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Rescuing the Low-Carbon Energy Transition From Magical Thinking

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Easy answers alleviate stress, avert change, and attract followers. Yet wishing that something is so does not make it so.

INTRODUCTION: NO EASY TRANSITION

In the past few years, the United States has taken important initial steps toward creating a low-carbon energy system. Total carbon-dioxide emissions peaked in 2007 and had fallen by about 9 percent in 2014. Carbon intensity, the amount of carbon emissions per unit of energy consumption, has declined at an even faster rate.[1]

Buoyed by this modest success, the United States helped shepherd the most recent round of global climate negotiations to a successful conclusion in Paris last year. The United States' Intended Nationally Determined Contribution (INDC), as commitments in Paris are known, is to reduce net greenhouse gas emissions by 26 to 28 percent below 2005 levels by 2025. The United States also committed to reduce emissions by 80 percent or more by 2050.[2]

If the nation is to fulfill these aggressive commitments, it must take many further steps along the low-carbon energy path. Energy use is responsible for 84 percent of total greenhouse-gas emissions. The substitution of natural gas for coal in electricity generation has driven recent emissions reductions, but natural gas will have to be replaced by even lower carbon resources in the not-too-distant future to meet this lofty goal. Transportation, now the nation's largest greenhouse-gas-emitting sector, will have to shift dramatically away from its dependence on petroleum. Buildings, appliances, industrial processes, and other end uses will have to continue to become less energy- and carbon-intensive, but even more quickly than they have in the recent past.

This transition will not be easy. Americans spent about $1.4 trillion on energy in 2014.[3] An enormous infrastructure extracts, processes, and delivers energy, and an even more enormous one uses it. The smooth operation of this infrastructure is essential to daily life. Our livelihoods, leisure, and well-being depend on it. The energy infrastructure is the supertanker of all supertankers—the source of the supertanker metaphor itself—and it will not change direction quickly. Prior transitions on this scale have taken roughly 100 years. None were driven by environmental concerns. The immediate needs of energy users and the price and performance of alternatives were the driving factors.[4]

Climate change is a global problem, so the low-carbon energy transition must also be global. Other high-income nations face challenges comparable to the United States. Lower-income nations face the additional challenge of building out a low-carbon energy infrastructure that will reach billions of people who currently lack essential energy services (lighting, cooling, heating, etc.). If these nations follow the fossil fuel-dependent development path that the West paved, the environmental consequences will be horrific.

Given the enormity of the challenge and the dire consequences of failure, it is not surprising that magical thinking about the energy transition is abundant. Easy answers alleviate stress, avert change, and attract followers. Yet wishing that something is so does not make it so.

Neither markets on their current trajectory nor social movements in the most optimistic scenario will produce the innovations that we need.

This paper describes four forms of magical thinking about the energy transition that are prevalent in the United States. "Climate-change denial" wishes away the need for any transition at all. "Science push" sees the transition as a mere matter of adequate investment in R&D. "Premature triumphalism" assumes that the necessary technology is available today and that the only barrier to the transition is willpower. "Carbon-price obsession" fixates on a single, simple policy that will by itself drive the transition.

Excepting the first, which must ultimately be overcome, each of the other three approaches has important contributions to make to a policy package that will accelerate the United States along a low-carbon energy path and, by doing so, help the world move in the same direction. Yet their advocates must also let go of certain illusions if they are to join together in the broad coalition that will be required to make a social change of this magnitude.

At the core of these illusions is certainty about the low-carbon energy path. A process as complex as this energy transition is intrinsically uncertain. No one technology nor policy nor behavioral adjustment is guaranteed to work. We need to generate innovative options, explore them in practice, gauge their value, and scale those that work as rapidly as possible. These options must include new technologies and new combinations of existing technologies, along with associated business models and behavior patterns.

All sectors of society will have to play important roles for the transition to occur. Businesses are especially important for exploration, valuation, and scaling of innovations. But government, especially the U.S. federal government, must lead. Neither markets on their current trajectory nor social movements in the most optimistic scenario will produce the innovations that we need.

Current federal policy falls far short, in no small part because of magical thinking. After reviewing the four forms of magical thinking, the paper concludes by advancing an aggressive, smart low-carbon energy innovation-policy agenda. The key items on the agenda include:

- Establishing a dedicated funding source for federal low-carbon energy-innovation investments.
- Steadily expanding federal investment in basic research fields that have the potential to dramatically accelerate low-carbon energy innovation.
- Dramatically expanding federal co-investment in applied research, demonstration, and infrastructural technologies for low-carbon energy.
- Enhancing connectivity and strengthening user pull along the low-carbon energy-innovation chain.
- Fostering regional collaboration for innovation in large-scale, low-carbon energy systems.
- Reforming low-carbon energy tax incentives, so they are permanent and technology-neutral, and phasing out support for each generation of technology as it matures.
- Using federal procurement strategically to build momentum for early deployment of low-carbon energy innovations.
- Encouraging business-model and regulatory innovation in conjunction with technological innovation in the electricity and transportation sectors.
- Tightening energy efficiency and carbon-control regulations in a predictable, innovation-inducing manner.

CLIMATE-CHANGE DENIAL: THE MOST HARMFUL FORM OF MAGICAL THINKING

The beliefs that climate change is not happening, is not human-caused, and is not harmful, and that therefore there is no need for a transition away from dirty energy, comprise the most harmful form of magical thinking. Climate-change denial has subverted public understanding and sidetracked public policy. While it might be possible to find points of commonality on an energy-innovation policy agenda with some of those who hold this position in the short run, there is bound to be a divergence in the long run.

In the Information Technology and Innovation Foundation's (ITIF's) 2013 report "The Logic Chain to an Effective Global Clean Energy Policy," Matthew Stepp and Megan Nicholson briefly reviewed the compelling scientific evidence that links carbon-dioxide emissions from fossil-fuel use to detrimental changes in the global climate.[5] The evidence has grown stronger since that report was issued. The 2014 report of the Intergovernmental Panel on Climate Change (IPCC), for instance, concluded that carbon-dioxide levels "that are unprecedented in at least the last 800,000 years" are (along with other drivers) "extremely likely to have been the dominant cause of the observed warming since the mid-

20th century." The IPCC linked human-caused warming to a host of emerging negative consequences and warned that the "continued emission of greenhouse gases increased the likelihood of severe, pervasive, and irreversible impacts for people and ecosystems."[6]

More recent research has brought those negative consequences into sharper focus. For example, researchers have made progress in identifying the regional effects of climate change, linking storms, droughts, and other extreme events to changes in the global climate system. They have also demonstrated the rising risks of infectious disease, which are caused by the extended geographical ranges of pathogens enabled by the warming climate. These two research areas together highlight the vulnerability of coastal cities, including the majority of the world's most populous urban areas, to climate change in the coming decades. In addition, a variety of challenges to earlier research, such as inconsistencies between the ground-based and satellite records of global temperatures, have been overcome.[7]

It is possible that the scientific consensus on harmful, human-caused climate change is wrong. The global climate is a complex and dynamic system, and its interactions with other complex and dynamic systems, such as the biosphere and human society, make the problem of predicting its future course and consequences exceptionally difficult. Yet forecasts of the impact of rising greenhouse gas concentrations on global temperatures made decades ago using simple models have proven to be surprisingly accurate, and a range of other physical and biological phenomena that were anticipated by pioneers in this field have now been observed. Moreover, the consensus might as easily be underestimating the severity of the impacts as overestimating them.[8] Given the scale of the risks involved, prudent policymakers might reasonably seek insurance against these risks, even if they have doubts about the consensus.

Unfortunately for the United States and, by extension, for the world, many policymakers have ignored or denied the evidence. House Science Committee Chairman Lamar Smith (R-TX), for instance, has rejected the reconciliation of past inconsistencies in the ground-based and satellite temperature records, subpoenaing scientists engaged in this research and calling on them to "come clean about why they altered the data to get the results they needed to advance this administration's extreme climate change agenda."[9] Senate Majority Leader Mitch McConnell (R-KY) denies the scientific consensus, stating "For everybody who thinks it's warming, I can find somebody who thinks it isn't."[10] Donald Trump, the 2016 Republican presidential nominee, puts it this way: "Global warming is based on faulty science and manipulated data."[11]

In doubting the evidence for harmful, human-caused climate change, these political leaders rely not on the vast majority of scientists, but on a dwindling minority who dissent, nonexperts who claim to be experts, and parties with a financial interest in sustaining fossil fuel use. As the historian Naomi Oreskes and her colleagues show, "low estimates of consensus arise from samples that include non-experts such as scientists (or non-scientists) who are not actively publishing climate research, while samples of experts are consistent in showing overwhelming consensus."[12] Systematic, long-term efforts by leading petroleum firms to sow confusion and doubt about climate change have been documented by investigative journalists recently as well, sparking an investigation by the New York attorney general.[13] Donald Trump's chief energy adviser, Harold Hamm, is the CEO of Continental Resources, a leading independent oil producer in the United States and the largest leaseholder in the Bakken oil field in North Dakota and Montana, and obviously has a vested interest in this issue.[14]

Adherence to climate-change denial may be heartfelt, or it may be an indirect way to oppose regulatory and tax proposals made by some low-carbon energy advocates. Either way, the worst form of magical thinking has contributed significantly to the gridlock in U.S. climate policy and associated efforts to stimulate low-carbon energy innovation. The intense conflict over appropriations for the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), for example, has its roots in this faction. More profoundly, climate-change denial by political leaders misleads the American public. As Oreskes and her colleagues put it, "Public perception of the scientific consensus has been found to be a gateway belief, affecting other climate beliefs and attitudes including policy support. However, many in the public, particularly in the United States, still believe scientists disagree to a large extent about anthropogenic global warming."[15]

Political leaders who doubt evidence for harmful, human-caused climate change rely not on the vast majority of scientists, but on a dwindling minority who dissent, nonexperts who claim to be experts, and parties with a financial interest in sustaining fossil fuels.

