scenarios labeled CP_{20} include a carbon price of $20 per ton (blue and dark green).

projected CO_2 emission reductions through 2040 for different policy and technology assumptions. The Base Case (purple bar) predicts what would occur under a business-as-usual scenario in which no new technologies emerge and policies remain the same. Relative to 2005 levels, emissions fall by 12 percent in this business-as-usual scenario. The Advanced Technology and Stretch Technology scenarios (light green bars) show the potential of new technology. Under the Advanced Technology scenario, which assumes that current DOE energy program technological goals are met, emissions fall by 23 percent.[1] The Stretch Technology scenario includes technological improvements from additional R&D pledged as part of Mission Innovation, in which more than 20 countries pledged to double energy R&D investments by 2020. These technologies alone would cause emissions to fall by 38 percent, even without additional changes to climate policy.

The figure also illustrates the importance of policy. Adding a carbon price of $20 per ton nearly doubles the potential emission reductions, as shown by scenarios labeled CP_{20} in figure 3 (blue and dark green bars). Still, even combining a carbon price of $20 with the technology assumptions of the Stretch Technology case leads to projected emission reductions of only 54 percent by 2040. Both stronger policy and further technological innovation are needed to reach deep decarbonization goals, such as reducing CO_2 emissions by 80 percent or more between 2040 and 2050.

This proposal begins with the premise that while broad-based climate policy such as a carbon tax would encourage clean energy innovation, simply relying on a carbon tax is neither realistic nor sufficient. The current political climate—which includes two rejections of carbon tax referenda in Washington State—makes passage of a national carbon tax in the United States unlikely in the near future. Thus, we must consider other policies to spur the needed innovation to reduce carbon emissions. Importantly, the resulting innovation will not just reduce the costs of further GHG emissions reductions but may also make broader policies such as a carbon price more likely in the future, both by making future policies more affordable and by creating political coalitions in favor of broad-based climate policy (Meckling et al. 2015).

Moreover, as I detail below, even if a carbon price were politically feasible, it is not sufficient to induce the level of innovation necessary to fully achieve climate goals. Although carbon taxes and equivalent policies such as cap-and-trade help get the price right by incorporating the social costs of emissions into energy prices, they still leave it to market forces to decide on which clean energy innovations are most-worth pursuing. Yet many of the breakthroughs needed, such as long-term energy storage solutions or carbon capture and storage, are still a long way from market feasibility (Cunliff 2018) and are unlikely to receive sufficient interest from the private sector even with a carbon tax in place. This lack of market interest is related to failures in the market for innovation, leaving room for targeted policies that could remain in place even if a carbon tax were eventually enacted in the United States.

STAGES OF TECHNOLOGY DEVELOPMENT

Understanding the challenge for energy innovation policy requires an understanding of the stages of technology development. Table 1, based on descriptions in DOE (2017b), describes these stages, including who funds and who performs research at each stage. Technological change begins with research—often categorized as basic or applied—to create new ideas. Basic research seeks to expand knowledge and understand scientific phenomena without any particular use in mind. Applied research also seeks to acquire new knowledge, but is directed toward a "specific, practical aim or objective" (National Science Board 2018, 105). Within the DOE, the Office of Science supports basic research, while technology offices such as the Office of Energy Efficiency and Renewable Energy support applied research. As found in National Science Board (2018), 39.2 percent of R&D funding supports basic research, 36.7 percent applied research, and 24.1 percent goes to development.

However, R&D activities are often more complex than suggested by a simple basic or applied dichotomy, as illustrated by the merged Blurred Boundaries cell at the bottom left in table 1. Applied research may lead to unexpected scientific breakthroughs. For example, during the creation of an improved battery technology, scientists may gain a better understanding of the chemical reactions involved (Goldstein and Narayanamurti 2018). Improved understanding of such basic scientific principles may then inform other research projects, both within and outside the energy domain. The DOE's Advanced Research Projects Agency-Energy (ARPA-E) program was designed to break down such barriers and help bridge the gap between basic and applied research (Goldstein and Narayanamurti 2018).

The ultimate goal of any R&D process is commercialization of a new product. Before commercialization can occur, demonstration projects must show the viability of new technologies. These two processes are often linked, as illustrated by the black arrows in the bottom right of table 1. For example, advances in wind turbines were aided by DOE-sponsored innovation on multiple turbine components, which complemented private sector efforts and allowed for feedback between public sector and private sector researchers (Norberg-Bohm 2000). Such feedback loops are only possible as products are tested in real-world conditions.

Because of the challenges of moving new energy technologies to market, government agencies also provide support for

TABLE 1.

Stages of Technology Development

	Basic Research	Applied Research	Demonstration	Commercialization
Definition	• Seeks to expand knowledge and understand scientific phenomena without any particular use in mind	• Seeks to acquire knowledge directed toward specific aims or objectives	• Demonstrates viability of new technology, either at small-scale or full-scale	• Uses work from previous steps to produce new or improved products or processes
Examples	• New materials • Physics behind better batteries	• Integration of renewables into the electric grid • New batteries	• Carbon capture and storage • Offshore wind	• Fine-tuning wind turbines in response to demonstration projects
Who funds	• DOE (e.g., Office of Science) • Private sector (e.g., Tesla)	• DOE Office of Energy Efficiency and Renewable Energy • Private sector	• DOE • Private sector	• Primarily private sector
Who performs	• Government laboratories • Universities • Private sector	• Government laboratories • Universities • Private sector	• Government laboratories • Private sector	• Private sector
Market failures	• Knowledge spillovers • Path dependency	• Knowledge spillovers • Path dependency	• Capital market failures • Learning by doing	• Externalities • Path dependency • Learning by doing

Blurred Boundaries

- Unexpected scientific breakthroughs from applied research
- Technology transfer barriers may hinder development of new products from scientific breakthroughs

Source: Based on descriptions in U.S. DOE 2017b.

the development stage of R&D. The need for government intervention stems in part from multiple market failures, which are described in greater detail in the next section.

CLEAN ENERGY INNOVATION AND DUAL MARKET FAILURES

As shown in table 1, market failures affect all stages of energy technology development, meaning that market forces alone will not lead to optimal allocation of resources. Properly targeted government policies can correct these market failures, leading to better allocation of resources. Two market failures are particularly relevant to energy and environmental technology: the economics of pollution and the economics of knowledge.

- *The Economics of Pollution*: Because GHG emissions are 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 be limited in the absence of a price or other regulations, 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 but not the innovator. Because they do not reap all the benefits of these spillovers, potentially innovative private firms and individuals perform less research activity than is desirable from society's perspective, even if environmental policies to address externalities are in place. Knowledge spillovers are particularly large during the basic and applied research stages of innovation. 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 R&D. Policies addressing knowledge market failures are often referred to as *technology-push* policies.

These two market failures could require separate solutions. Since knowledge market failures apply generally across technologies, economy-wide policies affecting all types of innovation could in principle address these market failures, leaving it to environmental policy (e.g., a price on carbon emissions) to address environmental externalities. However, recent evidence, discussed below, suggests that such broad policy strokes are not enough to promote clean energy innovation.

In addition to broad-based demand-pull policies such as carbon taxes or cap-and-trade, governments use a variety of targeted demand-pull policies to 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—and whether demand- or supply-focused—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. While a carbon tax is an example of a technology-neutral policy, so are more-targeted policies such as renewable energy mandates. Such mandates require that electric utilities generate a minimum portion of their output 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, the 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 (Organisation for Economic Co-operation and Development [OECD] 2013). Tax credits for electric vehicles or rooftop solar energy are available only to those consumers who purchase these specific products, not to those who purchase other products that limit emissions.

The distinction between technology-neutral and technology-specific support is important. Economists often favor using broad-based technology-neutral policies such as a carbon tax or tradable permits to reduce the price gap between low-emission energy and fossil fuels. Such policies aim to get prices right and leave it to the market to decide which technologies best address the externality. However, even the choice of technology-neutral policy implicitly favors some technologies over others. Technology-neutral policies promote those technologies that are closest to being competitive in the market without policy support. Within renewable energy, policies such as renewable portfolio standards historically favored the development of wind energy (Johnstone, Haščič, and Popp 2010). Of the various alternative energy technologies, wind had the lowest cost and was closest to being competitive with traditional energy sources at the time of this study. When faced with a mandate to provide alternative energy, firms focus their innovative efforts on the technology that is closest to market. Similarly, broad-based policies that target emissions directly, such as a carbon tax, will also increase demand for low-emission energy sources that are closest to market. In contrast, direct investment incentives such as feed-in tariffs supported innovation in solar energy (as in the German example above) and waste-to-energy technologies, which were less competitive with traditional energy technologies and required the guaranteed revenue from a feed-in tariff.

These results suggest particular challenges to policymakers who wish to encourage long-term innovation for technologies that have yet to near market competitiveness. Using technology-neutral policies that let markets pick winners leads to lower compliance costs in the short term because firms choose the lowest cost short-term strategy. However, the policy choice to let the market decide also implicitly picks a winner. Because no one technology will be fully able to meet all energy demands, complementary targeted policies to promote the development of specific low-emission technologies farther from the market are needed in addition to technology-neutral policies.

