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Inducing Innovation: What a Carbon Price Can and Can't Do

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A carbon price can be a useful tool to nudge the adoption of mature technologies, but it does little to pull forth disruptive new technology or stimulate the advance of basic knowledge upon which new technology is built.

The development of breakthrough technologies has underpinned waves of economic transformation and created solutions to problems like hunger, disease, and pollution. Today, many are looking to innovations in energy technology to solve problems of global warming and fossil energy dependence. But the key question is how to get that innovation.

In the current energy and climate debate, most advocates argue that putting a price on carbon emissions through either a carbon tax or a cap-and-trade program is the key to spurring breakthrough energy innovation. This conventional wisdom is based on the notion that higher dirty energy prices will provide the right market signals to entrepreneurs, who will then develop breakthrough clean alternatives. But advocates of the price approach provide little to no evidence for this notion, for the simple reason that there is little to no evidence for it. In fact, over the past century, in major innovation after major innovation, the pursuit of research and public support for early-stage technology and markets, and not price signals, have driven breakthrough innovation. As we argue, there is no reason to believe it will be any different for future clean energy innovation.

Despite the lack of evidence that price changes drive disruptive innovation, the belief in price as the main driver persists thanks to a widely-held "understanding" of technological change that is oversimplified at best and flawed at worst. While a carbon price can be a useful tool in helping to nudge the adoption and diffusion of nearly competitive technologies, it does little to pull forth early-stage, disruptive technology or stimulate the advance of basic knowledge upon which new technology is built. This is because the innovation process varies across industries and technologies, and is responsive to price signals only to a limited extent and in certain contexts. Existing technology has a role to play, but without breakthrough advances, it will not be possible to fully address climate change and displace fossil fuels, and the United States will miss out on an enormous opportunity to lead the clean economy.

This report documents the underlying assumptions about carbon pricing and innovation inherent to the debate about climate and energy policy and examines how, if at all, these assumptions square with real-world evidence of the sources of breakthrough innovation and general technical change. Where are they accurate and where do they fall short? The implications of the findings for crafting policies to accelerate innovation in clean energy technology are discussed.

A FLAWED UNDERSTANDING OF TECHNICAL CHANGE

Clean energy innovation is needed for several reasons. To stabilize atmospheric concentrations of greenhouse gases and avoid the worst impacts of climate change, global emissions should be at least halved by 2050. Further, the global population is expected to grow by 46 percent by that year, and per-capita income by 129 percent, which together means that the planet's economic activity must become 84 percent less polluting to halve emissions. In terms of energy technology, this will require a transition to clean energy sources of fifteen terawatts (TW) or more by mid-century — a massive figure equal to the existing capacity of the global energy system.[1]

Reliance on overseas fossil fuels also has implications for foreign policy, national security, and international trade: in 2009, petroleum imports accounted for 54 percent of the entire $374 billion trade deficit. And perhaps the most important motivator for large-scale energy innovation is the massive future demand for energy as global population and per-capita income growth. China, India and other nations will likely continue their rapid development. For example, China's total energy consumption is expected to more than double by 2035 — the equivalent of adding another United States to 2009 global demand. Meanwhile, the International Energy Agency has said that an oil production peak has likely been reached, such that global petroleum production is likely to plateau for the next few decades.[2] With fossil fuel prices facing an uncertain future, developing affordable clean energy sources is a necessity.

We cannot meet a long-term challenge of such magnitude with existing clean technologies. The reason is simple: most existing technology cannot compete with fossil energy sources on a price basis without significant subsidy or high carbon prices. The challenge is underscored by the U.S. Energy Information Administration's estimates of levelized costs of energy for plants entering service in 2016. According to these estimates, the levelized costs for new conventional coal plants would stand at $95 per megawatt hour (MWh), while advanced coal would stand at $109 per MWh, and coal with CCS, $136; combined cycle turbines, $66; advanced nuclear, $114; onshore wind, $97, and offshore wind, $243; solar thermal, $312; and solar PV, $211. As the Breakthrough Institute has pointed out, these cost disparities mean that a carbon price would have to rise to politically untenable levels — of $100 or more in some cases — to make many of these technologies cost-competitive with coal.[3] Compare these figures with prior failed proposals, which sought to limit carbon prices to the $15-20 range.

Further, it is not clear which technologies will shift sufficiently down their cost curves following diffusion and scale up. And many technologies that are nearly cost-competitive, such as wind, require enabling technologies that also depend on technical breakthroughs. This is more than an assumption, but a conviction widely held by many energy experts. Economist Jeffrey Sachs sums up the point well: “Even with a cutback in wasteful energy spending, our current technologies cannot support both a decline in carbon dioxide emissions and an expanding global economy. If we try to restrain emissions without a fundamentally new set of technologies, we will end up stifling economic growth, including the development prospects for billions of people.”[4]

Neoclassical economics makes simplifying assumptions that yield smooth, workable academic models but come with a steep price: they fail to accurately capture technological change as it happens in the real world.

Many of these technological shortcomings will only be solved through increased investment in innovation. This investment must come from somewhere — so what’s the proper way to spur it? Many in the academic, environmental, and business communities see a carbon price as the critical catalyst. The argument, albeit simplified, goes like this: with an increase in the market price of fossil fuels, firms will have an incentive to find alternative, low-carbon sources of energy, and will thus shift resources to either obtain these new resources where they exist, or develop them where they don’t. Higher carbon energy costs would increase market demand for cost-effective alternatives, and this increased potential for profits from clean energy technology would support additional R&D expenditures. Thus, in this world view, technological change is assumed to arise spontaneously due to a shift in relative prices, which induces firms to respond accordingly. A Resources for the Future report reflects the prevailing view: “Establishing a price on CO_2 emissions is the single most important policy for encouraging the innovation and adoption of emissions-saving technologies.”[5]

Economists’ focus on prices and prices alone is not surprising, given that that’s what they know and study. Neoclassical economics places utmost importance on achieving Newtonian equilibrium within markets to achieve efficient resource allocation, and this equilibrium is achieved via price mediation. In this view, markets, prices, and capital accumulation are keys. In the neoclassical world, the economy can be captured in an aggregate production function, which fails to differentiate between kinds of technology and research, and thus lacks necessary levels of microeconomic detail for effective policy or institutional recommendations. Further, firms are seen as rational optimizers with adequate information to calculate risk, choose the optimal R&D path, and shift labor and capital resources in response to price signals accordingly. Competition is treated as an end state rather than a process, and technological trajectories are neglected.