To be sure, there are reasons other than climate-change denial to take issue with specific policy proposals to reduce carbon emissions. Correspondingly, it may be possible to find common cause with climate-change deniers to advance elements of a low-carbon energy innovation program. Reducing coal consumption will improve local air quality and the incidence of asthma in children, for instance. Innovations that improve building-energy efficiency will free up cash for other forms of investment or consumption with no loss of comfort at home or work. Enhancing the responsiveness of the electrical grid will make it more resilient to terrorism and natural disasters.

Eventually, however, such strange bedfellows' coalitions are bound to dissolve. Other harmful emissions from fossil-fuel combustion can be scrubbed, for instance, without reducing carbon-dioxide emissions. Absent concern about climate change, the benefits of energy efficiency accrue more to private actors than to the public, undermining the rationale for policies to promote it. The requirements to ensure the security and reliability of a grid dominated by fossil-fuel-fired baseload power plants will diverge from those for a more diversified and flexible low-carbon grid.

The bottom line is that climate-change denial will ultimately have to be overcome if a low-carbon energy-innovation policy agenda is to succeed. That task lies outside the scope of this paper, but is critical to achieving the paper's ends.

THE PERILS OF PUSH: SCIENCE IS NOT (BY ITSELF) INNOVATION

The three other forms of magical thinking—"science push," "premature triumphalism," and "carbon-price obsession"—are far less pernicious than climate-change denial. They rest on important, but limited, insights and point toward essential, but partial, policies.

Unfortunately, the limits and partiality of these forms of thinking constrain progress toward innovative solutions to the low-carbon energy challenge.

The "science-push" argument rests on the insight that today's technologies are inadequate to serve as the infrastructure of a low-carbon energy transition, and it points to the conclusion that public investment in energy R&D should be significantly increased. Both the insight and the conclusion are valid, but to leave it at that is akin to casting a spell. The magic involves wishing away the profound advantages of incumbent energy technologies and the pervasive barriers to commercializing R&D results in this field. Sprinkling loads of fairy dust in the form of research grants and development contracts may make scientists happy, but it will not by itself turn our fossil-fuel frog into a low-carbon prince.

Princeton physicist Freeman Dyson is a pure exponent of science push. He places his faith in the development of genetically engineered carbon-eating plants. "After we have mastered biotechnology," he writes, "the rules of the climate game will be radically changed. In a world economy based on biotechnology, some low-cost and environmentally benign backstop to carbon emissions is likely to become a reality."[16] Others of this persuasion imagine nuclear fusion to be the "holy grail."[17]

Unfortunately, there is no such automatic, market-based pipeline—not in the fracking case, not in general, and certainly not in the low-carbon energy transition.

Manhattan Institute fellow Jim Manzi, who sharply criticizes fellow conservatives who fail to accept the scientific consensus on climate change, is not attached to any particular technological solution. He envisions the transition being driven by breakthroughs that may not yet be known. These breakthroughs, he posits, will emerge from government-funded labs and be taken up by private entrepreneurs who are endowed with strong property rights and operate in competitive, lightly regulated, and lightly taxed markets.

Manzi offers hydraulic fracturing, which has transformed the U.S. oil and gas industry over the past decade, as a case in point. Federally supported research in fields like geology and computing provided the knowledge base for this breakthrough; independent companies like Mitchell Energy ultimately combined public knowledge with their own R&D and applied the results in the field. The shale gas revolution that Mitchell led has been a major factor in reducing U.S. carbon emissions in recent years (although to meet national targets in the coming decades, natural gas will itself need to be replaced by lower-carbon resources). Manzi draws the lesson from this case that the federal government should "invest in visionary technologies that are too long-term, too speculative, or have benefits too diffuse to be funded by private companies," but do little else.[18]

Manzi's position recapitulates the "pipeline model" of innovation, which has long reigned in many corners of Washington. It reconciles conservative principles articulating a limited role for government in society with the undoubted fact that private investors will underinvest in "visionary technologies," because it is too hard to make money on them. If only there were a "pipeline" that would seamlessly transfer ideas from researchers to investors who could make money on them, the government's only essential role in innovation would be to fund research.

Unfortunately, there is no such automatic, market-based pipeline—not in the fracking case, not in general, and certainly not in the low-carbon energy transition. Michael Shellenberger and his colleagues at the Breakthrough Institute have documented the multiple, complex roles that public policy played in the development of fracking. The federal government not only funded fundamental research that contributed to this innovation, it also supported demonstration projects, countenanced and funded industry-wide collaboration that might otherwise have drawn antitrust scrutiny, and provided tax breaks for companies developing and deploying the technology. These efforts not only generated new knowledge, they also solved real-world problems that ultimately brought costs down and reduced risk to the point where the industry could take off without government support. The innovation process took several decades and involved inspired moments of "sheer desperation," without which it might easily have failed.[19]

The debunking of the pipeline model long predates this case study. The Department of Defense (DOD) famously butted heads with the National Science Foundation (NSF) in the 1960s when the two agencies commissioned rival studies to substantiate their contrasting approaches to science funding. The DOD's Project Hindsight concluded that basic research had made only a modest contribution to the enormous technological capabilities that it had built up in the early Cold War. NSF's Technology in Retrospect and Critical Events in Science (TRACES) study rebutted this proposition but nonetheless conceded that the pipeline model was wholly inadequate to explain the sources of innovation.[20] Generations of scholars since these studies have shown the complementarity of "science push" and "demand pull" in driving innovation. Princeton's Donald Stokes summed up the debate in 1997 by invoking Louis Pasteur, who drew insights that led to his pioneering germ theory of disease from his industrial experience, as a metaphor for the productive combination of "science push" and "demand pull."[21]

The energy transition poses even greater difficulties for the science-push approach than advances in defense and medical technology. The government is the sole source of demand for defense technology and, often during the Cold War and post 9/11 periods, has had a nearly unlimited budget to pursue technological innovation. In medicine, the government is a major source and mediator of demand; it provides health insurance to a large fraction of the U.S. population and subsidizes and regulates health insurance for the rest. Popular support has yielded a federal nondefense R&D budget that is disproportionally weighted in favor of biomedical research. In energy, by contrast, government demand makes up a relatively small fraction of the market, and even during the energy crisis of the 1970s, energy R&D programs were never given the blank check accorded their defense and biomedical counterparts. [22]

The challenges of commercializing and scaling up fracking pale in comparison to those that may face newer energy innovations.[23] Fracking provided a new way to produce a familiar fuel. Millions of American consumers were already using this fuel, thousands of companies were involved in producing and distributing it, and billions of dollars were invested in them. Fracking, in other words, entered into a well-established system of societal support, especially in places that had a preexisting oil- and gas-producing sector, like Oklahoma and North Dakota. If anything, despite all the trials and tribulations involved in bringing it to fruition, this technology was accepted too easily, while potential risks, like the possibility of triggering earthquakes and increasing methane emissions, were shrugged off.

For low-carbon energy innovations that lack such a system of organized production and social support, the processes of commercialization and scale-up are likely to be more difficult. Consumers will have to become comfortable with the technology. Businesses and workers will have to learn how to produce and install it. Financial markets will have to figure out how to value companies in the new field. Supporting infrastructure, such as pipelines, grids, and transportation, will have to be developed and put in place. (It should be noted that Manzi calls for government investment in physical and digital infrastructure as well as R&D.) Legislators and regulators may be required to adapt policies that were designed for older technologies in order for the newer ones to thrive. All of these barriers serve to "lock in" incumbents and "lock out" alternatives, compounding the lead provided by more than a century of investment that has made fossil-fuel energy so affordable and reliable.[24]

The threat of "stranded assets" also reinforces "lock out." If the low-carbon transition is successful, it is likely that the value of some existing technologies and infrastructure will be significantly diminished. This threat will intensify opposition to the transition from incumbents who could lose their investments, their livelihoods, and their status in society. The stranded-assets challenge goes far beyond retiring fossil-fuel-fired power plants before they wear out, wiping out physical facilities and financial investments. Coal miners and petroleum engineers (to pick just two examples) may not only lose their current jobs, but also their future earning power. Governments that represent fossil-fuel areas will see their tax bases erode. Values and identities may well be at stake in the transition, provoking the most bitter forms of political conflict.[25]

Science push alone is no match for social pushback of this magnitude. The entrepreneurs in whom Manzi places his faith can certainly make a difference in easing the entry of innovations and gaining societal acceptance. Elon Musk's Tesla, for instance, has given electric vehicles a much more attractive image than they had. But NASCAR has hardly gone out of style, and some truck owners have taken to modifying their vehicles to maximize their emissions (known as "rolling coal") as a protest against environmental activism and government regulation. "Why don't you go live in Sweden and get the heck out of our country," wrote one such owner. "I will continue to roll coal anytime I feel like and fog your stupid eco-cars."[26]

A low-carbon society should be able put up with a few coal-rolling eccentrics. But they must be few and marginal, while the mainstream accepts and values what is today on the margin. That process of acceptance, contrary to the pipeline model, will not follow automatically or quickly from laboratory publications, even were the United States to have even freer markets, stronger property rights, and fewer regulations than it has now. Fossil fuels are simply too cheap, too familiar, and too comfortable to be displaced on a time scale that will avoid the worst consequences of climate change if we rely on science push.