WHEN SHOULD POLICY TARGET SPECIFIC TECHNOLOGIES?

Recent research provides guidance for when technology-specific policies may be needed. Acemoglu et al. (2016) illustrate the technology-push role of science policy with a model that includes both clean and dirty technologies. Because innovation provides new research opportunities that stimulate future innovations, R&D subsidies help support emerging technologies. Thus, if the clean technology is less technologically advanced than the dirty technology, initial R&D subsidies are needed to make private R&D investments in clean technology profitable. Lehmann and Söderholm (2018) use a model of the electricity sector to illustrate when targeted rather than technology-neutral renewable energy policies are justified. These papers highlight the importance of the following market failures:

- *Learning by doing* (LBD) occurs when the costs to manufacturers or users fall as cumulative output increases (Arrow 1962; Rosenberg 1982). LBD justifies additional deployment policies to hasten technology development, particularly if the resulting cost reductions benefit not only early adopters, but also those who are waiting for costs to fall before they adopt (Lehmann and Söderholm 2018).

- *Path dependency* exists when high costs to switch from one technology to another locks in established technologies. Acemoglu et al. (2016) cite path dependency as one reason why emerging clean technologies cannot compete with more-advanced dirty technologies without R&D subsidies. Network externalities may exacerbate the problem (Lehmann and Söderholm 2018); one example is the difficulty of expanding both electric vehicle usage and charging infrastructure at the same time.

- *Capital market failures,* such as the long timeline from creation to profitability in renewable energy innovations and large fixed costs limit the amount of private capital available for renewable energy. Limited financing may impede the transition of innovations from the laboratory to commercialization, a challenge often described as a Valley of Death. Financial support targeting commercialization may help overcome these hurdles.

Fischer, Preonas, and Newell (2017) provide evidence on the importance of market failures such as these in the U.S. electricity sector. Their model distinguishes conventional from advanced renewable energy sources to capture differences in costs and innovation potential between the two types. Their results suggest governments should supplement broad-based policies with limited subsidies for technologies farthest from the market. These subsides will be most effective if they target other market failures. For example, if LBD is important, the experiences of early entrants will provide lessons for future technology development, suggesting subsidies for emerging technologies would be needed. In contrast, R&D subsidies help lower future costs and are particularly valuable when knowledge spillovers are high. Their simulation results suggest that knowledge spillovers are more important than LBD, such that public R&D spending is more effective than targeted deployment policies. However, current policy efforts favor deployment schemes justified through LBD.

Each of the aforementioned papers highlights cases when targeted support for renewables is justified, either though deployment support or through increased R&D spending. Thus, the appropriate mix of policy instruments depends on the relative importance of each of these market failures. Below I review evidence on each of the four potential knowledge market failures mentioned above: higher spillovers from clean energy R&D, spillovers from LBD, potential capital market failures, and path dependency. Table 1 indicates the stages of innovation where each market failure is most relevant.

Government R&D Spending

High social returns to R&D—relative to both private returns and social costs—justify government research investment. However, this justification is potentially true for all technologies, not just green technologies. So an important question becomes whether spillovers from green innovation are larger than the spillovers from other technologies, such that government R&D should play a *larger* role for green technologies.

Several recent papers use patent citations to study spillovers from energy innovations. Patents contain citations to earlier patents that are related to the current invention. 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. Overall, while the results of studies on knowledge spillovers are somewhat mixed, the bulk of these results provide support for a larger role for government-funded green R&D. Both Dechezleprêtre, Martin, and Mohnen (2017) and Popp and Newell (2012) find that clean-energy R&D generates large spillovers, comparable to spillovers in other emerging fields such as information technology (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 their innovations. In general, these papers suggest that spillovers into other sectors will be largest when technologies are still emerging, so that R&D support is particularly valuable in the early stages of technology development, during the basic and applied stages of research.

Learning by Doing

LBD occurs when the costs to manufacturers or users fall as cumulative output increases (Arrow 1962; Rosenberg 1982). LBD commonly is measured in the form of learning or experience curves that estimate how much unit costs decline as a function of experience or production. Typically, studies on new energy technologies find faster learning for younger technologies, with estimates of unit cost reductions for alternative energy sources such as wind and solar energy clustering around 15–20 percent when experience doubles (McDonald and Schrattenholzer 2001).

However, the simple presence of falling costs over time is not sufficient to justify policy intervention: Simple learning curves have limited ability to demonstrate that experience causes reduced costs (Thompson 2012). A set of papers by Klaassen et al. (2005), Söderholm and Klaassen (2007), and Söderholm and Sundqvist (2007) address this concern by attempting 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 cumulative capacity (LBD) and R&D (learning by searching). Söderholm and Sundqvist carefully separate the effects of the two, finding LBD rates around 5 percent and learning-by-searching rates around 15 percent. Although their results suggest that R&D, rather than LBD, contributes more to cost reductions, the results are very sensitive to the model specification, illustrating the difficulty of sorting through the various channels through which costs may fall over time.

Second, whereas LBD is evidence that early producers of a technology generate knowledge through the production and use of technology, early actors may be able to capitalize on these lessons through a first-mover advantage. Only if the benefits of learning spill over to other producers or consumers should policy subsidize early actors. In such a case, deployment subsidies to hasten commercialization of new technologies are warranted.

Several recent papers develop richer models that identify different channels of learning, providing evidence that many of the benefits from learning can be reaped by innovators, so that external spillovers are small. Using data on wind turbines installed in California between 1982 and 2003, Nemet (2012) finds evidence of both internal learning, in which the benefits of experience stay within the firm, and external learning, where spillovers occur. While such spillovers imply a role for deployment subsidies, learning is subject to diminishing returns and decays quickly. Thus, technology-specific subsidies become ineffective and expensive when they are too large, suggesting that deployment subsidies should be part of a policy mix, but not the only policy instrument chosen. Tang (2018) considers the role of learning from both wind turbine producers and operators, demonstrating that many of the benefits from learning accrue within the innovating firm. Reviewing the performance of U.S. wind farms, operation improves with experience, and these improvements are greater if the wind farm developer collaborates with a single turbine manufacturer. Similarly, a working paper by Bollinger and Gillingham (2014) on installer pricing for solar photovoltaic installations in California finds evidence of both internal and external learning. Using their results to calculate an optimal subsidy for solar photovoltaic technology, they find that the optimal subsidy initially increases to take advantage of learning, but then declines as the LBD externality becomes less relevant. Their results suggest that California's solar photovoltaic subsidy cannot be justified by learning externalities alone.

In sum, recent evidence on LBD provides some evidence of external benefits from learning, but not of a magnitude sufficient to be the only justification for deployment subsidies. Moreover, these externalities can be mitigated through lasting partnerships between suppliers and downstream users of technologies, so that markets can allow firms to capture at least some of the benefits from LBD.

Capital Market Failures

Within the clean energy sector, long time horizons and large fixed costs to energy capital can act as barriers to moving new technologies from the laboratory to commercialization (Mowrey, Nelson, and Martin 2010; Weyant 2011). Such concerns are often described as a Valley of Death. These capital market imperfections impede the transition of innovations from the laboratory to commercialization and may also justify government funding for clean energy innovation.

Overall, the evidence on capital market failures for energy is limited but suggestive of such market failures. The progression from basic research to a commercializable idea is slow, which may deter private investors and firms. Popp (2017) provides evidence of the long time frame needed to bring new energy technologies to market. He uses citations made by patents to earlier scientific publications to trace the evolution from more-basic research represented in a scientific article to a commercializable idea. The probability of a scientific article being referenced by a patent peaks 15 years after article publication (figure 4). This lag is longer than found in studies of other fields (Branstatter 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.

Large fixed costs also serve as a barrier to entry, particularly for smaller firms. In an evaluation of the DOE Small Business Innovation Research (SBIR) program, Howell (2017) provides evidence that early financing helps clean energy technologies overcome financial constraints. SBIR grants improve the performance of new clean energy firms, but are ineffective for older technologies such as coal, natural gas, and biofuels. Similarly, because significant energy innovations typically have disproportionately large capital expenses, collaboration with the public sector can support both initial project development and demonstration projects (Nemet, Zipperer, and Krause 2018). Palage, Lundmark, and Söderholm (2019a) find supporting evidence, showing that advanced biofuel patenting increases after investments in demonstration projects in European Union countries. As a result, government support can help provide financing that moves new ideas from development to commercialization, particularly through the support of demonstration projects to show the viability of new technologies. More research is needed to demonstrate the effectiveness of these investments, however, particularly in demonstration projects.