Of course, these simplifying assumptions, while yielding smooth, workable academic models, come with a steep price: they fail to accurately capture technological change as it happens in the real world. As a result, most neoclassical economists do not fully appreciate the various market failures associated with R&D and innovation, nor do they adequately capture the complex, messy, evolutionary innovation process or the importance of collaborative relationships between public and private institutions in the national innovation infrastructure.[6]

Indeed, neoclassical economics has never been entirely comfortable with the role of technology in economic growth. Early neoclassical growth models, such as that famously created by Nobel laureate Robert Solow, treated technology as an exogenous factor in economic growth, happening outside the model (as opposed to "endogenous" growth, which treats technology, knowledge, or related factors as quantifiable and responsive variables with defined relationships to other variables within the model). Neoclassical economists treated technology as inexplicable "manna from heaven," and innovation as something that happens in a "black box." The significant portion of economic growth unaccounted for in the model was dubbed by one noted economist as a "measure of our ignorance."[7]

Assumptions about the centrality of a carbon price continue to appear regularly in public comments by advocates, left and right. Glenn Hubbard, former Chairman of the Council of Economic Advisors in the second Bush Administration, claimed that "businesspeople don't innovate because it feels good; they innovate because there's a return to that innovation. If you want a return to that innovation, you will have to price it — you will need to put a price on carbon, which means having, either through a cap-and-trade system or an explicit tax, some incentive to innovate carbon-saving technology."[8] Peter Orszag, former Office of Management and Budget Director in the Obama Administration, said in his testimony before the House Budget Committee, "Incentive-based policies…use the power of markets to identify the least expensive sources of emission reductions. Thus, they can better reflect technological advances, differences between industries or companies in the ability to make low-cost emission reductions, and changes in market conditions."[9] And even as the debate on Capitol Hill has shifted away from carbon prices, noted economist and former Federal Reserve Vice Chairman Alan Blinder still refers to a carbon tax as a "miracle cure," writing in the *Wall Street Journal,* "Once America's entrepreneurs and corporate executives see lucrative opportunities from carbon-saving devices and technologies, they will start investing right away — and in ways that make the most economic sense. I don't know whether all this innovation will lead to 80% of our electricity being generated by clean energy sources in 2035, which is the president's goal. But I can hardly wait to witness the outpouring of ideas it would unleash."[10]

Even many scientists have bought into the primacy of carbon pricing as an inducement to innovation. James Hansen, NASA climatologist and noted climate activist, has argued for a cap-and-dividend approach, writing last year, "A higher carbon price is needed to transform consumer and life style choices, to make zero-carbon energy and energy efficiency cheaper than fossil fuels, to spur business investment, innovation and associated economic activity, and to move the nation to the cleaner environment beyond the fossil fuel era… A tax and dividend mechanism would allow the marketplace, not politicians, to make investment decisions."[11] Certain segments of the business community also regularly cite the importance of a carbon price in motivating clean energy innovation. Clean energy investors Martin Lagod and Jason Scott wrote in *Politico*, "Putting a market price on carbon would provide clear price signals to investors like us. Then, the U.S. innovation engine — our most valuable asset — would be turned loose, and capital and U.S. jobs would follow."[12]

While neoclassical economists apply convenient, simplifying assumptions to weigh the impacts of price changes on technological development, is there real-world evidence to demonstrate that radical technological breakthroughs occur in response to price changes? In a word, no.

The way many climate models treat technological change is illustrative. In many models, technical change is a central variable used to determine climate mitigation costs; thus any assumptions made about the sources and rate of change have major consequences in determining the costs and benefits of action.[13] Unfortunately, due in part to technical limitations within the latest models, the approach that neoclassical models use to assess induced technical change may be suspect. For example, many models treat technical change as arbitrarily responsive to changes in the price of carbon; still others treat technical change and learning rates as monolithic across the entire economy, ignoring major observed differences in learning rates across technologies and sectors.

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Perhaps the most egregious example of such reasoning is found in the modeling of the Intergovernmental Panel on Climate Change (IPCC) itself. In modeling various scenarios to estimate the magnitude and costs associated with necessary emissions reductions, the authors built in significant automatic emissions reductions due to assumed levels of technological change — without explaining where these reductions would come from.[14] Such a practice significantly underestimates the magnitude of the challenge. As economists William Pizer and David Popp write, "It is important to note that results from models that do not explicitly include R&D market imperfections would not be obtained without government support for R&D. Moreover, these models not only assume that government provides R&D support, but that it provides this support in an optimal manner, so that the gap between private and public returns is closed."[15]

Similarly, Harvard economist Robert Stavins has frequently cited the importance of a carbon price in spurring innovation while paying lip service to the role of R&D support. His evidence? A finding that household appliances become more efficient in response to energy prices.[16] This does in fact reflect the kind of incremental innovation we would expect to see given a price on carbon, but energy-efficient toasters and modular nuclear reactors are not the same thing. Other studies have also shown a similar relationship between changes in input prices and incremental improvements in input-saving directions. However, these comparisons stop "at the cutting edge," so to speak: there is no evidence to suggest that radical technological shifts are a function of price signals. Price changes do clearly contribute to technical change, but this kind of market-driven change tends to be incremental. As for radical, disruptive new technologies, they are a result of focused, strategic research that seeks fundamentally new or better ways of performing work or achieving other goals. This research can happen in private labs, in public labs, and in academia, but because risky, early new technologies are detached from the market, research efforts are rarely if ever responsive to a changing price environment.

The lesson here is that neoclassical economic models may be useful as guides to explore the most generalized consequences of selected policies, but significant caution should be used when drawing any specific conclusions. This is because such models frequently fail to capture the key insights of innovation economics.

WHAT A CARBON PRICE CAN'T DO

To understand the limitations of a carbon price, we need to understand how technical innovation happens. Innovation is more than "manna from heaven;" it is a complicated process that varies across technologies and industries, one in which both public and private actors and institutions have historically played important roles.

Conceptually, the roots of technical change can be found in two sources, dubbed *"technology-push"* or *"demand-pull."* The latter refers essentially to market dynamics that draw incremental innovations forth, as firms innovate in response to changing market conditions; the former refers to the non-market expansion of knowledge and technological development that has frequently driven radical innovation, apart from purely market forces.