An aggressive, smart low-carbon energy-innovation policy, one that embraces not just an aggressive low-carbon energy research and development agenda, but also measures "downstream" from the laboratory in the commercialization and scale-up phases of the innovation process, is required if we are to achieve that goal.

SOUNDING THE TRUMPETS TOO SOON: THE COSTS AND RISKS OF PREMATURE TRIUMPHALISM

Where science push advances a fairy-tale picture of heroic scientists who pass their discoveries over the transom to eager entrepreneurs and disregards economic, social, and cultural barriers to energy innovation, premature triumphalism puts forward the opposite perspective. Adherents of this form of magical thinking argue that deployment of current low-carbon technologies is the only policy objective that matters and call for policies that they believe will simply overwhelm the very barriers that science push ignores. [27]

An aggressive, smart low-carbon energy-innovation policy must embrace not just an aggressive research and development agenda, but also go "downstream" from the laboratory in the commercialization and scale-up phases of the innovation process.

Like science push, premature triumphalism builds on an important insight. The United States has taken major strides to improve its energy efficiency and increase the role of renewable resources in its electricity-generation mix, on top of the 20 percent share of electricity generated without carbon emissions by nuclear reactors. And, like science push, this analysis leads to a valuable policy recommendation. Public investments in deployment can and should accelerate the diffusion process for low-carbon energy innovations. However, this line of thought leads to fanciful extrapolation as well. Deployment policy, operating by itself on the required scale, will not only impose very high (and quite likely unacceptable) costs on energy consumers, it is also unlikely to stimulate the innovations needed to complete the energy transition. The low-carbon energy challenge is far too complex to declare victory over yet.

Former Vice President Al Gore articulated the premature triumphalist position in the 2006 film *An Inconvenient Truth*:

> We already know everything we need to know to effectively address this problem. … We have everything we need, save perhaps political will. But you know what? In America, political will is a renewable resource. We have the ability to do this. Each one of us is a cause of global warming, but each of us can make choices to change that.[28]

A report by the Finnish government funding body SITRA echoed the view during the run-up to the 2015 Paris climate meeting: "The world already has the tools available to bring global emissions under control, over the next 15 years. Critically, there are solutions that have already been deployed at scale and at a reasonable cost. Ambitious climate action is not only possible; it is attractive."[29] Center for American Progress senior fellow Joe Romm offered a slightly softened version in 2011: "Study Confirms Optimal Climate Strategy: Deploy, Deploy, Deploy, Research and Develop, Deploy, Deploy, Deploy."[30]

The triumphs highlighted by Gore, SITRA, and Romm are dominated by renewable electricity generation. They exaggerate the readiness of these technologies, which have yet to match the affordability and reliability of fossil fuels on a system-wide basis. Like some climate denialists, some premature triumphalists may be making a strategic rather than heartfelt argument: These advocates fear that the public and policymakers would go (as Al Gore put it) "from denial to despair" if they understood the true difficulty of the low-carbon energy challenge. Rosy optimism, the advocates hope, will thwart excessive caution. Yet disappointed optimism sometimes leads to even greater caution, as the history of nuclear power suggests.

That history notwithstanding, premature triumphalism is not unknown among advocates of nuclear power, either. Certainty about the nature of the solution has led renewable energy and nuclear-power advocates to denounce one another in uncompromising terms. Oreskes equated nuclear-power supporters, including climate-science pioneer James Hansen, with climate denialists in a December 2015 editorial.[31] Patrick Moore, co-founder of Greenpeace and, more recently, of the Clean and Safe Energy Coalition, which supports the expansion of nuclear power, called "the massive investment into expensive and unreliable wind and solar energy during the past decade" … "a big mistake."[32]

Ironically, neither of these solution sets lives up to the claims of its champions, even allowing for a generous contribution of energy efficiency in either case. Stephen Nadel, the longtime executive director of the American Council for an Energy Efficient Economy, recently reviewed major studies of the potential contribution of energy efficiency. He concludes that a range of 0.7 to 1.5 percent improvement per year is "likely feasible" in the coming decades and that 1.4 to 2.5 percent per year is "potentially possible."[33] Even at the high end, these savings will roughly be offset in the United States by projected population growth (0.6 percent per year) and modest economic growth (2 percent per year).[34]

That means that the United States will almost certainly use at least as much energy in 2050 as it does today and probably more. The nation has set a goal of reducing carbon emissions by 80 percent from 2005 levels, or about 78 percent from 2014 levels.[35] A mathematically simple pathway to this end would eliminate all carbon emissions from the electric power, building, and industrial sectors and reduce emissions from transportation by about a third. Such a shift would require a roughly tenfold expansion of nuclear power—going from about 100 reactors to about a thousand—or a nearly 40-fold expansion of wind- and solar-electricity production, if these technologies are to do the job alone.[36] These crude calculations are meant only to signal the scale of the challenge, but they are broadly consistent with sophisticated models of the U.S. energy transition.[37]

The proposal to vastly accelerate diffusion of today's nuclear-power technology does not pass the laugh test. Four light-water reactors (LWRs) are currently under construction in the United States, the first plants started since the 1970s; one begun in that decade was completed earlier this year. These projects will, at best, offset the loss of nuclear plants that are scheduled to shut down in the coming decade. Beyond them "there are no firm plans to build any more," as the National Academies put it in a recent report.[38] Since LWRs take a decade or more from conception to completion, an improbable explosion of construction involving hundreds of new reactors would have to occur in the 2030s and 2040s to add the required capacity by 2050.

Nuclear power has stalled for several reasons. One is cost. Building an LWR is a risky multibillion-dollar endeavor, one that typically costs much more and takes much longer than originally estimated. Worse, each new plant seems to be more expensive than the previous one. The plants currently under construction, from what one can tell to date, have not avoided these maladies.[39] In addition, the nation has made no progress toward better managing the high-level nuclear waste that these plants generate. Public opinion toward the growth of nuclear power in the United States is ambivalent at best, and a majority of the population is strongly opposed to local siting of plants.[40]

Premature triumphalists frequently cite Moore's Law, which links cumulative production of semiconductor chips to exponentially lower costs over a 50-year period, as a precedent for solar PV modules. This analogy is flawed.

Technological innovation is essential if these barriers are to be overcome. Basic design decisions made hastily in the 1950s and 1960s must be revisited to reduce cost and waste, and improve safety and security. The success of new nuclear-plant designs will, in turn, depend upon regulatory- and business-model innovation and, ultimately, on public acceptance. Efforts to bulldoze these barriers via scientific rationality in the face of the climate threat are no more likely to succeed than promises of power that is "too cheap to meter" did a half-century ago.

The premature triumphalist argument for renewables requires a more nuanced analysis. Over 35 years, 40-fold growth equals an annual growth rate of just over 11 percent. Recent experience bests that by a considerable margin. Over the last 10 years, wind-generated electricity in the United States has grown at a rate of about 25 percent per year. The official time series for solar-generated electricity is shorter, only about two and a half years, because the amount generated is so small, but the growth rate for this resource over that span has been even faster, almost 80 percent per year. The annual growth rate of solar PV capacity (that is, the potential to generate electricity, rather than actual generation) since 2006 has been more than 50 percent.[41]

A linchpin of the argument that rapid rates of growth of wind and solar power can be sustained for decades to come is that they will continue to get cheaper as quickly as they have in the recent past. The median installed price of a unit of solar PV capacity fell by 6 to 12 percent per year between 1998 and 2015, according to analysts at Lawrence Berkeley National Laboratory, with utility-scale system prices falling more rapidly and residential systems, more slowly. The cost reductions have not been as steep for land-based wind power, but this technology was closer to being cost competitive at the beginning of the period, and wind is now the cheapest generation resource in some locations. Unsubsidized solar power remains more expensive.[42]

These observations of the recent past have provoked a vigorous debate about the future shape of these cost curves. Premature triumphalists frequently cite Moore's Law, which links cumulative production of semiconductor chips to exponentially lower costs over a 50-

year period, as a precedent for solar PV modules. This analogy is flawed. Innovation in semiconductor manufacturing proceeds mainly by packing more circuits on each chip; by contrast, the efficiency of PV modules (the amount of electricity produced per unit of surface area) has not been the main driver of cost reduction.[43]