Path Dependency

Prior investments in dirty energy technologies may make it difficult for markets to transition to clean technologies, due to path dependency. But in contrast to the other market failures discussed, notably fewer empirical studies address path dependency explicitly. Exceptions include Aghion et al. (2016) on the auto industry and Stucki and Woerter (2017) on green innovation, both of which find evidence of path dependency. These papers examine a firm's previous patents on both green and non-green innovation to see how previous research results affect the direction of current research.[2]

Because successful innovation depends on both demand-side and supply-side motivations, the simple finding that innovators follow research paths that appear more promising is not a market failure. 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 (Lehmann and Söderholm 2018). Aghion et al. (2016) conclude their paper with a numerical simulation showing that path dependency creates lock-in for dirty innovation in a world without policies supporting clean technology (such as a carbon tax or R&D subsidy), but that path dependency also reinforces the growth of clean technology once such policies are in place. However, none of the aforementioned research explicitly tests whether the observed path dependency results from high switching costs or if path dependency results are simply a reaction to better research. Given the importance of path dependency as a justification for technology-specific policy interventions, more research on path dependency, particularly connecting path dependency to switching costs, is needed.

Summary

The studies cited above illustrate the importance of market failures justifying technology-specific policy solutions to promote clean energy innovation. In particular, evidence of high social returns to clean energy R&D suggests government R&D investments can complement private sector research. Similarly, evidence of capital market failures suggests a need for policies that help bridge the gap between laboratory research and commercial success. In contrast, mixed evidence on both LBD and path dependency suggests current policy overemphasizes deployment subsidies at the expense of policies to promote innovation and commercialization of new technologies.

EVIDENCE OF THE EFFECTS OF ENERGY POLICIES ON INNOVATION

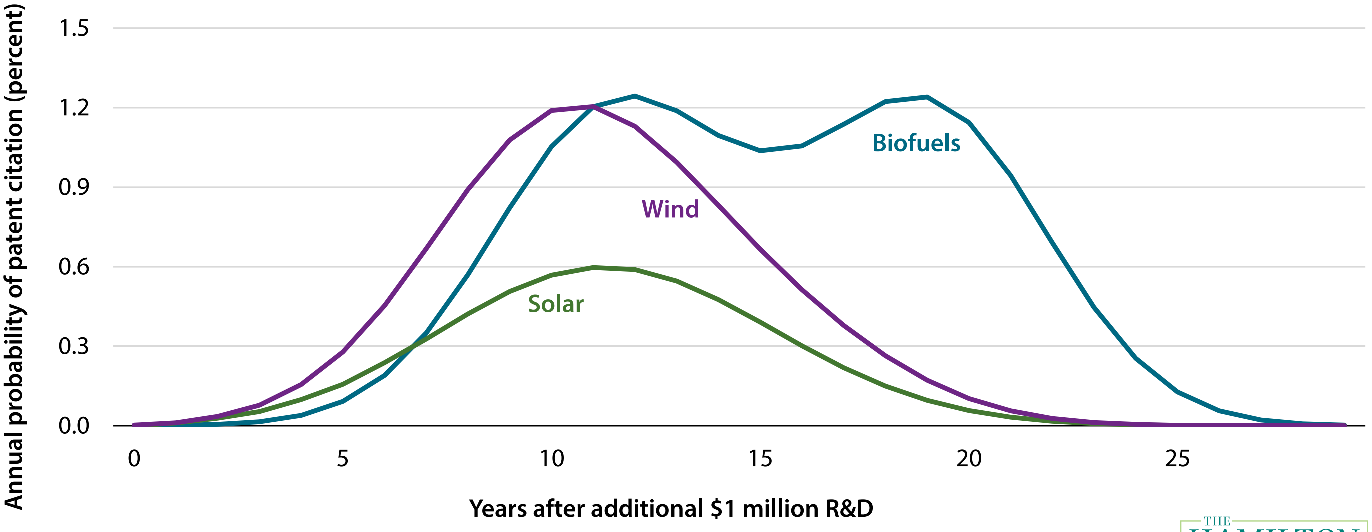
With these lessons in mind, we now turn to evidence on the effectiveness of individual policy instruments. How can governments invest in energy R&D most effectively? When are policies that help bridge the gap between the laboratory and commercial success most effective? What types of energy innovation are private sector firms most likely to do on their own?

Evidence on Broad-Based Energy Policy and Innovation

While the focus of this proposal is on technology-specific policy instruments, I first present evidence on innovation resulting from either market forces (e.g., higher energy prices) or broad-based policies. Most technological solutions to reduce GHG emissions address the energy sector in one of two ways: They provide cleaner energy resources or they improve energy efficiency. Understanding what innovation the private sector will carry out in these technological areas *without* targeted policy support is important for understanding when targeted support will be most effective. Three key lessons emerge.

FIGURE 4.

Annual Probability of Patent Citation from $1 Million of Additional Energy Research and Development



Source: Shambaugh, Nunn, and Portman 2017 based on Popp 2016.

Note: Model estimated using citations to journal articles published between 2000 and 2009.

The first key lesson is that 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 U.S. patents in 11 different alternative energy and energy-efficiency technologies (Popp 2002). Most of this patenting occurs quickly after a change in energy prices, with an average lag between an energy price change and patenting activity of 3.71 years. Verdolini and Galeotti (2011) find similar results using a multicountry sample from 1975 to 2000. When facing higher fuel prices, firms in the automotive industry tend to innovate more in cleaner 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 do not benefit the individual user, individuals will tend to underinvest in energy-efficient technologies without carbon pricing. In the absence of carbon pricing, energy-efficiency standards may also spur innovation. 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 (including carbon pricing) on energy-efficiency innovation is also limited by their saliency. While studies on the automobile industry and on renewable energy find that higher energy prices spur innovation, energy prices are found to be 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 that are not easily modified. Instead, building code changes are necessary to induce innovation for home energy efficiency (Noailly 2012).

A third key lesson, introduced earlier in this chapter, 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, Haščič, and Popp'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. Similarly, broad-based policies that increase energy prices, such as a carbon tax, will also increase demand for low-emission energy sources that are closest to market. Simulating climate policy in the U.S. electricity sector, Fischer, Preonas, and Newell (2017) find that a carbon tax should be supplemented with a wind energy subsidy of only an additional 0.7 cents/kWh but a solar subsidy of nearly 5.0 cents/kWh.

Given the relatively few jurisdictions enacting meaningful carbon pricing, few studies directly consider the effect of innovation from a carbon tax. However, the above studies illustrate that broad-based carbon pricing will encourage private sector innovation. Nonetheless, the presence of additional market failures suggests that broad-based policies will not be sufficient. Thus, it is worth considering how targeted policies may complement broad-based policies and when they will be most effective. I turn to that evidence next.

Evidence on Targeted Energy Policies and Innovation

An important general principle is that targeted policies will direct innovation toward the target, whether or not policymakers actually intended for that to occur. For example, before passage of the 1990 amendments to the 1963 Clean Air Act (1990 CAAA), new power plants were required to install a flue gas desulfurization (FGD) unit capable of removing 90 percent of sulfur dioxide (SO_2). As a result, the innovations that occurred before the 1990 CAAA focused on reducing the cost of FGD units, rather than on improving their environmental performance. The 1990 CAAA introduced permit trading for SO_2, providing potential rewards to firms that exceeded 90 percent removal of SO_2. As a result, 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 (Popp 2003).

Among renewable energy policies, feed-in tariffs best exemplify this principle. As noted earlier, Johnstone, Haščič, and Popp (2010) show that the more-flexible nature of renewable portfolio standards directs innovation toward wind energy, whereas targeted feed-in tariffs were necessary to encourage innovation on solar energy. Gerarden (2018) estimates that, by permanently reducing future costs, innovation induced by German feed-in tariffs increased the benefits of tariff subsidies by at least 22 percent. Reichardt and Rogge (2016) provide a case study of offshore wind innovation in Germany. Their interviewees suggest that feed-in tariffs were the most-important policy supporting offshore wind development. Because offshore wind is more expensive than onshore wind, this finding is consistent with Johnstone, Haščič, and Popp's finding that direct financial support is more important for technologies that are farther from the market.

Subsidies, feed-in tariffs, and renewable energy mandates focus on deployment, and induce innovation by creating new markets for renewable energy. They do not address market failures that affect the supply of innovation. However, targeted policies can complement supply-side innovation policies by creating demand for newly improved technologies. In a study of solar photovoltaic patent data from 13 European countries from 1978 to 2008, Palage, Lundmark, and Söderholm (2019b) find that public R&D support for solar photovoltaic innovation induces more private sector patenting when that support is accompanied by a feed-in tariff. Their result emphasizes that technology-push policies can complement demand-pull policies to enhance innovation, but are not a substitute for demand-pull policies.

Evidence on Government Energy R&D Spending

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. That paper provides four key results: First, $1 million in additional government R&D funding leads to one to two 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 public funding efforts appear to support different types of research than what is generated by the private sector. Finally, since the ultimate goal of government energy R&D funding is not an academic article but rather a new technology, Popp (2016) uses citations from patents to scientific literature to link these articles to new energy patents. Although 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 more than a decade to go from a published article to a new patent.