The debate over the relative importance of these two sources of technological advancement has lasted for decades, and evolved over time. Several mid-century studies sought an answer to this important question; many of these came down on the side of market demand as the primary driver of technical change, seemingly settling the question. A seminal study of this kind, by economist Jacob Schmookler, found that patenting activity did appear to have a strong relationship with market demand in several industries, most notably railroads.[17] However, later modeling using broader or improved data sets demonstrated that this relationship was weaker than Schmookler originally had found.[18] Schmookler himself would eventually argue that both demand-pull and technology-push were necessary components of innovation.

As experts gained a deeper understanding of the technical change process, many similar demand-oriented studies were likewise criticized as standing on shaky ground. A common criticism was that these studies placed too much focus on commercially successful innovations that had already been widely adopted, thus biasing the findings towards market demand, while underestimating the role of non-market technology supply. In a review of these studies, economists David Mowery and Nathan Rosenberg wrote, "The notion that market demand forces 'govern' the innovation process is simply not demonstrated by the empirical analyses which have claimed to support that conclusion."[19] Further, many studies make use of patent data and R&D expenditures to identify relationships between price and innovating activity, but do not distinguish among *kinds* of activity: not all patents are created equal, and not all R&D is of the early-stage, high-risk variety, nor is the underlying knowledge derived entirely from either the public or private sectors. Without a thorough understanding of both the importance of the patent in the overall system and the source of the underlying knowledge embodied in the patent, the true source of technical change will be obscured.

To be clear, the dichotomy between "pull" and "push" is fairly artificial and, in reality, of only limited use, in that a consensus has emerged that the supply of technology and the pull of the market both have roles to play in facilitating technical change. Indeed, innovation scholars Robert Rycroft and Don Kash have dubbed the either/or debate an "anachronism."[20] As Mowery and Rosenberg write, "Rather than viewing either the existence of a market demand or the existence of a technological opportunity as each representing a sufficient condition for innovation to occur, one should consider them each as necessary, but not sufficient, for innovation to result; both must exist simultaneously."[21]

A more sophisticated understanding of technical change recognizes that technology supply and market demand play very different roles at different stages of technological development. As a technology moves closer to market and is taken up in the selective demand-pull process, the effects of relative price changes are stronger, which is why many advocates for existing technology rightly see a high carbon price as one way to drive diffusion. But the converse is also true: the farther a technology is from market adoption, the less likely it is that changes in market prices will play a role. Given the inherent uncertainty during the early technology development phase, it is impossible for firms to accurately determine optimal search paths, in the "rational" fashion envisioned by neoclassical economics. Whereas the neoclassical doctrine sees firms as rational actors making rational (and thereby efficient) resource choices, innovation economics recognizes that uncertainty makes truly efficient resource allocation impossible. As economists Richard Lipsey, Kenneth Carlaw, and Clifford Bekar have argued, two firms with the same resources and information about potential technological outcomes may make radically different but equally justifiable choices about where to allocate those resources in pursuit of technology; the efficient choice is invisible, or at least impossible to determine.[22]

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An additional challenge for firms seeking to efficiently allocate resources to develop breakthrough technologies is the recognized inability of any one firm to reap all of the benefits of its R&D activities. The possibility of future profits is an incentive for firms to pursue research activities, but inevitably knowledge spillovers to other industry competitors serve to reduce that incentive for individual firms even as spillovers help drive of technological development in the aggregate. Some studies have demonstrated that the private returns on R&D investment are less than half those of the social, industry-wide returns,[23] and others report an even greater rate of return to society across multiple industries at the national economic scale.[24] Because the public-good benefits of R&D are much greater than the private benefits, the socially optimal level of investment in R&D is greater than the privately optimal level. Private firms operating in competitive markets, and relying on market signals to inform decision making, are thus unlikely to invest adequately or effectively in R&D activities, even where market conditions may make such research activities more attractive. Underinvestment in research activities to expand knowledge and broaden technical horizons is particularly a problem for the energy sector, which compares poorly to other sectors in R&D intensity.[25]

The above observations point to the fact that institutional arrangements in the technology development realm have significant influence, and public-private collaboration is to be promoted wherever possible and appropriate. For example, public research institutions can drive or augment private-sector research activities, while private-sector feedback can help guide the process to ensure relevance and useful results. Policies can incentivize private research activities or reduce related uncertainties, and likewise assist private actors with early-stage technology demonstration. Public institutions can provide crucial early markets for new technologies through targeted procurement policies, and further assist with financing or regulatory changes to remove barriers to diffusion and boost the translation of technologies into the market.

From this perspective, a price change in the market has only a limited role to play in the search for breakthrough technologies. As South Korean economists Wonjoon Kim and Jeong-Dong Lee write in their study of the global dynamic random access memory (DRAM) market, "All the DRAM generations in our empirical analysis shows that technology-push is greater than demand-pull in the early stage and decreases over the course of time."[26]

To re-state our argument, then, disruptive innovation comes not from price-based demand-pull but from focused (and occasionally, not-so-focused) technology supply-push, in the form of research-driven technological development.

This reasoning makes clear the importance of drawing a distinction between off-the-shelf technologies and technologies requiring additional development when crafting a policy support regime. It also necessitates differentiating between *kinds* of demand. In a competitive market, buyers have less incentive to take higher risks and are compelled to minimize costs, factors that along with path-dependence and non-price-based market barriers can conspire to make market entry for new products difficult. On the other hand, demand originating through targeted public-sector procurement can be an important tool in spurring innovation.[27] This is because procurement can ensure a critical early market and guaranteed buyer for new technologies that have not yet entered the larger market but that meet critical performance thresholds. Proactive and targeted government purchasing can drive down technology costs and provide real-life demonstrations of a technology's viability, making it more attractive to buyers, but freeing it of the life-or-death competitive pressures on the market. It incentivizes the creation of disruptive new technology in a way that an economy-wide carbon price would not. Similar to innovation prizes, but very different from price changes in the open market, public-sector procurement can be considered a form of strategic innovation policy.

To re-state our argument, then: truly disruptive innovation comes, not from price-based demand-pull, but from focused (and occasionally, not-so-focused) technology supply-push, in the form of research-driven technological development. Demand-pull, in the form of lower relative prices and expanding markets offering the promise of greater payoff, is best suited for inducing incremental innovations and diffusion in mature technologies where market barriers apart from price are minimal.