A variety of other factors has been more important in lowering PV costs than module efficiency, and some of these may be reaching their limits. Economies of scale, both in manufacturing and installation, are one important factor of this sort. Wind turbines have grown as large as 180 meters (about 600 feet) in diameter, for instance, requiring towers even taller, so that they can rotate safely. Utility-scale solar-PV installations have grown from thousands of modules to millions. Scaling of this sort cannot continue indefinitely at the same unit cost. At some point, the complexity of managing large-scale systems outweighs economies of scale. The size of utility-solar installations, for example, seems to have surpassed its optimum; an authoritative recent report suggests that there may be diseconomies of scale for very large projects.[44]

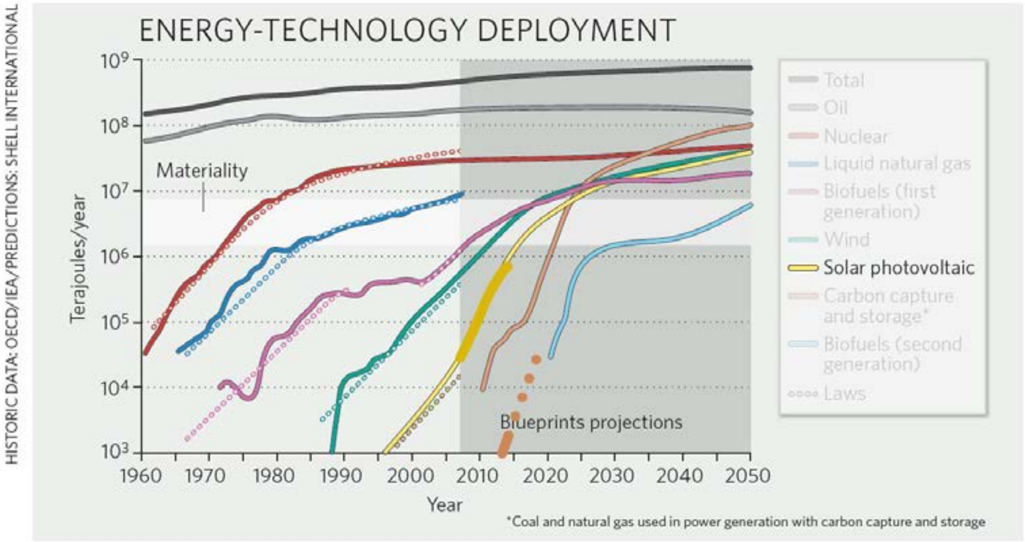
Much of this discussion revolves around the cost of generation capacity, but it must be extended to the value of the power that renewable resources actually produce, which in turn depends on their integration into the power system as a whole. Wind and solar resources vary greatly geographically; many of the best locations require the construction of transmission capacity in order to be utilized. They also vary greatly over time, as the sun and wind come and go. Because the power grid must be balanced between supply and demand on a real-time basis, large-scale use of these intermittent renewable resources will require significant innovation elsewhere on the grid. Large-scale electricity storage (either stationary or in electric vehicles) is one possibility, but it is currently very expensive. Rapid adjustments in demand, through sophisticated demand-management systems, is another. A third option is to keep conventional power plants on standby, so they can ramp up generation to compensate as needed. Natural gas-fired plants typically provide this service now; "load-following" nuclear power might be an alternative in the future. All of these capabilities will need to be tied together through the broader and more effective use of information technologies that comprise the "smart grid."[45]

Technical factors like these do not rule out the possibility that the tremendous progress in renewables can be sustained until 2050, but they do induce doubt. Stanford engineer Mark Jacobson has laid out a pathway to 100 percent renewable energy in the United States by 2050. It calls for, among other things, 156,200 offshore wind turbines to be in place by that date. Considering that the first five offshore wind turbines in the United States are expected to go into service this fall, this target seems "particularly aggressive," a phrase that Jacobson's critics have applied to his work in other contexts. As ITIF's Megan Nicholson and Matthew Stepp have argued, such analyses confuse thought experiments with practical plans.[46]

Some of the policies that have propelled deployment also induce doubt. Quantitative mandates, such as renewable portfolio standards, and fixed subsidies, like the production and investment tax credits, actually provide relief from pressure to innovate under many circumstances. In other circumstances, concentration only on present costs and indifference about the source of supply may have reduced the capability of producers to drive down future costs. The shift in PV-module production to China, for instance, has decimated domestic producers who were exploring alternative technological trajectories to the dominant crystalline silicon paradigm.[47] While the shift to China produced a short-term benefit in the form of lower prices, it may have produced a long-term negative impact on solar innovation.[48]

To these diverse factors must be added the possibility that currently unknown societal forces will slow down the ubiquitous diffusion of renewables, either by shifting the cost curve, blocking new sites, or some other mechanism. Rosy forecasts for older energy technologies, like nuclear power, proved to be acutely disappointing, especially in light of the promise that electricity would become too cheap to meter. A recent analysis by Shell scenario planner David Hone puts solar PV in the context of other major energy resources, abstracting from the unique forces that shaped each one. "[G]rowth," he states, "becomes more linear as the given energy source becomes a material part of the energy system."[49] (See figure 1.) Rapid exponential growth is simply very hard to sustain as the installed base gets bigger.

Figure 1: Energy-Technology Deployment, 1960-2050 (Source: Hone 2016)



"Research and develop," then, must not simply be an afterthought in an all-out push to "deploy, deploy, deploy" renewables. Publicly funded RD&D is a key requirement to accelerate non-incremental innovations that will sustain cost reductions in the power generated by wind and solar (and other renewable) technologies. Moreover, deployment policies must become smarter, so that they induce continuing private investments in innovation in these dynamic, emerging sectors. Complementary innovations in hardware, software, institutions, and behavior that facilitate renewables integration, such as the "smart grid" and charging networks for electric vehicles, require well-designed policy support.

(Innovation policies will also be needed to maintain the energy-efficiency trajectory outlined by Nadel.)

The most persuasive argument against premature triumphalism of any flavor wraps all of the above points together in one unsexy phrase: diversification in the face of extreme risk. The climate challenge poses one of the biggest risks in human history. Science and technology have only scratched the surface of potential low-carbon energy options. Some of these may ultimately be more affordable, have fewer drawbacks, and be better suited for particular applications than current technologies. Prudent risk management calls for hedging one's bets.

An aggressive, smart energy-innovation policy would support low-carbon energy research, development, and demonstration as a way to complement and support deployment. Enactment of such a policy is not an excuse to do nothing, as some fear, nor an expensive way to pray for a miracle.[50]

Science and technology have only scratched the surface of potential low-carbon energy options. Some of these may ultimately be more affordable, have fewer drawbacks, and be better suited for particular applications than current technologies. Prudent risk management calls for hedging bets.

OVERCOMING THE OBSESSION: INNOVATION POLICY AS A CARBON-PRICE ENABLER

The fourth and final form of magical thinking centers on the belief among mainstream economists that imposing a price on carbon emissions is not only the most efficient way to drive low-carbon innovation but also will be politically acceptable. It combines the faith in markets expressed in science push with the dismissal of societal obstacles inherent in premature triumphalism, wrapped up with a lack of understanding of the process of technological innovation. Economists' carbon price obsession contributes to missed opportunities to accelerate mitigation through innovation policy and ultimately reduce the carbon price that may be required to complete the energy transition.

The insight embedded in this view is that if something is more expensive and people know it will stay that way, they will buy less of it. This notion of price elasticity is central to the discipline of economics, and it has been validated for energy. The rise of gasoline prices in the 2000s, for instance, led Americans to drive less and to buy more fuel-efficient cars.[51] The policy recommendation that follows from this insight is to raise the price of fossil energy and other sources of carbon emissions, ideally through a tax, or second best, through a cap-and-trade system. They are right that the market will never incorporate the costs of climate change into energy prices because they are not borne by the producer. In the jargon of economics, these costs are negative environmental externalities that fall on the public, which (economists argue) should therefore be internalized through public policy.

The consensus among mainstream economists about carbon pricing is nearly as firm as the scientific consensus on climate change. "[A] widely-held view across a broad spectrum of economists is that policies that put a direct, uniform price on carbon," wrote the President's Council of Economic Advisors (CEA) in a September 2016 report, "are the most efficient and comprehensive way to both meet the goals set forth in the Paris Agreement and efficiently transition to a clean energy economy."[52] The consensus arises from a paradigm that elevates allocative efficiency above other values and assumes that innovation is shaped only by relative prices. The irrefutable logic of the externality and the beauty of the carbon-pricing solution in this context leads to obsession. William Nordhaus articulated the point bluntly in his 2008 book on climate change: "To a first approximation, raising the price of carbon is a necessary and sufficient step for tackling global warming. The rest is at best rhetoric and may actually be harmful in inducing economic inefficiencies."[53]

By the standards of economic rationality, opposition to carbon pricing should be futile, but unfortunately for economists, it is not. Americans, in particular, like their energy cheap.[54] High-profile attempts by the federal government to deliberately and overtly raise energy prices have often ended in disaster for their political champions. Jimmy Carter was defeated in 1980 after serving only a single term as president in part because of his endorsement of higher energy prices. President Bill Clinton's proposal for a broad-based tax on energy went down to an ignominious defeat in 1993.[55] The failure of the Waxman-Markey bill in 2009, which would have set up a nationwide cap-and-trade program for controlling greenhouse gas emissions, is the most recent example of the phenomenon. The carbon-price obsession calls to mind the oft-quoted definition of insanity: doing the same thing over and over again and expecting different results.