Technologies farthest from the market are those that benefit the most from public R&D investments. Costantini, Crespi, and Curci (2015) compare patenting in conventional first-generation biofuels to patenting in more-advanced second-generation biofuels.[3] For first-generation biofuels technology, public R&D spending has no effect on the number of related patents generated in a country. However, for more-advanced second-generation biofuels, public R&D plays an important role. Thus, while public R&D is not important for more-mature technologies, it is important for fostering foster development in emerging, more-advanced technologies.

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. Clean energy patents awarded to government entities are more likely to be cited than are clean energy patents awarded to other institutions, signaling patent quality and highlighting the high 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 are similar articles from any other institutions, including universities. This suggests that clean energy research performed at government institutions plays an important role in linking basic and applied research.

Collaborations across institutions further promote this interlinkage. For alternative 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 aiding the commercialization of new technologies, often referred to as technology transfer. Such projects typically combine basic and applied research and are often done through government-industry partnerships (Wolfe 2008). 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 (Jaffe and Trajtenberg 1996; Trajtenberg, Henderson, and Jaffe 1997). Mowrey, Nelson, and Martin (2010) and Weyant (2011) argue that this difference in quality stems from the roadblocks to commercialization faced by new energy technologies, as described above in the discussion on capital market failures.

Moving Forward: A Role for State and Local Governments

A final challenge is presented by the current political climate. While proposals such as the Green New Deal have made climate change a prominent campaign issue, national climate policy initiatives are unlikely without bipartisan support. As a result, state and local governments are filling the void: 24 states have pledged to reduce GHG emissions by amounts consistent with the Paris agreement (United States Climate Alliance 2019). Cap-and-trade policies in California and the Northeast cover a substantial part of the population, and 29 states and the District of Columbia use renewable portfolio standards to promote clean energy.

How might these state efforts affect innovation? Fu et al. (2018) compare wind innovation across U.S. states. They consider both the effect of own-state policies and policies in other states and find that overall demand for wind within the country—rather than in any particular state—drives innovation.[4] As more states adopt renewable portfolio standards, wind innovation will increase throughout the United States. In fact, one of the states with the most wind patent activity, South Carolina, generates little energy from wind and has no renewable energy mandate, suggesting that other factors such as lower taxes or lower labor costs also influence where innovation takes place. Thus, while additional state renewable energy policies are likely to encourage more innovation, politicians should be aware that such innovation may not occur in their own states, and will not necessarily make the state a leader in the development of renewable energy technology.

Studies examining the effects of regulation across *countries* find similar results. Peters et al. (2012) find both domestic and foreign demand-pull policies (such as renewable portfolio standards) are important for the development of solar photovoltaic technology, but that technology-push policies such as R&D subsidies affect only domestic innovation. Dechezleprêtre and Glachant (2014) compare wind energy patents across OECD countries. Because foreign markets are much larger than domestic markets 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. One key difference between these studies and the state-level work is that local policies are more important when comparing regulation across countries, rather than across subnational jurisdictions. Across countries, trade barriers diminish the influence of foreign environmental policy on local innovation (Dechezleprêtre and Glachant 2014).

Summary

The empirical evidence on policy-induced innovation provides several key lessons:

- Both higher energy prices and broad-based policies such as carbon taxes will encourage private sector innovation.
- Targeted demand-side policies should focus on technologies underserved by broad-based policies because there are other market failures. Home energy efficiency and higher-cost renewables such as offshore wind are examples.
- There is room to increase government R&D investments in clean energy, because there is little evidence of diminishing returns at current funding levels. However, policymakers must be patient, since the benefits from these innovations can take years to realize.
- To avoid duplicating private R&D efforts, government R&D financing should focus on technologies farthest from market competitiveness.
- Government R&D policy can also facilitate technology transfer, both across institutions and within research networks.
- Innovators care about overall market demand. State and local policies increase deployment of clean energy, but will not necessarily help localities become leaders in the development of clean energy technology.

The Proposal

As shown in The Challenge, there is no silver-bullet policy to promote the many types of innovation necessary to meet the climate challenge. Policy support for energy innovation includes both *demand-side* policies that increase potential market size for innovation and *supply-side* policies that address market failures hindering the development of new knowledge more broadly. Demand-side policies have an important role to play: Much of the innovation successfully lowering the costs of wind and solar power occurred in the private sector, driven in part by demand-side policies that increase the use of new energy sources, such as renewable energy mandates, energy taxes, or adoption subsidies (Gerarden 2018; Johnstone, Haščič, and Popp 2010; Peters et al. 2012). However, demand-side policies are most useful for technologies that are almost market-ready (Johnstone, Haščič, and Popp 2010). Even if a national carbon tax or cap-and-trade policy were politically feasible, supply-side policies would still be necessary as a means of promoting breakthrough innovation.

Breakthrough innovations are imperative if policymakers aim to reduce carbon emissions to near zero in the long term. Roughly 50 to 70 percent of emissions from the power sector could be eliminated using currently available technologies (Cunliff 2018). Getting to 100 percent requires replacing coal and natural gas with dispatchable (i.e., adjustable on demand as conditions change) zero-emission energy sources. This may include fossil-based energy, such as coal plants with carbon capture and storage. It may also include improved energy storage that makes it possible to control when energy generated from wind and solar is used on the grid. In the transportation sector, electric vehicles offer promise for reducing emissions, but the batteries currently available are unlikely to meet the needs of long-distance road transport (Cunliff 2018).

Faced with these technological challenges, this proposal begins with advice for targeting government energy R&D spending on long-term needs that are less likely to receive private sector support, but that hold the promise of larger benefits over time. Such spending complements both broad-based carbon pricing and the more-targeted policies (e.g., renewable energy targets) currently in place, and should continue even if the United States eventually moves to a national carbon-pricing scheme. Conversely, the research also makes clear that R&D is not a panacea and should be used in combination with other energy policies. While public energy R&D funding can aid the development of clean energy technologies, in many cases it will not be sufficient to reduce private costs below those of other technologies, necessitating additional incentives to encourage the adoption of clean energy. Simulations of energy and climate policy show that both broad-based policies such as carbon taxes or targeted policies such as renewable energy targets or feed-in tariffs (which ensure a minimum price for clean energy) will do more to incentivize the use of clean energy than will energy R&D subsidies. Thus, I propose targeted deployment policies that foster clean energy innovation by focusing on technologies in the commercialization stage of innovation. I divide these policies into two categories: (1) those that address innovation market failures and thus complement broad-based carbon pricing, and (2) those likely to be more politically feasible than broad-based carbon pricing, but that could be removed should a sufficiently high price be implemented. Based on a review of the evidence presented above, I provide the following recommendations for federal innovation policy:

- Restore progress toward Mission Innovation goals.
- Phase in spending increases over a four-year period.
- Emphasize high-risk, high-reward opportunities that are unlikely to receive private sector support.
- Emphasize applied research on public good infrastructure that are unlikely to receive private sector support.
- Be patient evaluating project outcomes, but be willing to adjust decisions over time.
- Enhance opportunities for technology transfer through DOE laboratories.
- Ensure targeted technology support policies address at least one important market failure.
- Complement technology-specific deployment policies with technology-neutral policies at the broadest level possible until broad-based carbon pricing is in place.

GUIDELINES FOR GOVERNMENT ENERGY R&D SPENDING

Determining how much to spend on public energy R&D requires an interdisciplinary approach. While engineers are better suited to determine which projects are most deserving from a technical standpoint, economists can provide guidelines as to how funding increases can be implemented and how funds should be allocated given the technical merits of different projects. Thus, I focus on guidelines for properly selecting technologies to support, rather than suggesting specific R&D funding goals. At current levels of investment, there is little evidence that the effectiveness of public energy R&D falls after large increases, suggesting that there is room for government energy R&D budgets to expand. Given the need for a diversified energy portfolio to address climate change, it is unlikely that there would not be enough deserving technologies to support if research funding levels were to increase. However, there may be constraints on investment related to the limited pool of scientists and engineers currently available to work on energy projects, and how quickly this pool can grow.

Recommendation 1: Restore progress toward Mission Innovation goals.