To illustrate this dynamic, we now take a brief tour of some key technological advances over the previous two centuries, including many that have been cited by the National Academies as the greatest engineering achievements of the twentieth century, and analyze the role that both technology push and market pull played in their development.[28]

Dyestuffs

An early example of the dynamics between push and pull can be found in the evolution of the chemical industry, starting with synthetic dyes in the nineteenth century.[29] In the first half of the century, demand for dyes grew dramatically. This growth induced incremental producer-led innovations that improved production processes and quality of existing natural dyes. The transformative event, unrelated to any price shift in natural dyes, came with the invention in 1856 of the first synthetic dye, mauve. It fundamentally changed the industry. This development was not market-induced, but was built upon expansion of the knowledge base, in this case advancements in organic chemistry.

Some entrepreneurs recognized the potential utility of synthetic dyes and entered into commercial ventures after their discovery, but market growth for synthetic dye did not accelerate until fifteen years later. This growth was driven, not by demand for synthetic dyes, but by innovations that sprang from Germany's invention of the industrial R&D lab.[30] Vivien Walsh, a researcher at the University of Manchester, writes, "It was deliberate policy in Germany, after unification in 1871, to stimulate industrialization by encouraging science and technology. A tremendous investment in both academic and industrial research and development, the training of large numbers of scientists and engineers by establishing scientific institutions, and various official policies relating to finance and patents, all contributed to the rapid rate both of scientific discovery and innovation and to Germany's domination of the world chemical market."[31] From this point onward, as German research activities created improved products that found a home in the growing market, demand became an important driver of innovation. Decades later, after synthetic dyes had diffused through the world market, the level of innovation in synthetic dyes decreased as the technology life cycle reached maturity.

Electrification

The National Academy of Engineering has dubbed electrification the greatest engineering achievement of the twentieth Century — and it was largely achieved through technological development for its own sake, not in response to any price signals from electricity substitutes. The technology was built upon a series of storied discoveries prior to the Second Industrial Revolution, most notably Michael Faraday's invention of the first dynamo. By the late nineteenth century, academic work into the field had progressed to the point that it could be applied, in an early example of modern technological development flowing directly from the scientific knowledge.

Any discussion of modern electrification should start with the work of Edison, Tesla, and Westinghouse. Edison, of course, is well known as an inventor and innovator, and established one of the nation's first industrial research laboratories, six years before his first electricity generation systems went active in lower Manhattan and London. It was in this lab that Edison and his team of researchers steadily probed the technological frontier. A similar technological search process characterizes Tesla's development of the alternating current system, in response to the technical limitations of Edison's direct current. Tesla's alternating current, coupled with the development of the transformer under Westinghouse, eventually won out after a prolonged and exceedingly costly "War of the Currents."[32] Subsequent years saw efforts to accelerate cost declines and incrementally improve the technology as the market developed, as well as the invention of new technologies like the converter. Much of the work involved properly re-designing factories to make the best use of electrification and the new capabilities it offered.[33] Another critical innovation was the development of the steam turbine, in response to perceived technical limitations of existing steam engines. The steam turbine, developed through advances in knowledge in electrical engineering, represented a sharp break technologically with prior generators. However, it did not see extensive diffusion for several years as firms sought to continue making use of their existing equipment.[34]

One of the early goals for electrification was to replace gas-powered lighting. However, the historical record does not provide evidence of any particular price spikes in town gas. Rather, electric light offered several specific non-price advantages over town gas — for example, freedom from acidic fumes or vapor leakage and associated health hazards. Further, electricity was able to power machines that made certain technologies newly possible, from labor-saving household items to industrial turbines like those mentioned above. And each of these progressions was a product of the search for better ways of doing things — not of any change in price of the incumbent technology increased.

Automobiles

The development of the automobile was undertaken by enthusiasts, technicians, and hobbyists in the eighteenth and nineteenth centuries as a means to expand the frontier of transportation technology, not because of increases in the price of horses, hay, or oats. Nicholas-Joseph Cugnot, a French military engineer, is often credited with developing the first automobile in 1771. The steam-powered vehicle was highly unstable and had to stop every ten to fifteen minutes to rebuild steam power. In fact, the machine was mostly useless—it is primarily renowned for precipitating the world's first automobile accident when it crashed into a stone wall.

Like other examples on our list, the automobile is an accumulation of technological breakthroughs over several decades — a time span that would render the influence of any price spikes in substitute goods or inputs irrelevant.

Decades of experimentation and innovation would follow to develop a useful, practical model. Steam-powered designs competed with primitive internal combustion engines throughout the nineteenth century, yet even the most advanced models were "open topped, bone-jarring contraptions often steered by tillers" and of little commercial value.[35] Automobile innovation was energized in 1876, when Nicolaus August Otto invented a four-stroke internal combustion engine, universally incorporated into later models. In 1885, the German mechanical engineer Karl Benz developed the Benz Patent-Motorwagen, which, despite having only three wheels, tiller-controlled steering and a tiny fuel tank, is often credited as being the first practical automobile. The first automobile manufacturers and markets began to emerge in the late 1890s.

Yet, even as excitement about the "horseless carriage" began to grow among the general public at the turn of the century, the automobile's imagined potential far outweighed its market viability. Indeed, it became a status symbol for the wealthy.[36] It was not until the first decade of the twentieth century, with inventions like telescope shock absorbers and drum brakes, that the automobile became sufficiently reliable and viable for the general transportation market — in other words, adequate operability was needed, not a sudden increase in the price of alternate forms of transportation. Like other examples on this list, the automobile is thus an accumulation of technological breakthroughs over several decades — a time span that would render the influence of any price spikes in substitute goods or inputs irrelevant.

And what of the modern-day price disparities in fuel inputs? Gasoline taxes are substantially higher in Europe than in the United States, in some nations accounting for 60 percent or more of fuel prices and driving up fuel costs. Whereas mid-November retail premium gasoline prices in the U.S. reached $3.13 per gallon, prices in several European nations including Germany, France and the U.K hovered around $7.00 per gallon.[37] Has this led to disruptive innovation? No, of course not — but it has lead to something much more predictable: vehicle fuel economy standards and consumer expectations have responded accordingly over time, trading marginal behavioral changes and more-efficient existing technology for American-style cars and driving habits. The average fuel economy of the US passenger fleet in 2008 stood at just over twenty-two miles per gallon, whereas the fuel economy of typical European vehicles reached thirty or forty miles per gallon, and more efficient diesel engines are more common. [38] Europeans also tend to drive less. This is not a case of high prices spurring new technology; rather, it's a case of high prices making existing internal combustion technology more efficient.