There are exceptions to this pattern at the state level. California runs a cap-and-trade program jointly with the Canadian province of Quebec, and several northeastern states banded together to do the same in the Regional Greenhouse Gas Initiative (RGGI). In California, allowance prices have ranged from about $10 to $13 per metric ton of CO_2 since the program's inception in 2012; in RGGI, the range has been $2 to $7 since 2008.[56] These prices are well below most estimates of the externality, which range from $11 to well over $100 per ton.[57] They emerged in an era of relatively low energy prices, which may have aided their public acceptance. They are also concentrated in states with more liberal governments; New Jersey departed from RGGI in 2011 after Republican Chris Christie was elected governor. It is doubtful that they will be replicated at the federal level any time soon. Neither major party candidate in the 2016 presidential election has proposed a carbon-pricing plan.[58]

Economists have put much less effort into promoting federal low-carbon energy innovation policy than a carbon price, even though such a policy is equally consistent with their paradigm. Scientific and technological knowledge produce positive externalities: The benefits of creating such knowledge spill over beyond those who create it. The creators may not understand all of the potential applications of what they have learned, for instance, or they may not be able to keep the knowledge that they have created secret. The inability to secure these benefits acts a deterrent to investment in knowledge creation; some potential investors may prefer to "free ride" on investments in knowledge made by others. In the extreme case, no investor is willing to take the risk that she may wind up sharing the payoffs with free riders, leaving innovation opportunities without support.[59]

Economists agree that public policy should try to fix the problem of underinvestment in knowledge, much as they do about controlling pollution, since both are externalities. A trio of prominent environmental economists titled their paper on this topic "A Tale of Two Market Failures: Technology and Environmental Policy."[60] Yet the received wisdom in this literature has placed a much heavier weight on the carbon price than on innovation policy. [61] Nordhaus's dismissal of policies other than carbon pricing as "at best rhetoric" is a good example. However, in recently published work, MIT's Daron Acemoglu and his colleagues have challenged this received wisdom. They find not only "a major role for both carbon taxes and research subsidies," but also that "[t]he research subsidy is initially more aggressive and then declines over time, while ... optimal carbon taxes are back-loaded."[62]

Economists should seek to grow such RD&D programs to a size commensurate with the climate challenge, and to improve their designs, rather than undercutting them by constantly relegating them to the position of second best.

Whether or not the work of Acemoglu et al. ultimately reshapes the professional consensus on the weighting and sequencing of carbon pricing and innovation support, the difference in the political logic of the two policies is compelling. Federal programs to address the positive knowledge externality already exist, but are significantly underfunded, whereas a national carbon price that would address the negative environmental externality remains a remote prospect. Innovation-oriented programs include public RD&D spending on low-carbon energy options as well as tax incentives that aim to induce greater private energy-innovation investments. Economists ought to seek to grow such RD&D programs to a size that is commensurate with the climate challenge as well as to improve their designs, rather than undercutting them by constantly relegating them to the position of second best. Innovation is not "manna from heaven," as the economist Robert Solow once put it, that is beyond human influence, but is instead in large part the result of deliberate public and private investment.[63]

An aggressive, smart low-carbon energy-innovation policy may ultimately make it easier for politicians to support imposing a carbon price. Innovation that leads to lower prices for low-carbon energy will induce more rapid switching to low-carbon resources. That, in turn, will reduce demand for fossil fuels, putting downward pressure on their prices. In such a circumstance, the public is more likely to accept a carbon tax.

Innovation policy that narrows the price gap between high- and low-carbon energy would also increase the likelihood that carbon pricing will mitigate climate change, rather than just compensate for it. It is vital to recognize that the standard economic model is indifferent between these two outcomes. The economists' carbon price is based on the estimated cost of the negative environmental externality. If burning a barrel of oil would cause $10 of damage to the environment, by this logic, $10 should be added to its price. If the alternative fuel costs more than $10 more than oil, the oil price increase will lower consumption, but not induce switching to cleaner energy resources.

For example, ITIF has shown the de facto carbon price on oil for transportation in most European nations is around $600 per ton (a reflection of their high gas taxes), yet electric-vehicle use remains extremely limited. These taxes have encouraged less driving and the purchase of smaller cars and diesel-engine cars, but not the development of battery technology to power electric vehicles. If, by contrast, the difference between dirty and clean energy is less than the efficient carbon price, that price will induce technology switching. In this scenario, the overall cost of the carbon price to the public is reduced as well, since fewer barrels of oil will be sold.[64]

In addition, it is extraordinarily difficult to estimate the cost of the damage likely to be caused by climate change in the future. Models that do so must incorporate guesstimates about the future course of the global economy as well as the natural world over many decades. It will be even more difficult to ensure that those upon whom damage would be imposed—those who may lose their housing as a result of flooding fed by extreme storms and sea-level rise, for instance—are compensated by the carbon-pricing scheme, as the internalization of the negative externality theoretically requires. The public's skepticism that the practice of carbon pricing will match the theory is warranted in these respects.

An aggressive, smart low-carbon innovation policy now should lead to a less costly, more politically attractive, and more effective carbon price in the future.

The carbon-price obsession leads economists to forget the limits of their model. In addition to the challenges of implementation noted above, the model is limited in its depiction of the innovation process. It assumes that incremental tradeoffs on the margin over time will ultimately lead to deep decarbonization. Instead, they may lead to technological cul-de-sacs, rather than breakthroughs.

Substituting natural gas for coal in power generation, for instance, will reduce carbon emissions in the short run, but ultimately could be a "bridge to nowhere," if affordable, low-carbon options are not available once the "bridge" is built.[65] In this case, gas consumption would continue on a large scale, even with a hefty carbon tax. In their highly cited 2008 paper, economists Carolyn Fischer and Richard Newell candidly note that "we focus on reductions over the near-to-mid-term and incremental improvement in existing technology, rather than breakthrough technologies that might achieve deep reductions. It seems likely that R&D policies have greater salience in the latter context, although this lies beyond the scope of the current paper."[66]

There is certainly room for disagreement about the appropriate scope of low-carbon innovation policy and the modalities for implementing it. Economists may fear wasteful government R&D spending of the sort that Linda Cohen and Roger Noll labeled the "technology pork barrel" in their 1991 book.[67] They may be skeptical that private financing is too costly to sustain a robust portfolio of high-risk, capital-intensive low-carbon energy projects. They may object to deployment subsidies that do not produce learning-by-doing of value beyond the firm that receives the subsidy.

If so, they should stop neglecting these debates in favor of chasing the carbon-price obsession. An aggressive, smart low-carbon innovation policy now should lead to a less costly, more politically attractive, and more effective carbon price in the future.

KEY ITEMS IN AN AGGRESSIVE, SMART LOW-CARBON ENERGY-INNOVATION POLICY AGENDA

Climate-change denial, science push, premature triumphalism, carbon-price obsession: These four forms of magical thinking obscure the focus and impede progress on the urgent task of accelerating low-carbon energy innovation. The United States and the world need solutions that are not yet available. The search for these solutions is a matter of probability, not magic. With sufficient public and private investment, appropriate incentives, and institutional reform, many innovative solutions will surely be found and adopted, drastically narrowing or even eliminating the gaps that may have to be dealt with through measures that increase energy costs or reduce services.

Previous ITIF reports have laid out many details of a smart, aggressive low-carbon energy-innovation policy agenda, and future reports will elaborate the agenda further.[68] This agenda addresses the entire innovation process and uses all the tools in the policy toolkit, matching these tools to the appropriate problems. Among the key items on the agenda:

- **Establish a dedicated funding source for federal low-carbon energy-innovation investments.** Long-term investments by organizations and individuals drive the low-carbon energy-innovation process. Whether they are young technologists, owners of homes or buildings, mid-career entrepreneurs, or mature industry incumbents considering diversification, such investors must accept the risks intrinsic to the innovation process. However, unpredictable shifts in public policy priorities add unnecessarily to these risks. Given the ebbs and flows of federal low-carbon energy investments over the past half-century, potential innovators currently face the possibility that their blood, sweat, and tears will be wasted by short-term thinking in Washington. A dedicated federal funding source will induce greater confidence that their efforts will lead to a fair test of their innovations. Ideally, the revenue stream for this funding source will also support the low-carbon energy transition. Royalties from fossil-fuel extraction on federal lands and the reform of the Strategic Petroleum Reserve are two potential funding sources.[69]

- **Steadily expand federal investment in basic research fields that have the potential to dramatically accelerate low-carbon energy innovation.** Basic research, especially strategic basic research, by definition, yields new applications that are unanticipated and occasionally game-changing.[70] While it is essential to sustain the momentum of the low-carbon energy transition that has begun in the United States, the transition, domestically and globally, will take decades, long enough for basic research findings to have an impact. Federal investment in basic research has stagnated in recent years, not even keeping pace with the growth of the economy. Underinvestment is particularly pronounced in the physical sciences and engineering. Sustained, steady growth in federal support of basic research of these disciplines through agencies such as the National Science Foundation, Department of Energy's Office of Science, and National Institutes for Standards and Technology, would encourage talented young researchers to take on the hardest problems underlying low-carbon energy innovation.[71] The knowledge generated by such investments will contribute to U.S. competitiveness beyond the energy challenge as well.