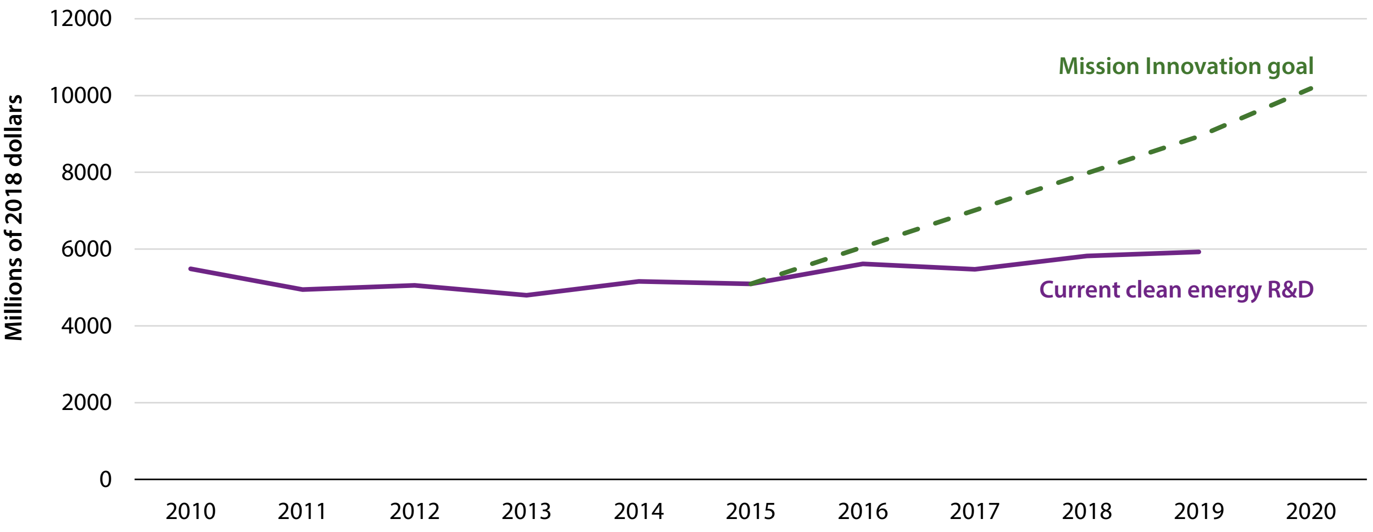
During the December 2015 Paris climate meetings, a coalition of governments—including the United States—created Mission Innovation, which is a global initiative to accelerate global clean energy research. The 25 members—currently 24 countries and the EU—pledged to double their renewable energy R&D budgets by the end of 2020 (Sanchez and Sivaram 2017). Overall, Mission Innovation members increased public sector clean energy investment by 55 percent through 2018, leaving them on track to meet the goal of a 100 percent increase by the end of 2020 (Mission Innovation 2019). However, clean energy investments in the United States have not kept pace. While Congress has resisted attempts by the Trump administration to reduce clean energy R&D, there have been only modest annual increases to the DOE clean energy R&D budget since 2015 (figure 5).[5] Current clean energy R&D funding is just two-thirds of what would be needed to meet the Mission Innovation target. The United States should recommit to doubling clean energy R&D.

Recommendation 2: Phase in spending increases over a four-year period.

Long-term sustained research support is more effective than short bursts. The ability of research infrastructure to absorb large sudden increases in funding is limited, suggesting that steady incremental increases in funding will be more effective, as illustrated by the evidence of significant adjustment costs faced by researchers when National Institutes of Health budgets were quickly doubled from 1998 to 2003 (Freeman and Van Reenan 2009). Similarly, Popp et al. (2013) provide evidence that energy research success is the culmination of several advances building on one another, rather than resulting from one single breakthrough. Wind energy provides one such example (Dykes 2010a, 2010b). Rather than experiencing a single breakthrough invention, the success of wind energy resulted from a series of successful innovations that built on the most-recent major improvement. At each

FIGURE 5.

Current U.S. Clean Energy Research and Development vs. Mission Innovation Goals, 2010–20



Source: Gallagher and Anadon 2018; U.S. DOE 2019; author's calculations.

Note: Figures are in millions of 2018 USD. "Current Clean energy R&D" includes DOE spending on basic energy sciences, carbon sequestration, energy efficiency, hydrogen energy, renewable energy, electricity transmission and distribution, nuclear, and ARPA-E. "Mission Innovation Goal" shows the path needed to achieve a doubling of clean energy R&D by 2020.

step, innovations such as variable speed, improved power electronics, better materials for rotors, and the ability to feather rotors required success of the previous innovation. Combined, these illustrate the need for steady, continuous support for clean energy research. Thus, restoring progress toward the goal of doubling energy R&D investment cannot be done in a single year, but should be committed to over the next four years.

Recommendation 3: Emphasize high-risk, high-reward opportunities that are unlikely to receive private sector support.

Funding efforts must continue to emphasize novel research that would not otherwise take place. Although Popp (2016) suggests that current energy R&D funding efforts do appear to support different types of research than what is performed in the private sector, earlier studies find instances where government energy R&D crowds out private R&D efforts, particularly when the government targets applied research topics (Popp 2002). Government R&D will continue to be most effective if it focuses on breakthrough technologies that are not yet close to market. Although potential short-term payoffs may be low, these technologies have potential for large long-term payoffs if successful, but their payoff is less certain.

However, the government should not simply invest in all high-risk, high-cost technologies. Rather, the key is to identify high-risk, high-reward technologies. A simple risk-reward analogy illustrates this principle. Suppose an investor sets a goal of a 10 percent return on an R&D portfolio. A portfolio with two equally costly projects, both with a 50-50 chance of success, yields an expected 10 percent return if each individual project has a projected 20 percent return if successful. A portfolio with 10 high-risk research projects, only one of which is expected to succeed, yields only a 10 percent return if each individual project has a projected 100 percent return if successful.

In a situation where failure is more likely than success, but the successes will have great social value, government can diversify its R&D portfolio (and bear the costs of failures) more easily than could 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 past two decades (National Research Council 2001). Using both estimates of overall return and case studies, the report concluded that there were only a handful of programs that proved highly valuable. The report's estimates of returns suggest, however, that the benefits of these successes justified the overall portfolio investment. Uncertain returns also suggest that government research portfolios should be diversified, rather than trying to pick winning technologies at early stages of development.

What principles should administrators use to identify high-risk, high-reward projects? Such projects will often be more basic, because successful basic research can provide the building blocks for a multitude of future technologies. Funding levels for basic energy sciences at the DOE have fallen since 2016.[6] Increasing spending on basic energy sciences should be a priority when recommitting to Mission Innovation investments.

Applied research may also provide potentially large payoffs, too. Such applied research should not simply produce incremental improvements to existing technologies (e.g., reducing the cost of solar panels by 10 percent), but rather should also offer the opportunity to replace or change the way existing technologies are used.

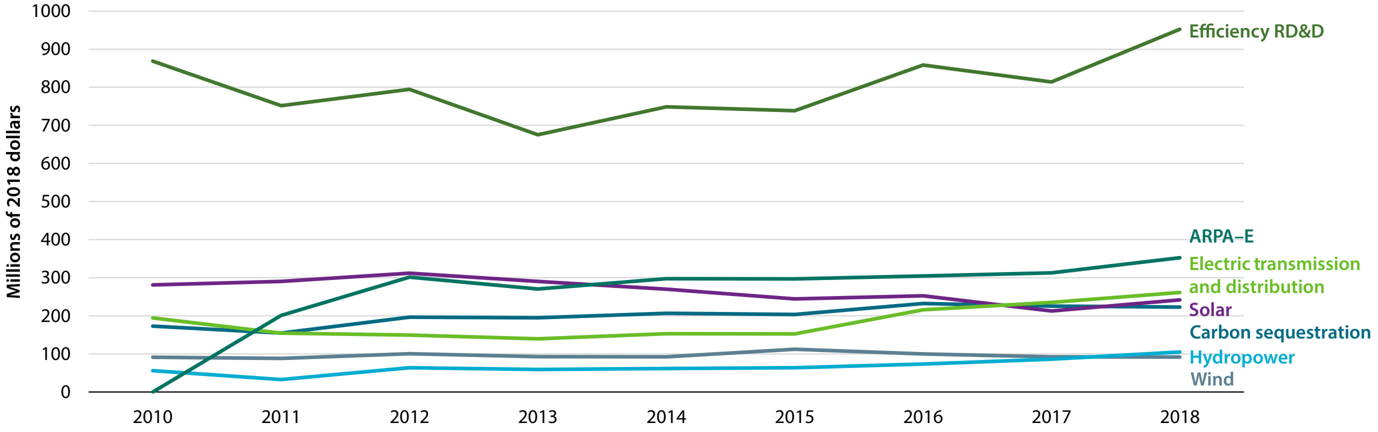
Carbon capture and storage is an example of such a technology. Successful carbon capture and storage would enable continued use of fossil fuels in situations where clean renewable sources are not viable, due to intermittency or other resource quality constraints. Carbon capture and storage could also help reduce industrial emissions in industries such as cement, and iron and steel production, whose industrial processes require high heat and cannot simply be eliminated by switching to clean electricity as an energy source (Cunliff 2018). Similarly, advances in energy storage affect multiple sectors, including both electricity grid management and transportation, and provide a means through which intermittent renewable sources could provide a reliable source of power throughout the day. While DOE R&D investments in electric transmission and distribution have increased in recent years, that is not the case for carbon sequestration (figure 6). R&D investments in both technologies should be increased.

Recommendation 4: Emphasize applied research on public good infrastructure that is unlikely to receive private sector support.