Agriculture Mechanization

The agricultural sector presents an interesting case study in induced innovation and technological adoption. Indeed, diffusion of new agricultural technology has formed the basis for a large literature that illustrates both demand-pull and technology-push as the sources of different kinds of innovation. On the one hand, a fair extent of the diffusion of new technologies has historically been driven by changes in factor prices — so, for example, as labor becomes more expensive, technology adoption has generally occurred in a labor-saving direction. On the other hand, however, the roots of many of these innovations are found in efforts to expand the frontiers of knowledge and technology, outside of changes in price.

Perhaps the clearest example of this dynamic is the tractor. The first gasoline-powered tractor incorporated an adaptation of the internal combustion engine in the 1890s; the technology behind the engine itself, of course, had been in development for decades prior. The original tractor design was subsequently subject to multiple design generations and production-process innovations over succeeding decades. This period was marked by steady improvements in the fundamental technology and declining manufacturing costs as innovators sought to drive costs down, in a typical technology-push fashion as the technology matured over time.

Adoption did not accelerate until the 1920s, as technical improvements helped to boost tractor performance. Adoption of the tractor in the decades before and after World War II was a complex dance spurred by fluctuating prices of crops, labor, and alternatives to machinery like workhorses, and was tied to the slow conversion of farmland for mechanized production over several decades. Tractor sales peaked in the early 1950s, and by the 1960s the market was approaching saturation.[39] The diffusion of mature tractor technology was clearly induced by changing market conditions, but only decades after initial conception, when the technology could be developed to reach an adequate performance threshold so that short-term economic gains were clear and the risk was minimized. A similar pattern followed the self-propelled mechanized combine harvester.

What can we take from the experience of agricultural mechanization? An important lesson seems to be the role of both uncertainties and path-dependence in decision-making at the firm level. Diffusion was largely dictated at specific places and times by the character of individual farms, their existing capital stock and land-use patterns, their prior knowledge of mechanized tools and methods, and relative prices of products and substitute goods, not to mention the actual ability of machinery to perform the work adequately.[40] These factors, quite common in the diffusion literature, contributed to the perception of uncertainty and the assessment of risk by each farmer. Of course, for most farmers, the decision to adopt came long after the initial breakthroughs in mechanization, breakthroughs made before there was a viable market for mechanized products, and requiring a long period of product development. Many alternative energy technologies are still at this early development phase, while technologies reaching competitiveness and on the brink of diffusion are currently subject to the complex dance referenced above.

Lastly, it should be noted that substantial productivity improvements have happened *outside* the realm of pure mechanization, as public science institutions improved yields through new methods and breeds of produce, perhaps most notably in the realm of hybrid corn in the 1950s.[41] The role of public research programs in solving problems in agricultural science and engineering, and working with farmers to implement these solutions, has been central to domestic agricultural productivity gains for most of the twentieth century — and has largely occurred through a concerted effort to expand the boundaries of agricultural science over decades, rather than in response to changing market signals.[42]

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Airplanes

Like electrification and other general innovations on this list, the aviation industry has its own storied history, highlighted by the Wright Brothers' famous flight at Kitty Hawk. But the Wright Brothers were just two players in a large-scale narrative of a non-market supply of technology and knowledge expansion, which delivered a series of radical innovations creating the foundation for modern aviation. The search for manned flight, of course, was fundamentally a venture about new knowledge and technological capabilities, and not a reflection of any increase in the price of hot air balloons, railroads, or other forms of transportation, as indicated by the historical record.

An important area of discovery and technical advancement was in the aerodynamic character of wing shape and form and associated control surfaces. While the intellectual roots of this work extend back centuries, the most direct contributors to control surface technology were the diverse group of European researchers who developed gliders in the late nineteenth century. The advancements that allowed the first controlled glider flights included both horizontal and vertical control surfaces. A set of similarly diverse researchers expanded the bounds of technical knowledge that would lead to the aileron; the original holder of the American patent for the aileron was Alexander Graham Bell's Aerial Experiment Association. The Wright brothers themselves contributed critical insights while also drawing heavy inspiration from prior technical work. The first all-metal plane was developed by German mechanical engineer Hugo Junkers in 1917.

It is telling that some of the most critical advances in aviation technology followed the establishment of public institutions devoted to enhancing the supply of technology. The National Advisory Council for Aeronautics, a precursor to NASA, was established in 1915 in response to World War I, with the goal of pursuing “the scientific study of the problems of flight, with a view to their practical solution."[43] NACA would contribute significant, radical innovations to aviation through its laboratory research programs over the next few decades, notably including engine cowling and modern airfoils, and was also instrumental in establishing the industry-based Aircraft Manufacturers Association.[44] The early aviation industry had been marked by fierce legal battles over intellectual property, but the association removed such competitive pressures by establishing a cooperative patent pool, allowing greater technical flexibility on the part of manufacturers for the war effort.

The role of the military in producing or influencing technical change in the aviation sector should not be understated, especially with regard to modern jet propulsion technology.[45] The military needs of World War II served to drive the development of the jet engine in the United States, with the Air Force playing a critical role. Overseas, most major powers, including the United Kingdom and Germany, also moved aggressively towards jet engine development. The technology was first deployed within a fighter craft via the German Messerschmitt; generally speaking, wartime procurement drove private-sector knowledge gains that were later applied commercially across the industry. Again, evidence is scant that any of these innovations were induced via price changes in incumbent technologies.

Radio and Television

By now, the pattern of knowledge expansion and early-stage innovation, followed by later practical application and diffusion, should be apparent. In the field of radio and television broadcasting, early invention was built upon the work in electromagnetism by James Clerk Maxwell and Heinrich Hertz in the nineteenth century. Technological exploration was carried out by a clutch of early scientists and pioneers, including Tesla, before Guglielmo Marconi applied the technology in a primitive telegraphic system around the turn of the century.

The vacuum tube, so important for computing, also played a critical role in the development of early radio. The vacuum diode (1904) provided a technology that could receive radio signals, and the “Audion” (1906) provided a subsequent improvement that could both receive and send signals. Broadcast of the first AM radio program came in 1906. American inventor Edwin Armstrong further boosted the amplification of the triode, through the development of the regenerative circuit in 1912 and the superheterodyne circuit in 1917. The early wave of experimental stations gave way to regular commercial stations that proliferated in the 1920s, three decades after the initial breakthroughs.

Electromechanical television devices began to appear in the nineteenth century, and updated models were developed up through the 1920s. The first electronic television would appear in the late 1920s, utilizing the cathode ray tube invented in 1897. Competition for a growing television market would grow throughout the 1930s, but a variety of different television technologies persisted in different markets throughout the decade. The National Television System Committee, convened by the Federal Communications Commission, established national standards governing the technical aspects of black-and-white television broadcasting in 1941 (standards for color television would follow in 1953). Market diffusion would follow rapidly.