- **Dramatically expand federal co-investment in applied research, demonstration, and infrastructural technologies for low-carbon energy.** The middle stages of the innovation process are particularly important for innovations that seek to enter markets for well-established commodities like energy. Practical hurdles of affordability and reliability, which are addressed primarily in these stages, loom larger in this industry than in sectors that are brand new. Yet these stages have proven particularly difficult to fund. They promise both public and private benefits, which calls for sometimes unwieldy public-private partnerships, and they may be very costly. Federal programs that have successfully filled these gaps through cooperation with the private sector, such as the Advanced Research Projects Agency-Energy (ARPA-E) and the energy-focused institutes within the Manufacturing USA network, should be scaled up significantly, and new models to fill other gaps in the low-carbon energy innovation process should be explored.[72]

- **Enhance connectivity and strengthen user pull along the low-carbon energy-innovation chain.** Technology transfer, as the saying goes, is a contact sport. Complex systems are not easy to understand, build, or change; these tasks require constant and careful communication among diverse actors. Yet today's energy innovation system has many isolated silos, institutions, and communities that are only weakly connected with eventual applications and the needs of users. Federal policy has too often strengthened these silos. Recent experiments have begun to break them down; examples include new policies and practices that aim to build stronger linkages between the private sector and the Department of Energy's national laboratories. Such efforts to deepen collaboration and improve connectivity from basic research to practical use should be ramped up and extended into new areas.[73]

- **Foster regional collaboration for innovation in large-scale, low-carbon energy systems.** Energy resources, consumption patterns, and public attitudes vary considerably across the regions of the United States. Energy systems operate at the regional scale, both across multiple states, such as wholesale electricity markets, and across metropolitan areas and urban districts, like public transit and district heating systems. This regional diversity could translate into a diversity of large-scale energy-innovation efforts from which successes could be diffused nationally.[74] However, federal programs have not always encouraged the development of regional energy-innovation systems. For instance, the focus of key agencies on national missions, such as defense or space exploration, may lead them to neglect regional opportunities. At the same time, states and localities often have difficulty cooperating with one another for regional gains; they compete for jobs and tax revenue, among other things. Federal programs that seed regional low-carbon energy-innovation efforts and challenge disparate regional actors to collaborate to scale them, like the recent clean cities challenge and the Regional Innovation Demonstration Funds proposed by the National Academies, would be welcome.[75]

- **Reform low-carbon energy tax incentives, so they are permanent and technology-neutral, and phase out support for each generation of technology as it matures.** Tax incentives are an important mechanism for sharing risk with private investors in the early deployment phase of the innovation process. These incentives suffer from two problems at the moment. One is authorization on a year-to-year basis only. Incentives so authorized are subject to frenzied last-minute bargaining at the end of each fiscal year as the "tax extenders" package is assembled on Capitol Hill. Uncertainty about their availability deters some potential beneficiaries, even as it leads others to join a mad rush to get projects qualified before the expected expiration date. The other problem is insensitivity to technological maturity. Tax incentives of this sort are set at a fixed rate for many years, even after the technologies to which they are applied are no longer risky. These incentives then become subsidies that deter, rather than support, innovation, because they lock in existing technologies.[76] To eliminate both problems, Congress should establish a permanent system of low-carbon energy-innovation tax incentives that supports all promising immature technologies, but methodically steps down the incentive level as each technology matures. Decisions about which versions of which technologies should qualify for which rate should be delegated to an appropriate expert body.

- **Use federal procurement strategically to build momentum for early deployment of low-carbon energy innovations.** The federal government owns more buildings and vehicles and consumes more energy than any other organization in the nation. It can and should use this leverage to act as an early adopter of innovations and establish their credibility for later adopters. Federal standards for constructing and leasing commercial buildings, for instance, have helped diffuse "green-building" practices.[77] While federal agencies have often been creative in using their procurement power to accelerate low-carbon energy innovation, a variety of legal and regulatory barriers inhibit them. These barriers should be cleared away.[78] That said, procurement policies, like tax incentives, must be regularly revisited so that they drive a continuous stream of innovation, rather than lock in technologies that have already matured.

- **Encourage business-model and regulatory innovation in conjunction with technological innovation in the electricity and transportation sectors.** Technological innovation has a symbiotic relationship with business-model and regulatory innovation, particularly in complex systems, such as electricity and transportation. New technologies open up opportunities for new business models, which regulators may or may not encourage, which in turn may or may not feed further technological innovation. Distributed energy resources and the application of information technology to the electricity and transportation systems offer opportunities to trigger a virtuous cycle of this sort with large-scale economic and environmental benefits.[79] But the regulatory system in these sectors is a complex patchwork of federal, state, and local entities. Some of these entities are extraordinarily risk averse, while others are captured by incumbent providers that would be harmed by innovation. Federal agencies should exert leverage on the system to encourage innovation through their rulemaking powers, and they should also use their funding authority to support pilot programs and regulatory experiments that establish the viability of innovative approaches.

- **Tighten energy-efficiency and carbon-control regulations in a predictable, innovation-inducing manner.** Federal regulations on appliances, vehicles, power plants, and industrial facilities (as well as state and local building codes supported by federal technical assistance) have prevented a substantial amount of greenhouse-gas emissions and will prevent much more in the future. In most cases, they have cost much less than anticipated and had little impact on the quality of energy services.[80] However, the regulatory process has also failed on some occasions. At its best, the process engages technically savvy regulatory staff with industrial experts in order to set aggressive but feasible targets on a time frame that allows industry to plan ahead to meet them. Long-term targets provide a focus for industrial investments in innovation as well as opportunities to make adjustments if the innovation process does not yield hoped-for results in the expected time frame. Predictable, steady, collaborative ratcheting-down of standards may also avert litigation from parties who have participated in the standard-setting process.

It's time for innovation policy to rise to the top of the debate over the future of energy in America.

This agenda takes a long-term perspective, but recognizes the importance of taking short-term steps. Climate change is both an urgent priority and a century-long challenge. We must seize current opportunities without neglecting the creation of new opportunities in the mid- to long-term.

It’s time for innovation policy to rise to the top of the debate over the future of energy in America. Such a policy must be aggressive and smart, aggressive enough to overcome the fear that innovation is nothing more than an excuse for business as usual and smart enough to avoid the risk of bottomless subsidies that nonetheless leave us short of the emissions reductions that we need. So formulated, this approach offers a way to unite forces that share a common goal but have been at odds. Strong leadership to this end might just work some political magic.