Government R&D should not invest only in technologies at early stages of development, but should also invest in applied research with benefits that are difficult to capture through market activity. Within the energy sector, the next wave of energy innovation is likely to require public infrastructure such as smart-grid technologies, the integration of intermittent renewable energy technologies into the grid, the adoption of connected vehicle infrastructure, and charging infrastructure for electric vehicles. Governments and regulated utilities will be the main consumers of many of these technologies. The public goods nature of these investments may make it difficult for private sector investors to fully capture the social value of innovation. These technologies exemplify many of the market failures discussed earlier. Illustrating the challenges of raising capital, they require up-front investments in infrastructure that must be coordinated between the public and private

FIGURE 6.

Department of Energy Research and Development Spending by Type of Clean Energy Technology, 2010–18



Sources: Calculated from data in Gallagher and Anadon 2018; author's calculations.

Note: Figures are in millions of 2018 USD. ARPA-E spending cannot be broken out into the technology categories shown in the figure. "RD&D" refers to research, design, and development.

THE HAMILTON PROJECT BROOKINGS

sectors. The need for charging infrastructure to be in place for electric vehicles to be successful may lead to path dependency, where the first chosen technological solution dominates the market.

Much of the discussion in this policy proposal focuses on electricity generation. Because electricity affects such a wide portion of the economy, and because until recently electricity generated the largest share of carbon emissions, electricity has garnered most of the funding for clean energy. However, other types of energy use in industry are important. Since energy is underpriced when externalities are not incorporated into prices, incentives to improve industrial energy efficiency are insufficient (in the absence of carbon pricing) to reduce emissions enough to meet zero- or near-zero carbon goals. Whereas investing in industrial energy-efficiency R&D will not directly increase incentives to adopt these technologies, it may do so indirectly by lowering the cost and/or increasing the potential energy savings resulting from these technologies. Since it will be more difficult to develop targeted deployment policies on an industry-by-industry basis, in the absence of broad-based carbon pricing increased mission R&D support for industrial energy efficiency can be a second-best policy solution. Examples of priority areas for research in industrial energy-efficiency R&D include

- new steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron;
- inert anodes for aluminum smelting;
- full oxy-fueling kilns for clinker production in cement manufacturing;
- enhanced catalytic and biomass-based processes for chemical production; and
- integration of carbon capture and storage in energy-intensive industrial processes (International Energy Agency [IEA] 2017).

It is promising that DOE R&D investments in energy efficiency are among the fastest growing category in recent years (figure 6). These increases should continue, with a focus on mission research aimed at niche technologies not likely to experience large market shares upon completion.

Recommendation 5: Be patient evaluating project outcomes, but be willing to adjust decisions over time.

Patience is important since the studies cited earlier find it takes a decade or more for the effects of government energy R&D to be fully realized. R&D is uncertain and some projects will fail. It is important to evaluate the full portfolio of research rather than focus on individual examples of failure. Nonetheless, it is also important to grant project administrators the authority to cancel projects they deem no longer likely to succeed. The National Research Council's (2001) study of DOE research programs from 1978 to 2000 noted that, while efforts to develop new energy supplies were not successful, funding continued for political reasons even after early failures. Thus, the political will to cancel projects seen as unsuccessful is needed.

The DOE's Advanced Research Projects Agency-Energy (ARPA-E) provides an example of a government agency that has successfully promoted and managed high-risk, high-reward innovation (box 1) and illustrates how to separate decisions to cancel unsuccessful projects from politics. ARPA-E both requires research teams to set clear, measurable goals through various stages of research and gives program directors the ability to terminate or redirect projects that are not achieving these predetermined milestones (National Academies of Sciences, Engineering, and Medicine [NASEM] 2017). Granting program directors such authority takes the decision to end funding out of the hands of politicians. Providing other program directors with similar discretion will make it easier for funding agencies to take on more high-risk, high-reward projects.

Unfortunately, policymakers face political constraints making it difficult to support policies with little short-term payoff. Although ideally government-funded R&D funding should focus on riskier projects less likely to be performed in the private sector, the long lags between funding and success from such projects may make it difficult to sustain political support for research on these long-term projects. Thus, as a second-best solution, governments can develop a diverse portfolio of projects that includes some low-risk projects likely to have relatively quick returns. While these projects could result in some crowding out of private R&D, any success stories will help build public support for a continuous, steady stream of public energy R&D funding. Funding agencies will need to weigh the cost of such crowding out against the potential gains of political support for a portfolio of research that also includes the necessarily riskier, but less politically popular, R&D projects.

BOX 1.

Advanced Research Projects Agency-Energy Program

The DOE's Advanced Research Projects Agency-Energy (ARPA-E) began operating in 2009. Its mission is "to overcome long-term and high-risk technology barriers in the development of energy technologies" (NASEM 2017, 15). ARPA-E aims to identify and fund high-risk, potentially high-return research in technologies that will "reduce imports of fossil fuels, reduce energy-related emissions, improve energy efficiency . . . and ensure that the United States maintains a technological lead in the development and deployment of advanced energy technologies" (NASEM 2017, 25). Recognizing the high-risk nature of their investments, ARPA-E requires projects to set specific, measurable milestones for various stages of the research. ARPA-E program directors are authorized to terminate projects that are not meeting their predetermined milestones. Providing program directors this authority avoids the risk of politicization of funding decisions that could unnecessarily prolong investments in failed projects.

ARPA-E was designed to bridge the gap between basic and applied research at DOE. Rather than focusing specifically on basic or applied research, ARPA-E looks to complement DOE's basic and applied R&D programs by identifying projects "too technology focused to be funded as basic research but . . . too novel to be funded as applied research" (Goldstein and Narayanamurti 2018, 1507). ARPA-E supports two types of projects: proof-of-concept projects designed to provide preliminary data or test new concepts and technology development projects designed to create laboratory-scale prototypes.

ARPA-E also represents an example of successfully targeting projects for technology transfer. Prime recipients are required to share at least 20 percent of the total project cost. Because ARPA-E expects successful projects to attract funding from other sources, before receiving funds awardees must submit a technology-to-market plan that includes commercialization strategies. ARPA-E helps awardees develop relationships with technology transfer offices, companies, and private investors (NASEM 2017).

While the long time frames for developing new energy technologies makes any evaluation of ARPA-E only preliminary, the NASEM report on ARPA-E concludes, "ARPA-E has funded research that no other funder was supporting at the time. The results of some of these projects have prompted follow-on funding for various technologies, which are now beginning to enter the commercial market" (NASEM 2017, 128). ARPA-E's willingness to support risky projects, its program directors' ability to cancel underperforming projects, and its focus on bridging the gap between basic and applied research provide a model other clean energy funding programs can emulate both to promote technology transfer and to best allocate resources toward high-risk, high-reward projects that are less likely to be funded solely with private sector funding.

Recommendation 6: Enhance opportunities for technology transfer through DOE laboratories.

In addition to correcting for underinvestment by private firms, many government R&D projects aim to improve commercialization of new technologies. The studies cited earlier show that government laboratories have played an important role fostering technology transfer. The ARPA-E example in box 1 provides an example of successful promotion of technology transfer within a DOE program.

The research also suggests that collaborations among different institutions, such as government laboratories and industry, produce high-value research. Thus, promoting collaborative research activities is important (Canter et al. 2016). Goldstein et al. (2017) provide one possible means for promoting additional collaborative research: enhancing the ability of DOE laboratories to work with energy industry start-up companies by encouraging a more entrepreneurial culture among lab researchers. This includes rewarding researchers for working with start-ups and adjusting performance and evaluation standards to account for the high failure rate of start-up firms.

GUIDELINES FOR TECHNOLOGY SUPPORT POLICIES THAT COMPLEMENT CARBON PRICING

Although R&D policy plays an important role developing new energy technologies, it is not a substitute for energy and environmental policies that create demand for clean energy. With the exception of loans and demonstration projects to aid commercialization, most government R&D does not focus on the final product. By focusing on the supply side of technology development, R&D funding only creates demand indirectly, by improving the quality of the product or by lowering costs and thereby shifting along the demand curve to a higher equilibrium demand. Thus, government R&D should be viewed as complementing other energy policies. Even supporting technology transfer will not be successful unless market and policy conditions justify the use of new technologies.

While broad-based carbon pricing should be an important part of any policy effort to promote clean energy innovation, there is no immediate prospect of implementation at the national level. Even at the state level, only California's cap-and-trade program covers multiple sectors, providing incentives to allocate emission reductions efficiently across sectors. As an alternative, this proposal focuses on targeted policies that support specific technologies. Such policies potentially address market failures that remain even when broad-based carbon pricing is in place, and to the extent that they do so should remain in place once a carbon price is implemented. Moreover, by helping to lower the costs of clean energy, these policies may reduce the costs of broader-based policy measures.

Recommendation 7: Targeted technology support policies should address at least one important market failure.

Table 2 provides examples of relevant technologies for each market failure, along with the types of policies needed to address each market failure. Direct R&D support and help with financing to aid commercialization are particularly important, but they will not be enough. Encouraging at least limited deployment of emerging technologies is necessary for their long-term development, even if these technologies are not currently the lowest-cost option. For example, tax credits for rooftop solar increased deployment and encouraged LBD in California (Bollinger and Gillingham 2014). Thus, such policies help bridge the gap from idea to implementation.