Electronics / Computing

Like advances in aviation and electrification above, the advent of modern electronics and computers presents another powerful example of the role of technology supply activities long before the establishment of anything that can be called a competitive market. And perhaps more than in any other industry, the role of public institutions in drawing the industry forward is clear.

The United States government played an enormous role in the long-term development of computing technology, with the military serving as a large early buyer and thereby creating a substantial early market. The first electromechanical calculators were built for Navy and Air Force usage in the early 1940s, and throughout the postwar years, domestic technology development was substantially driven by the needs of the armed forces, as well as NACA and other agencies. The Aberdeen Ballistics Research Laboratory funded the development of the first digital computer for the purpose of artillery calculations.[46] The military simply sought a better tool to perform these calculations; it was not responding to an increase in the cost of pencil and paper. This machine, dubbed the ENIAC (for Electronic Numerical Integrator and Calculator), was built at the University of Pennsylvania in 1946. The success of this machine spurred further military interest in more advanced machines, in spite of limited commercial applications at the time. This interest led to the EDVAC (Electronic Discrete Variable Automatic Computer), which also went to the Aberdeen lab, and the UNIVAC (UNIVersal Automatic Computer), the first of which was built for the Census Bureau. Public institutions and universities played a pivotal development role through research funding and procurement in the early years.[47]

The next revolution came with the invention of the point-contact transistor at Bell Labs in 1947, as the result of long-term efforts to boost the electrical amplification of semiconducting material for communications technology — a development that did not arise because existing substitutes became more expensive. Researchers spent the next few years improving the design of their new device, and would ultimately be awarded the Nobel in 1956. The first-generation transistor-based computers (as opposed to the vacuum-tube-based) began appearing in the 1950s, with the first commercial transistor computer produced by IBM in 1959. Federal contracts and procurement continued to play a crucial role in industry development, though the private sector also saw substantial growth.[48]

Researchers at Texas Instruments invented the integrated circuit in 1958, followed in short order by a silicon-based microchip at Fairchild Semiconductor. In the decade that followed, primary demand for these chips came from the Air Force and from NASA's Apollo program; Stanford professor Scott Hubbard has emphasized the role NASA played in driving technological development by saying that without the Apollo program's push for high performance, "you wouldn't have a laptop. You'd still have things like the UNIVAC."[49] By the end of the decade, Intel would develop the first microprocessor — an integrated circuit designed specifically to process information, rather than simply store it — and computers employing the device began appearing in the early 1970s. Public support for the growing industry remained critical throughout this time period.[50] As early technical and knowledge advances were driven largely by military procurement, in the 1970s the military was also largely driving expansions of basic computer science knowledge through R&D funding, including through the Advanced Research Projects Agency, which would eventually develop the computer network now known as the Internet.[51]

We wrap up this brief tour with two final examples from the energy technology realm.

Gas Turbines

Like other technologies mentioned above, modern gas turbines have their roots in scientific and engineering discoveries achieved over centuries: in fact, the first patent for a true gas turbine was granted in 1791, though workable models wouldn't emerge until the early twentieth century. The foundational technology for the modern gas power industry, however, came not from changes in the price of coal, oil, or other energy sources, but from the impetus of war: specifically, from efforts by the United States, Germany and the United Kingdom to develop jet engines before and during World War II, as mentioned above.

The foundational technology for the modern gas power industry came not from changes in the price of coal, oil, or other energy sources, but from the impetus of war: specifically, from efforts by the United States, Germany and the United Kingdom to develop jet engines before and during World War II.

During and after the war, the military invested large sums in jet engine R&D and procurement, fostering the infant turbine industry, much as it was doing for computers around the same time.[52] Apart from aviation, it was apparent from the beginning that the new engines powering military aircraft could also be modified for electric power generation. Over the following decades, military jet engine R&D provided significant opportunities for spillovers, spin-offs, and other contributions to the commercial gas turbine sector.[53] Private industry moved into commercial gas power beginning with industrial applications in the 1950s and 1960s, as jet engine and gas turbine development paths split and energy-specific R&D picked up. Meanwhile, the Federal Power Commission established interstate price controls, initially making gas an attractive energy source to consumers for peak demand and expanding the market in the late 1960s; its attractiveness was also helped by the fact that natural gas turbines' technical performance was a better fit for peak power needs than steam turbines, which were slower to stop and start. However, price controls on natural gas also reduced the incentive for suppliers to further expand supply to meet this demand. States without robust intrastate natural gas production and trade began to experience gas shortages in the 1970s, and the national market began to contract.[54]

Nevertheless, in spite of both price controls and market contraction, manufacturers achieved steady improvements in turbine performance and cost trends. An important development was the introduction of cooling technology, which the private sector was able to transfer from military jet usage, drawing in part on analytical tools developed by NASA, and from work under the federal High Temperatures Technology Program. The 1960s and subsequent decades also saw the evolution and steady improvement of now-common combined cycle technology through intensive private-sector R&D.[55] Finally, the Department of Energy's Advanced Turbine Systems Program, a collaborative public-private-university venture in the 1990s, contributed to the advent of next-generation turbines this decade.

In terms of market diffusion, gas turbines stagnated in the 1970s and 1980s for a few reasons, including the supply shortages described above. Earlier price controls remained in place until the passage of the Natural Gas Policy Act in 1978. This act sought to deregulate gas prices by 1985, but also allowed gas prices to spike significantly in the years immediately after passage, thus delaying its eventual competitiveness. The Power Plant and Industrial Fuel Use Act, also passed in 1978, further restricted market growth by placing limits on gas usage, under the mistaken assumption that the nation's natural gas supply was limited. These limitations were partly counteracted by the 1978 passage of the Public Utility Regulatory Policies Act, which promoted cogeneration facilities. Price deregulation was completed by 1985, the Fuel Use Act was lifted in 1987, and the market for gas turbines soon expanded rapidly.[56] Natural gas became the major source of capacity expansion in the 1990s.[57]

Clearly, the natural gas turbine market has experienced turmoil over the past few decades, due in no small part to mistaken regulatory actions. Yet technological improvements continued steadily. At its heart, gas turbine development is a story about technology supply, and not about price-induced innovation. The original foundations were laid by military technology, and the power applications gestated for decades before the late-century market boom. Turbine technology was marked by steady incremental performance improvements even during the 1970s and 1980s, when the market stagnated. Ultimately, the development trajectory demonstrates a directed, strategic effort from private and public sector actors alike.