ENDNOTES

1. “Greenhouse Gas Inventory Data Explorer,” Environmental Protection Agency, accessed October 10, 2016, https://www3.epa.gov/climatechange/ghgemissions/inventoryexplorer/; U.S. Energy Information Administration (EIA), “U.S. Energy-Related Carbon Dioxide Emissions, 2014” (Washington, DC: EIA, November 23, 2015), http://www.eia.gov/environment/emissions/carbon/.
2. The White House, “U.S. Reports Its 2025 Emissions Target to the UNFCCC,” news release, March 31, 2015, https://www.whitehouse.gov/the-press-office/2015/03/31/fact-sheet-us-reports-its-2025-emissions-target-unfccc.
3. Energy Information Administration, U.S. States, (Table E9. Total End-Use Energy Expenditure Estimates, 2014 (Millions of Dollars); accessed October 11, 2016), http://www.eia.gov/state/seds/data.cfm?incfile=/state/seds/sep_sum/html/sum_ex_tx.html&sid=US.
4. Arnulf Grubler, “Grand Designs: Historical Patterns and Future Scenarios of Energy Technological Change,” in *Energy Technology Innovation*, Arnulf Grubler and Charlie Wilson, eds., (New York: Cambridge University Press, 2014), 39–53.
5. Matthew Stepp and Megan Nicholson, “The Logic Chain to an Effective Global Clean Energy Policy” (Information Technology and Innovation Foundation, 2013), 4–6, http://www2.itif.org/2013-logic-chain-effective-global-clean-energy-policy.pdf.
6. Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2014: Synthesis Report* (Geneva: IPCC, 2015), 4–8.
7. Andrea Thompson, “Attribution Studies Home In on Climate Change Signal,” *Climate Central*, November 5, 2015, http://www.climatecentral.org/news/attribution-studies-hone-climate-signal-19640; Kate Kelland, “Climate, Population Changes Used to Predict Diseases,” *Climate Central*, June 18, 2016, http://www.climatecentral.org/news/climate-population-changes-predict-diseases-20459; Thomas R. Karl, et al., “Possible Artifacts of Data Biases in the Recent Global Surface Warming Hiatus,” *Science* 348 (June 4, 2015): 1469–1472.
8. M. Webster et al., “Analysis of Climate Policy Targets under Uncertainty” (MIT Joint Program on the Science and Policy of Global Climate Change, 2009), http://globalchange.mit.edu/research/publications/1989.
9. Dave Levitan, “Smith Misfires of Climate Science,” FactCheck.org, November 5, 2015, quoting from Rep. Lamar Smith statement from October 28, 2015, http://www.factcheck.org/2015/11/smith-misfires-on-climate-science/
10. Scott Wartman, “McConnell: Don't Expect Much From Congress This Year,” *Cincinnati Inquirer*, March 7, 2014, http://www.cincinnati.com/story/news/politics/elections/2014/03/07/mcconnell-expect-much-congress-year/6170921/.
11. Donald J. Trump, @realDonaldTrump, Twitter post, November 2, 2012, 11:59 a.m., https://twitter.com/realdonaldtrump/status/264377842157092865.
12. John Cook et al., “Consensus on Consensus: A Synthesis of Consensus Estimates on Human-Caused Global Warming,” *Environmental Research Letters 11*, no. 4 (April 13, 2016): 048002. See also Naomi Oreskes, “The Scientific Consensus on Climate Change,” *Science 306*, no. 5702 (December 3, 2004): 1686.
13. Paul Barrett and Matthew Philips, “Can ExxonMobil Be Found Liable for Misleading the Public on Climate Change?” *Bloomberg Businessweek*, September 7, 2016, http://www.bloomberg.com/news/articles/2016-09-07/will-exxonmobil-have-to-pay-for-misleading-the-public-on-climate-change.
14. “About Us,” Continental Resources, accessed September 8, 2016, http://www.contres.com/about.
15. Cook, “Consensus on Consensus.”
16. Freeman Dyson, “The Question of Global Warming,” *The New York Review of Books*, June 12, 2008.

17. Maria Gallucci, “Paris Climate Talks: Nuclear Fusion Is the ‘Holy Grail’ of Clean Energy Technology,” *International Business Times*, December 3, 2015, http://www.ibtimes.com/paris-climate-talks-nuclear-fusion-holy-grail-clean-energy-technology-2208495.

18. Jim Manzi, “Conservatives and Climate Change” (Manhattan Institute, June 21, 2015), https://www.manhattan-institute.org/html/conservatives-and-climate-change-6272.html.

19. Michael Shellenberger et al., “Where the Shale Gas Revolution Came From: Government’s Role in the Development of Hydraulic Fracturing in Shale” (Breakthrough Institute, May 2012), http://thebreakthrough.org/archive/shale_gas_fracking_history_and; Loren King et al., “Lessons from the Shale Revolution: A Report on the Conference Proceedings” (Breakthrough Institute, April 2015), 14, http://thebreakthrough.org/archive/shale_gas_fracking_history_and.

20. Edwin Layton, “Mirror Image Twins: The Communities of Science and Technology in 19th-Century America,” *Technology and Culture 12*, no. 4 (October, 1971): 563–565.

21. Donald E. Stokes, *Pasteur’s Quadrant: Basic Science and Technological Innovation* (Washington: Brookings Institution Press, 1997). See, more recently, Daniel Sarewitz, “Saving Science,” *New Atlantis*, Spring/Summer 2016, http://www.thenewatlantis.com/publications/saving-science

22. Charles Weiss and William B. Bonvillian, *Structuring an Energy Technology Revolution* (Cambridge: MIT Press, 2009); William B. Bonvillian and Charles Weiss, *Technological Innovation in Legacy Sectors* (New York: Oxford University Press, 2015).

23. Staffan Jacobsson and Volkmar Lauber, “The Politics and Policy of Energy System Transformation—Explaining the German Diffusion of Renewable Energy Technology,” *Energy Policy 34* (2006): 256–276, http://seg.fsu.edu/Library/The%20politics%20and%20policy%20of%20energy%20system%20transformation%20-%20explaining%20the%20German%20diffusion%20of%20renewable%20energy%20technology.pdf.

24. Gregory C. Unruh, “Escaping Carbon Lock-In,” *Energy Policy 30* (2002): 317–325.

25. Jesse D. Jenkins, “Political Economy Constraints on Carbon Pricing Policies: What Are the Implications for Economic Efficiency, Environmental Efficacy, and Climate Policy Design?” *Energy Policy 69*, no. C (2014): 467–477; Gabrielle Wong-Parodi, “The Great Debate,” *Science 353*, no. 6303 (September 2, 2016): 997.

26. Hiroko Tabuchi, “‘Rolling Coal’ in Diesel Trucks, to Rebel and Provoke,” *The New York Times*, September 4, 2016, http://www.nytimes.com/2016/09/05/business/energy-environment/rolling-coal-in-diesel-trucks-to-rebel-and-provoke.html.

27. On this theme, see also Megan Nicholson and Matthew Stepp, “Challenging the Clean Energy Deployment Consensus” (Information Technology and Innovation Foundation, October 2013), https://itif.org/publications/2013/10/23/challenging-clean-energy-deployment-consensus.

28. “An Inconvenient Truth: Movie Script,” Springfield! Springfield! website, accessed September 29, 2016, http://www.springfieldspringfield.co.uk/movie_script.php?movie=an-inconvenient-truth.

29. Oras Tynkkynen, ed., *Green to Scale: Low-Carbon Success Stories to Inspire the World* (Helsinki: SITRA Studies 105, November 2015), 7, http://www.sitra.fi/en/ecology/green-scale.

30. Joe Romm, “Study Confirms Optimal Climate Strategy: Deploy, Deploy, Deploy, Research and Develop, Deploy, Deploy, Deploy,” *Think Progress*, October 31, 2011, https://thinkprogress.org/study-confirms-optimal-climate-strategy-deploy-deploy-deploy-research-and-develop-deploy-deploy-49c9129e35ac#.kq0fa14vu.

31. Naomi Oreskes, “There Is a New Form of Climate Denialism to Look Out for—so Don’t Celebrate Yet,” *The Guardian*, December 16, 2015, https://www.theguardian.com/commentisfree/2015/dec/16/new-form-climate-denialism-dont-celebrate-yet-cop-21.

32. "The Pro-Nuclear Environmentalist Movement: A Q&A With Dr. Patrick Moore," *Forum on Energy*, July 22, 2013, http://forumonenergy.com/2013/07/22/the-pro-nuclear-environmentalist-movement-a-qa-with-dr-patrick-moore/.

33. Steven Nadel, "The Potential for Additional Energy Savings Including How the Rebound Effect Could Affect This Problem," *Current Sustainable/Renewable Energy Reports 3* (2016): 41.

34. U.S. Census Bureau, Population Estimate (international database; accessed September 19, 2016), http://www.census.gov/population/international/data/idb/informationGateway.php.

35. This estimate ignores other greenhouse gases and sources. Reduction is calculated from the EPA's site, U.S. Environmental Protection Agency (EPA), "Greenhouse Gas Inventory Data Explorer," accessed on September 19, 2016, https://www3.epa.gov/climatechange/ghgemissions/inventoryexplorer/. Data are available through 2014.

36. These calculations draw on energy and carbon flow data from Lawrence Livermore National Laboratory (LLNL) for 2014. LLNL, Energy Flow Charts: Charting the Complex Relationships Among Energy, Water, and Carbon (LLNL flow charts; March 2016), https://flowcharts.llnl.gov/. A 78 percent reduction of carbon emissions in 2014 (5,410 million metric tons or MMTs) yields total emissions in 2050 of 1,190 MMTs, which is the equivalent of 65 percent of transportation-related emissions in 2014. Total energy use in 2014 minus 65 percent of transportation energy use is 80.7 quadrillion BRUs (quads). Nuclear power provided 8.33 quads in 2014; wind and solar combined provided 2.16 quads. Other renewable resources include biomass (4.76 quads), hydro (2.47 quads), and geothermal (.2 quads).

37. See for example, J.H. Williams et al., *Pathways to Deep Decarbonization in the United States* (Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations, revision with technical supplement, November 16, 2015), vii, http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Technical_Report.pdf. This report states that achieving an 80 percent reduction in greenhouse gas emissions from 1990 levels "would require the deployment of roughly 2,500 gigawatts (GW) of wind and solar generation (30 times present capacity) in a high renewables scenario ... or more than 400 GW of nuclear (4 times present capacity) in a high nuclear scenario."

38. National Academies of Sciences, Engineering, and Medicine, *The Power of Change: Innovation for Development and Deployment of Increasingly Clean Electric Power Technologies* (Washington, DC: National Academies Press, 2016), 115.

39. Arnulf Grubler, "The Costs of French Nuclear Scale-Up: A Case of Negative Learning by Doing," *Energy Policy 38* (2010): 5174–5188; Walter C. Jones, "Georgia Power Seeks Approval of Higher Costs at Plant Vogtle," *The Augusta Chronicle*, January 22, 2016, http://chronicle.augusta.com/news/2016-01-22/georgia-power-seeks-approval-higher-costs-plant-vogtle.