However, these policies should not be the primary tool for promoting clean energy. Both Bollinger and Gillingham's (2014) work on solar panels and Fischer, Preonas, and Newell's (2017) study of the U.S. electricity industry find that the LBD benefits do not justify the level of targeted technology policies currently in use. Pillai (2015) finds that polysilicon prices and usage, industry investment, and technological improvements, rather than industry experience, explain the observed cost reductions in solar photovoltaics from 2005 to 2012. These results provide justification for policy supporting upstream manufacturing and R&D of polysilicon, rather than simply focusing on deployment of solar panels to reduce costs. Thus, while LBD may be a justification for providing *new* support to clean energy technologies not already subsidized, *it is not a justification for expanding existing deployment subsidies.*

Instead, what should policymakers look for when deciding whether technology-specific policies are needed? First, they should focus on other market failures besides externalities to ask whether supporting a *specific* technology is justified. Are there barriers to financing that could be surmounted with additional tax credits or public loans? The DOE Loan Programs Office (box 2) provides an example of overcoming financing barriers. Is path dependency a problem? For example, developing charging infrastructure is necessary before consumers will be comfortable purchasing electric vehicles. But the private sector will not develop charging infrastructure unless there is a sufficient number of electric vehicles on the road to make investment profitable. Thus, early adopters of electric vehicles provide external benefits through network effects, justifying subsidies.

It is also important to think about the efficiency costs of targeted policies. Overall, the goal should be to focus investment on the most promising investment sites: move the technology forward, but do not force it into places where it does not make sense. For example, California's mandate for solar panels on all new homes will require panels be installed in inefficient locations, such as a new home surrounded by shade trees. Tax credits may be a better option, because

TABLE 2.

Market Failures That Impede Low-Carbon Technology Innovation

Market Failure	Example	Relevant Policies	Importance
Negative externalities	• Emissions from fossil fuels	• Carbon taxes • Cap and trade	High

Large knowledge spillovers	• Emerging technologies:
	  • Energy storage
	  • Materials research
	• Public goods:
	  • Grid management
	  • Electric vehicle charging infrastructure
		• R&D subsidies
		• Intellectual property rights
			High

Capital market failures	• Demonstration of large capital infrastructure • Carbon capture and storage	• Government financing • Loans • Demonstration projects	Medium
Learning-by-doing	• Improved siting strategies for wind farms • Increased durability of materials	• Targeted deployment subsidies	Low
Path dependency	• Firms build on previous knowledge base to create new research • Emerging technologies with network effects (e.g., electric vehicle charging infrastructure)	• R&D subsidies • Targeted deployment subsidies	Low (R&D subsidies) to medium (deployment subsidies when switching costs are high)

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they nudge consumers toward more-efficient choices but do not force suboptimal technologies in locations where they do not make sense. However, tax credits for solar panels have their own weaknesses since they (1) lower government revenues and (2) primarily benefit higher-income households (Borenstein and Davis 2016). Such concerns emphasize the point made earlier that there is no silver bullet: All policies have strengths and weaknesses, making the use of a broad range of policies vital.

Recommendation 8: Until broad-based carbon pricing is in place, complement technology-specific deployment policies with technology-neutral policies at the broadest level possible.

Political constraints also suggest a role for broader-based technology-neutral policies such as renewable portfolio standards. While these policies let markets decide which technologies best meet policy goals, because they focus on an individual sector such policies are less efficient than economy-wide policies that allow for optimal choices across sectors. Greenstone and Nath (2019) estimate that U.S. renewable portfolio standards have reduced carbon emissions, but at a cost of $115 per ton abated, which exceeds many estimates of the social cost of carbon. However, those authors acknowledge that their estimates do not capture the social benefits of innovation brought about by these renewable mandates.

Technology-neutral policies promote the deployment of the most cost-effective technologies *within the targeted field* (e.g., renewable energy mandates promote the most cost-effective renewable energy source). These policies represent both a way to get renewables to market and a way to develop long-run political support for broader climate policies. Nearly two-thirds of jurisdictions with carbon pricing in place by 2013 first had either a feed-in tariff or renewable portfolio standard. These policies demonstrate the viability of clean energy and promote coalitions of industries and consumers to support further clean energy policy initiatives (Meckling et al. 2015). However, such technology-neutral policies do not address the additional market failures listed below externalities in table 2, and thus become redundant under a carbon tax. These policies should be phased out once broad-based carbon-pricing is in place.

BOX 2.

Department of Energy Loan Programs Office

Private sector financing for clean energy can be hard to obtain. The Title XVII loan guarantee program through the DOE Loan Programs Office helps overcome financing barriers (DOE n.d.). Created as part of the Energy Policy Act of 2005, the loan guarantee program finances the first deployments of new energy technologies perceived as being too risky to receive private sector financing. Because it is difficult to identify projects that are guaranteed to produce successful outcomes given the great uncertainty associated with innovation, a portfolio approach—in other words, providing support to numerous projects and technologies to reduce the overall funding risk—is more effective. Governments with high risk tolerance, a long-term perspective, and adequate resources are in an excellent position to support a diversified portfolio of projects. For example, although the Loan Programs Office was criticized for its support of the failed Solyndra project, overall the program that supported Solyndra made money, since interest payments from successful projects outweighed losses from failed projects such as Solyndra (Eckhouse and Roston 2016).

GUIDELINES FOR STATE AND LOCAL GOVERNMENTS

State governments, rather than the federal government, have taken a leading role promoting clean energy (Carley 2011). Cap-and-trade policies in California and in some Northeastern states cover a substantial part of the population, and 29 states and the District of Columbia use renewable portfolio standards to promote clean energy. All of the guidelines discussed here apply to state and local governments as well as to the national government. What additional concerns should local governments consider? Two priorities are to coordinate targeted policy efforts and to enhance investment in research and development:

Coordinate Targeted Policy Efforts

For state governments, many of the benefits from technology policy will spill over to other states. For instance, some states require that a minimum share of renewable energy come from solar technology (e.g., a carve-out for solar). These requirements increase the costs of generating electricity but help promote additional development of solar. However, similar to the public goods problem for knowledge discussed earlier, the resulting technology improvements benefit consumers everywhere, not just consumers in the local community.[7] For smaller local governments, appropriating the external benefits from innovation will be even more difficult. Thus, while first-order benefits such as reduced emissions may be enough to justify the use of clean energy policies at the state and local levels, the second-order benefits of induced technological change may be of less concern to local policymakers.

One way to overcome this problem is for states to coordinate renewable energy policies. The Regional Greenhouse Gas Initiative limiting emissions from the electricity sector among ten Northeastern states is an example of such coordination. Since overall market size is more important than local environmental regulations for spurring clean energy innovation, coordinated policies can better create the market scale necessary for inducing private sector innovation. Automotive emissions provide an example. Historically, California has been allowed to set separate emission standards for automobiles that were more stringent than national standards, which other states could then adopt. Such coordination avoids the need for automakers to comply with 50 different state-level regulations. Twelve other states currently follow California's emission standards. Whether California's ability to set emission standards applies to fuel efficiency as well is currently under debate in Washington. If allowed, other states will again be able to follow California's lead, creating new markets for more fuel-efficient vehicles. This example illustrates the importance of one state acting as a leader to set standards that others can adopt. Recent proposals from both New York and California to achieve net zero emission economies by mid-century provide examples of leadership that other states can follow.

Another example where policy coordination may be particularly helpful is in building codes. As noted in Noailly (2012), changes to building codes in Europe increased energy-efficiency innovation. Because building codes are set at the state and local levels in the United States, coordination among local governments is more likely to create the market scope necessary to spur innovation in response to building code changes.

Enhance Investment in Research and Development

The federal government is in a better position to fund energy R&D spending, both because it is better able to diversify risk and because federal research spending also avoids potential duplication of research programs across multiple states. Even if a national climate policy is unlikely in the current political context, pushing to continue support for clean energy research at the national level should be a priority. Nonetheless, states do fund some energy R&D. While spillovers across states make it more difficult for individual states to benefit from their own energy R&D investments, in the absence of federal funding further investment from states could help close the gap between current federal energy R&D levels and the Mission Innovation goals.

In 2017 U.S. state governments spent $307 million on energy R&D. Although that is just a fraction of the $9.2 billion spent by the DOE, almost 80 percent of this funding came from just two states: California ($185.6 million) and New York ($55.9 million). Thus, there is room for other states to expand energy R&D budgets. However, enhancing state energy R&D investments faces two particular challenges. First, much of the R&D support from states focuses on deployment, rather than on early stage research. The California Energy Commission (2015) explicitly states, "Energy Commission RD&D [research, design, and development] programs bridge the gap between the laboratory and the market." In April 2019 New York allocated $280 million to finance energy storage projects in an effort to reduce storage costs (T&D World 2019). These efforts are motivated by a LBD market failure, but do not address more-important market failures that may slow energy investment. In contrast, recent efforts by both New York and California to address capital market imperfections for clean energy investment provide a better example of how state R&D funds could be targeted (box 3).