Wind Power

Power generated from wind has a centuries-long history; for this discussion, we'll focus on modern turbine technology. The modern era of turbine development began in the 1970s, coinciding with that decade's energy shocks. The price of oil more than doubled in the period 1973-1974, and doubled again in the period 1979-1980.[58] Prices of other energy sources like coal also doubled over the course of the decade, yielding what would seem to be a natural experiment in how price changes impact innovation. It is worth bearing in mind that the magnitude of these energy price changes is very different from the potential effects of the relatively modest cap-and-trade or carbon tax proposals for slow, steady price increases over the long run. Nevertheless, because of this large increase in price, neoclassical economists might have predicted rapid private-sector innovation as firms responded to changing market conditions. So did this actually happen?

Private sector R&D did in fact react to these massive price spikes. A report for the Pacific Northwest National Lab finds a "large surge in U.S. private sector investments in energy R&D that peaked in the period between 1980 and 1982 at approximately $3.7 billion to $6.7 billion per year" in 2010 dollars. But a substantial portion of this increase was in fossil fuels.[59] Further studies have shown that much of this research also focused on energy efficiency and conservation, as energy intensity steadily improved.[60] Ruttan thus states that the price spike ended up "biasing the technical change in an energy-saving direction."[61] On balance, then, much of this work sought to simply minimize the more expensive energy inputs. This incremental result is not unexpected, and will be discussed further in the next section.

At the same time as private R&D increased, federal energy R&D also spiked — and here we see some substantial results for wind energy technology. Early wind power research in the U.S. was carried out by two programs: a large joint NASA/DOE program, and a smaller program administered by DOE through the organization that would become the National Renewable Energy Lab. The larger program was ultimately unsuccessful in producing viable, commercially applicable technology, but did yield some beneficial technical demonstration results. On the other hand, the smaller NREL program found substantial early research success. As Harvard's Vicki Norberg-Bohm wrote, "Of the 12 key innovations in wind turbine components…seven relied on partial or total public funding, and three were developed in the private sector for other industries and transferred for use in wind turbines."[62] It should be noted that the same study finds a similarly high ratio of public or public-private funding of key solar photovoltaic innovations.

When it comes to developing new radical technologies, ensuring a healthy supply of technology through R&D activities is the critical component, not changes in prices of competing goods.

So what does this brief history tell us about the relationship between disruptive innovation and price changes? Again — as should also be clear from the preceding overviews — when it comes to developing such radical technologies, ensuring a healthy supply of technology through R&D activities is the critical component, *not* changes in prices of competing goods. Further, policy support is frequently necessary to achieve these breakthroughs, allowing for high-risk, directed research and counteracting systematic underinvestment in private sector R&D.

Price changes do not lead to radical innovation — but they *can and should* play a role in a comprehensive clean energy policy regime, as will be discussed below.

WHAT A CARBON PRICE CAN DO

The above examples do not necessarily imply that there is no place for a carbon price in spurring the development and deployment of new clean technologies. To the contrary, a modest carbon price could help to alter individual consumption as well as investment decisions in the power sector to boost the diffusion of mature, available alternatives, initially through incremental substitution — the so-called low-hanging fruit, including wind at peak hours, and energy efficiency measures. In the energy context, a marginal increase in the price of fossil energy may induce a manufacturer to seek more energy-efficient capital equipment or processes, as happened in the 1970s. And as many have pointed out, there could be *substantial* economic gain from incremental improvements in energy efficiency and carbon productivity, even if efficiency gains are only part of a sound strategy for decarbonization. For example, the McKinsey Institute has estimated that $170 billion in investments over ten years could yield $900 billion in energy savings.[63]

The tendency for firms to seek low-hanging fruit first is aligned precisely with the original insight on induced innovation, provided by economist John Hicks early in the twentieth century: "A change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind — directed to economizing the use of a factor which has become relatively expensive."[64] In other words, when an input gets more expensive, private firms will seek the least expensive means to minimize that input. A higher price on carbon means a more energy-efficient economy, but does not mean the large-scale substitution of new clean technologies for dirty old ones, unless viable, low-risk, reliable, and affordable new technologies are readily available—and they are *not* currently available in the clean energy space.

One illustration of this principle is seen in Europe's responses to higher gas prices, mentioned above: rather than turn to electric cars, Europeans simply rely on more efficient but common diesel engines, and drive less. Another readymade example is found in the experience of Norwegian firms with a carbon price. In the 1990s, Norway passed a series of carbon taxes at varying rates, targeting a variety of offshore and onshore energy sources including gasoline, mineral oil, and coal. Several energy-intensive onshore industries were exempt, and the tax ended up covering 52 percent of the nation's greenhouse gas emissions.[65] The tax began at approximately $50 per ton of CO2 for offshore emitting activities in the middle of the decade (though it has since been lowered).[66]

Accordingly, offshore petroleum and gas firms operating on the Continental Shelf took several innovative — but generally incremental — steps. Statoil, the largest entity operating in the region, undertook several process innovations, switched to more energy efficient gas turbines, and other steps. Norsk Hydro purchased a land-based combined cycle gas turbine — well established, mature technology on land — and adapted it to offshore platform use. An attempt was made to power offshore gas field development via onshore hydroelectricity, but these plans were eventually discarded.[67] Lastly, the carbon tax drove the four firms that owned the Sleipner natural gas field to capture and sequester their carbon emissions. This was a notable development, as it was the first such commercial venture in the world; however, the project used readily available technology that had been in use for years, albeit in different contexts. Helping this decision was the fact that the firm was able to recover expenses in approximately eighteen months.[68] In all of these cases, the technology necessary to achieve change was relatively mature, and posed only moderate uncertainty; new inventions were not required. As Christiansen writes in his study of the Norwegian Continental Shelf case, "The rate and direction of technological change is mostly associated with cumulative improvements, incremental process innovations, technology adaptation, and dissemination of technologies already available."[69]

A further demonstration can be found in the implementation of the sulfur dioxide emissions trading program under the 1990 Clean Air Act amendments. Flue gas desulfurization units, known as scrubbers, were an important tool in mitigating SO_2 emissions, and were thus a primary target for technical improvements once the emissions trading program was established. The technology for these units was fairly low-risk and well-known: its initial application came prior to World War II, with multiple generations under development over many years. EPA pursued a successful R&D program in the early 1970s, conducting basic research, development, and demonstration, with industry input, to develop new scrubber methods and improve technological efficiency.[70] Indeed, steady performance improvements had been underway for some time upon the adoption of regulatory measures to accelerate their adoption, meaning that private emitters had viable technologies readily available.