Second, although both California and New York have taken leading roles in clean energy investment, for smaller states it is difficult to invest in research at levels that would have an impact on technological improvements. For smaller states, coordinating energy R&D efforts would increase the impact of individual investments. Coordination would also help states avoid potential duplication of research effort. As an example, in 2018 staff from New York and California helped review research proposals on microgrids and energy storage to each other's state R&D programs to learn about the national state of research on each technology (Orta 2019). Coordination would also help diversify risk by both spreading initial investments across multiple jurisdictions and providing sufficient funding to develop a diverse portfolio of projects.

The EU Strategic Energy Technology Plan (SET-Plan) provides an example of efforts to increase coordination of research efforts across jurisdictions (Dechezleprêtre and Popp 2017). Implementation of the SET-Plan currently includes 17 joint programs in the European Energy Research Alliance; these programs set research priorities for various renewable technologies and encourage coordination among researchers in different countries and different sectors, including industry (European Energy Research Alliance n.d.). Since the inception of the SET-Plan in 2006, EU researchers have become more integrated, as demonstrated by increasing rates of patent citations among EU researchers in different countries (Conti et al. 2018). A consortium of states could similarly pool funds for energy R&D, both allocating it among researchers in member states and setting aside a share of funding specifically for cross-state collaborations.

BOX 3.

State Programs Addressing Capital Market Failures

Both New York and California provide examples of state programs addressing capital market failures. NY Green Bank, founded in 2014, leverages private sector financing to increase clean energy investments. The Green Bank works "to address and alleviate specific gaps and barriers in current clean energy capital markets through a variety of approaches and transaction structures" (NY Green Bank n.d.a). Green Bank addresses potential capital market failures by operating in markets with limited competition. The goal is to work "with entities already achieving success in clean energy, but whose progress is constrained by the lack of available financing" (NY Green Bank n.d.b). As of March 2019, NY Green Bank had invested approximately $737.6 million in clean energy investments in New York State.

In response to dwindling venture capital interest in clean energy, California created the Energy Innovation Ecosystem in 2016 to support clean technology ventures. Described as a system to provide "entrepreneurs with access to the networks, funding opportunities, mentoring, facilities, and expertise needed to take their inventions from the idea stage to the impact stage" (California Energy Commission n.d.), the Energy Innovation Ecosystem includes two main initiatives: innovation clusters to bring together clean tech investors in individual communities and seed funding through California Sustainable Energy Entrepreneur Development Initiative (CalSEED) awards.

Questions and Concerns

1. What about energy use in other sectors, such as agriculture or manufacturing?

Energy usage permeates all sectors of the economy. As such, regulations from multiple government agencies affect energy consumption. Addressing all of these in a single policy proposal is impossible, which further illustrates the importance of first getting prices right through carbon pricing. But the recommendations in this proposal would reduce the average carbon content of energy, so even if other sectors did not adjust their consumption, their emissions would still be lower. In addition, increasing awareness of the impact of each sector of the economy on energy consumption may be a starting point. Requiring all government agencies to incorporate an assessment of the impact of major regulations on climate change could be a possible way to increase awareness of each sector's contributions to climate change.

2. What about intellectual property rights?

While broader sharing of intellectual property pertaining to environmental technologies could accelerate global carbon emissions reductions, such calls must balance the need to promote innovation with the need to promote beneficial spillovers. Intellectual property rights (IPR)—such as patents—reward inventors for the fixed costs of innovation. Successful patent applicants receive a temporary monopoly, lasting twenty years from the initial application date, 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 to encourage innovation. 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 than without the IPR. The role of demand for clean technologies cannot be overstated, however, and is consistent with the limited research to date on intellectual property in the clean energy sector. In a literature review on patent protection, Hall and Helmers (2010) cite work by Copenhagen Economics (2009), as well as by Barton (2007), that suggests developing country policies such as tariffs on renewable energy technology and subsidies for fossil fuels do more to limit technology transfer of clean technologies than do IPR. They conclude that additional research is needed to assess the specific implications of IPR for green technologies.

3. Are building codes effective in reducing energy consumption?

The evidence that building codes reduce energy consumption is mixed. For example, after passage of building codes designed to enhance energy efficiency in Florida homes, electricity consumption initially fell, but recovered to pre-policy levels in just three years (Kotchen 2017). This is an example of the *rebound* effect, where improving energy efficiency reduces the costs of using energy-using equipment, allowing for increased usage that negates potential energy savings. Such rebound effects illustrate the limitations of relying on direct regulation such as building codes or fuel efficiency regulations to reduce energy consumption, and point to the importance of higher carbon prices. However, the focus of this policy proposal is increasing innovation. The rebound effect relates to whether such regulations reduce energy consumption. Whether or not they do, regulations that require installation of better technologies will increase innovation on those technologies.

4. Could research prizes be a viable policy option?

Another policy tool used to manage uncertainty are research prizes. Prizes offer a reward to the first inventor (or team of inventors) to meet specific technological goals specified in the prize. Prizes give inventors flexibility to decide *how* to best meet the goals specified by the awarding agency. However, prizes shift the risk of failure from the funder to the researcher, and this may be a problem in the clean energy sector. As discussed above, there are long lags between innovation and deployment of clean energy technologies. In conjunction with the high risk of failure of any one project, this may make it difficult to successfully implement prizes in the clean energy sector.

Williams (2012) provides a review of recent research on technology prizes. One failed example is a prize that was 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. Because firms bear greater risk, prizes may be better used to encourage final development of nearly commercial products, rather than as a tool to encourage breakthrough innovation.

Conclusion

Despite remarkable progress over the past decade, further clean energy innovation is necessary to achieve deep decarbonization goals currently under consideration. While carbon pricing would help incentivize further innovation, many remaining technological challenges involve complementary technologies such as energy storage or improved electricity grid management that will be difficult for the private sector to develop on its own. Complementary policies to promote long-run innovation include increased government R&D spending, financing support to help young companies commercialize new innovation, and select use of tax credits and subsidies to increase deployment of new technologies. Although all of these should be included in the policymaker's toolbox, careful attention must be paid to implementing targeted policies where they are most needed, and thus most likely to be effective.

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Endnotes

1. These goals include reduced costs for power plants with carbon capture and storage and enhanced electric transmission capacity (U.S. Department of Energy 2017).
2. In addition, Rexhäuser and Löschel (2015) and Noailly and Smeets (2015) find that much renewable energy innovation comes from specialized firms with prior renewable innovation experience. Both groups of authors are careful to note, however, that path dependency is just one possible interpretation of their results.
3. Combining keyword and patent classification analysis, Costantini, Crespi, and Curci (2015) identify biofuel patents in 35 countries from 1990 to 2010. In addition to the role of public R&D, they consider two demand-side policy instruments: quantity-based mandates of biofuel usage, and excise tax exemptions as an example of price instruments.
4. Out-of-state policies are weighted by the population of each state and the distance between states, so that larger nearby states have the greatest influence on innovation.
5. There is no clear definition of the term “clean energy R&D” for the Mission Innovation goals. Figure 5 includes DOE spending on basic energy sciences, carbon sequestration, energy efficiency, hydrogen energy, renewable energy, electricity transmission and distribution, nuclear, and ARPA-E.
6. Calculated from data in Gallagher and Anadon (2018) and DOE (2019).
7. For example, feed-in tariffs for solar energy raised electricity prices in Germany. Gerarden (2018) calculates that innovation induced by these feed-in tariffs increase the external benefits of those subsidies by 22 percent. However, most of those benefits are generated by future solar panel adoption that occurs outside Germany due to the lower solar panel prices that result.

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Highlights

In this paper, David Popp of The Maxwell School of Citizenship and Public Affairs at Syracuse University points out that despite the recent progress made in clean technology innovation, much remains to be done in order to decarbonize our economy. The author describes the evidence on different public policy approaches to spurring more clean energy innovation. Grounded in that evidence, Popp provides a set of guidelines for how best to target energy R&D investments and support the deployment of low-carbon technology innovations.

The Proposal

Restore progress toward Mission Innovation goals over a four-year period. Social returns to increased investment continue to be high and would remain so even with substantial increases in funding.

Increase federal support for high-risk, high-reward investments unlikely to receive private sector support. Government R&D should focus on breakthrough technologies that are not yet close to market as well as applied research on public infrastructure.

Enhance opportunities for technology transfer through DOE laboratories. Adjust performance and evaluation standards for researchers to encourage more engagement with start-ups.

Benefits

As the author explains, negative spillovers from carbon emissions are not the only market failure that policymakers must address; substantial barriers exist to creating and deploying clean energy technologies. The author's proposal will help policymakers efficiently invest in clean energy innovation, making climate goals more achievable. Achieving these climate goals while maintaining strong economic growth will ultimately depend on the success of clean energy policy.

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