Higher SO_2 emissions costs further helped diffusion by tipping the balance of market forces further against the costs of polluting; increasing these costs also induced incremental changes like fuel switching and blending.[71] This kind of activity is fairly common in policy areas where there is clear and fairly predictable short-term economic gain for innovative activities: firms are more likely to seek increases in the productivity of existing technology, than to displace older technologies with immature and risky new ones, if for no other reason than that it's bad business.

A transition to a low-carbon economy will require activities of a very different magnitude. Nevertheless, a carbon price may be expected to induce a level of technical change along incremental, predictable paths that include energy efficiency. A carbon price could also serve as a revenue generator to invest in needed clean energy innovation. And, as we stated above, a carbon price could improve cost-competitiveness of existing near-market, low-carbon generation technologies, thereby improving incremental adoption and diffusion. However this will happen only if the price is high enough to push new technologies past the competitiveness threshold in electricity markets; the infrastructure is in place to support them; financing for capital-intensive projects is available; and all of the necessary supporting innovations are mature and deployable. The increased incremental adoption of such technologies could also accelerate learning curves where available — though there is no guarantee that any productivity or performance gains by existing clean technology could yield sufficient price declines to make them competitive without subsidy.

So, to summarize our expectations: if a carbon price were adopted in the absence of strong federal support for energy innovation, we would expect firms to squeeze out productivity from existing technology first — which is not a bad thing — and switch to newer technologies later assuming viable alternatives exist, are available at acceptable costs, and do not pose excessive risk. A mild carbon price thus has a role to play in inducing investment and in reducing per-capita emissions, but it will be far from sufficient to meeting the long-term challenge on its own.

POLICY IMPLICATIONS

The conventional wisdom, based on the neoclassical economic doctrine, is that a price on carbon — whether through a tax or an emissions trading regime — would spur the private sector to deliver the massive technological innovation we need to address the world's energy challenge. To assess this claim, we have reviewed the theoretical underpinnings of technical change, identified the dual forces — technology push and market pull — that may lead to innovation, and reviewed the sources of well-known and not-so-well-known innovations.

Our results show that non-incremental innovation comes from investment in directed research activities and technology development — not from changes in price. This is not surprising given the high levels of risk associated with early-stage R&D, the long development time scales, the difficulty private firms have in recouping the financial benefits of R&D activities, and the need for firms in competitive markets to allocate their limited resources on ventures with relatively reasonable certainty of gainful outcomes. As such, market-based price signals tend to be better suited for inducing incremental technological improvements, in which private firms are able to rationally identify the short-term economic costs and benefits of a given activity and adapt.

That said, while we are skeptical that a carbon price could induce radical innovation, we acknowledge that a carbon price could expand the market size for clean technology and contribute to incremental technological innovations. Likewise, we invite our neoclassical colleagues and others who have argued for the primacy of a carbon price to acknowledge that prices are *not* the be-all, end-all when it comes to clean energy innovation, and that support for clean energy innovation is just as critical.

What does this mean for the carbon price debate? It should be clear by now that a carbon price is *not* an adequate solution to our technology barriers and will *not* deliver the kinds of revolutionary technologies experts say we need. Rather, a truly effective, comprehensive approach would be to directly support the development and deployment of technology at all stages. The level and kinds of specific policies will vary based on where in the development cycle the technology resides. That means ensuring an early-stage supply of technology, including through robust R&D support, as well as supporting early markets and ensuring that existing institutions are properly aligned to facilitate deployment. For example, an early-stage technology may need institutions like NSF, ARPA-E, or the national labs to assist with basic or applied research and funding, while a later-stage technology may require institutions like DOD to assist with technology demonstration and provide an early market through procurement, or like the proposed Clean Energy Deployment Administration (CEDA) to support financing and translation to the marketplace. All of these programs would have to be designed to ensure maximum collaboration between public and private sector entities, and with a mind towards eventual commercialization and use. This also suggests the need for tax policies that support innovative activities and high levels of human capital.

A truly effective, comprehensive approach will directly support development and deployment of technology at all stages; the level and kinds of specific policies will vary based on where in the development cycle the technology resides.

Finally, we offer three foundational principles upon which any effective clean energy innovation policy should be built.

Develop a National Energy Innovation Strategy

Because of the size of the challenge and the heterogeneous nature of technologies, it's important for any policy framework to adhere to a clear coordinated strategy to boost the supply of technology. Such a strategy should recognize the complexity of the innovation process and the role institutions must play; identify specific technical challenges and barriers to target those areas where clear help is needed, and where the best chances for success lay; establish clear, achievable targets and benchmarking to ensure effective and efficient activities and pursuit of learning curves; and organize the proper resources to meet the energy challenge. The strategy should also ensure that the private sector plays a prominent guiding role, as close public-private collaboration has historically produced great success in technical innovation, while lack of collaboration has been a recipe for failure. An effective strategy would also be mindful of the need to develop a high-skilled workforce. It would ensure both that adequate energy infrastructure is in place, and proper alignment and long-term stability of research tax incentives, intellectual property law, and technology transfer programs.

Expand Public Investment in Clean Energy Innovation

The private sector tends to underinvest in early-stage research activities due to significant market failures and uncertainties, and public-sector research is critically important. This implies strong and persistent public-sector funding and incentives for technology research, to be carried out both by public and private-sector actors. An innovation economics approach also recognizes, however, that not all R&D activities are created equal, and that different institutions possess different strengths. R&D programs should be aligned to play to the strengths of both public research institutions and private research ventures.

Support Technology Throughout the Development Cycle

Technological innovation doesn't occur through market activities alone. Rather, it occurs along a clear continuum, from the search for basic knowledge, to high-risk applied technology development, to demonstration and pilot projects, and finally to market deployment and diffusion. Technologies at different points on this continuum require different kinds of support, and policies should reflect this need. Early-stage research implies funding for basic sciences and university researchers. Technology development occurs both in public and private laboratories and funding and tax incentives should reflect this. Demonstration programs test proof-of-concept, and market viability. As products move towards the market, risky or advanced new products may need financing assistance, loan guarantees, and manufacturing tax credits. Finally, federal policy can support markets for new clean energy products through targeted procurement or other measures.

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