40. Stephen Ansolabehere and David M. Konisky, *Cheap and Clean: How Americans Think About Energy in the Age of Global Warming* (Cambridge: MIT Press, 2014), 48–61.

41. Electricity generation data are calculated from the U.S. Energy Information Agency (EIA)'s electricity data browser. EIA, Electricity (data; accessed September 20, 2016), http://www.eia.gov/electricity/data.cfm. For wind, the calculation uses data from March 2006 to March 2016 (the most recent peak of production); for solar, the calculation runs from January 2014 to May 2016 (the full available data set). Solar photovoltaic capacity data are drawn from BP, "Statistical Review of World Energy 2016" (London: BP, June 2016), http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

42. Galen Barbose and Naim Darghouth, "Tracking the Sun IX: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States" (Berkeley, CA: Lawrence Berkeley National Laboratory and Sunshot, August 2016), 16, http://eetd.lbl.gov/sites/all/files/tracking_the_sun_ix_report.pdf; Ryan H. Wiser et al., "Wind Vision: A

New Era for Wind Power in the United States," *The Electricity Journal 28*, no. 9 (November, 2015): 120–132; U.S. Energy Information Administration (EIA), "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016" (Washington, DC: EIA, August 5, 2016); Jason Channell et al., *Energy Darwinism II: Why a Low Carbon Energy Future Doesn't Have to Cost the Earth* (Citi Global Perspectives & Solutions, August 2015).

43. Fraunhofer Institute for Solar Energy Systems, ISE, "Photovoltaics Report" (Fraunhofer Institute for Solar Energy Systems, ISE, June 6, 2016), https://www.ise.fraunhofer.de/en/news/news-archive/news-2012/fraunhofer-ise-publishes-photovoltaics-report.
44. Shaun Campbell, "10 of the Biggest Turbines," *Windpower Monthly*, July 26, 2016, http://www.windpowermonthly.com/10-biggest-turbines; Mark Bolinger and Joachim Seel, "Utility-Scale Solar 2015" (Berkeley, CA: Lawrence Berkeley National Laboratory and Sunshot, August 2016), 15–16, https://emp.lbl.gov/sites/all/files/lbnl-1006037_report.pdf.
45. Council of Economic Advisers, "Incorporating Renewables into the Electric Grid: Expanding Opportunities for Smart Markets and Energy Storage" (Washington, DC: Executive Office of the President of the United States, June 2016), https://www.whitehouse.gov/sites/default/files/page/files/20160616_cea_renewables_electricgrid.pdf.
46. Mark Z. Jacobson et al., "100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States," *Energy and Environmental Science 8* (May 27, 2015): 2093–2117, https://web.stanford.edu/group/efmh/jacobson/Articles/I/USStatesWWS.pdf; John E. Bistline and Geoffrey J. Blanford, "More Than One Arrow in the Quiver: Why "100% Renewables" Misses the Mark," *PNAS 113*, no. 28 (July 12, 2016): E3988; Nicholson and Stepp, "Challenging Clean Energy Deployment Consensus."
47. Erica R.H. Fuchs, "Global Manufacturing and the Future of Technology," *Science 345* (August 1, 2014): 519–520.
48. Matthew Stepp and Robert D. Atkinson, "Green Mercantilism: Threat to the Clean Energy Economy" (Information Technology and Innovation Foundation, June 2012), http://www2.itif.org/2012-green-mercantilism.pdf?_ga=1.257280779.1008483478.1469403098.
49. David Hone, "Solar Deployment Rates," *The Energy Collective*, August 31, 2016, http://www.theenergycollective.com/davidhone/2386926/solar-deployment-rates?platform=hootsuite.
50. Joe Romm, "Bush Climate Speech Follows Luntz Playbook: 'Technology, Technology, Blah, Blah, Blah,'" *Think Progress*, September 28, 2007, https://thinkprogress.org/bush-climate-speech-follows-luntz-playbook-technology-technology-blah-blah-blah-1281f60c681c#.ozala7lb7; Bill Gates, "We Need an Energy Miracle," *Gates Notes*, June 25, 2014, https://www.gatesnotes.com/Energy/Energy-Miracles.
51. See, among many, Keith Gillingham, "Identifying the Elasticity of Driving: Evidence From a Gasoline Price Shock in California," *Regional Science and Urban Economics 47*, no. C (2014): 13–24.
52. Council of Economic Advisors (CEA), "The Economic Record of the Obama Administration – Addressing Climate Change" (Washington, DC: Executive Office of the President of the United States, September 2016), 58.
53. William Nordhaus, *A Question of Balance: Weighing the Options on Global Warming Policies* (New Haven: Yale University Press, 2008), 22.
54. Ansolabehere and Konisky, *Cheap and Clean.*
55. Meg Jacobs, *Panic at the Pump: The Energy Crisis and the Transformation of American Politics in the 1970s* (New York: Hill & Wang, 2016); Dawn Erlandson, "The BTU Tax Experience: What Happened and Why It Happened," *Pace Environmental Law Review 12*, no. 1 (1994), http://digitalcommons.pace.edu/pelr/vol12/iss1/9.
56. California Environmental Protection Agency Air Resources Board, "California Cap-and-Trade Program Summary of Joint Auction Settlement Prices and Results," August 2016, https://www.arb.ca.gov/cc/capandtrade/auction/auction.htm; Regional Greenhouse Gas Initiative

(RGGI), Auction Prices and Volumes (CO_2 Auctions, Tracking & Offsets; accessed September 22, 2016), https://www.rggi.org/market/co2_auctions/results.

57. CEA, "Addressing Climate Change," 19.

58. Coral Davenport, "Hillary Clinton's Ambitious Climate Change Plan Avoids Carbon Tax," *The New York Times*, July 2, 2016, http://www.nytimes.com/2016/07/03/us/politics/hillary-clintons-ambitious-climate-change-plan-avoids-carbon-tax.html?_r=0.

59. The classic statement of the free rider problem is Richard R. Nelson. Richard R. Nelson,"The Simple Economics of Basic Scientific Research," *Journal of Political Economy 67* (1959): 297–306. Other challenges to private investment include the long time horizon and high risks of science and technology projects.

60. Adam B. Jaffe, Richard G. Newell, and Robert N. Stavins, "A Tale of Two Market Failures: Technology and Environmental Policy" (Resources for the Future, October 2004), http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-04-38.pdf.

61. See National Academies of Sciences, Engineering, and Medicine, *Power of Change*, 283–287.

62. Daron Acemoglu et al., "Transition to Clean Technology," *Journal of Political Economy 124*, no. 1 (2016): 55. The authors of this article note that in their model "research subsidies are not used simply to correct a market failure for an uninternalized externality in research. In fact, in our model, in the absence of externalities from carbon, or in the special case in which there is only a dirty or a clean sector, the social planner does not have a reason to use research subsidies."

63. Robert D. Atkinson and David Audrestch, "Economic Doctrines and Policy Differences: Has the Washington Policy Debate Been Asking the Wrong Questions?" (Information Technology and Innovation Foundation, September 2008), http://www.itif.org/files/EconomicDoctrine.pdf?_ga=1.257855243.1008483478.1469403098.

64. Matt Hourihan and Robert D. Atkinson, "Inducing Innovation: What a Carbon Price Can and Can't Do" (Information Technology and Innovation Foundation, March 2011), http://www.itif.org/files/2011-inducing-innovation.pdf.

65. David Rotman, "Natural Gas Changes the Energy Map," *Technology Review*, October 15, 2009, https://www.technologyreview.com/s/415725/natural-gas-changes-the-energy-map/.

66. National Academies of Sciences, Engineering, and Medicine, *Power of Change*, 287.

67. Linda R. Cohen and Roger G. Noll, *The Technology Pork Barrel* (Washington, DC: Brookings Institution Press, 1991).

68. These reports include Stepp and Nicholson, "Logic Chain"; Nicholson and Stepp, "Challenging Clean Energy Deployment Consensus"; Hourihan and Atkinson, "Inducing Innovation"; Robert D. Atkinson, "An Innovation-Based Clean Energy Agenda for America" (Information Technology and Innovation Foundation, June 2015), http://www2.itif.org/2015-energy-innovation-agenda.pdf; and Scott Andes, Mark Muro, and Matthew Stepp, "Going Local: Connecting the National Labs to Their Regions for Innovation and Growth" (Brookings Institution, Center for Clean Energy Innovation, and Information Technology and Innovation Foundation, September 2014), https://www.brookings.edu/wp-content/uploads/2016/06/BMPP_DOE_Brief.pdf.

69. Atkinson, "Innovation-Based Agenda," 10; Heather L. Ross, "Turning Rainy Day Oil Into Clean Energy Gold: Funding Mission Innovation With a Strengthened Strategic Petroleum Reserve" (Resources for the Future, April 2016), http://www.rff.org/files/document/file/RFF-DP-16-14.pdf. A portion of the revenues from a carbon tax might also be dedicated to this purpose, if such a tax were ultimately to be approved.

70. Stokes, *Pasteur's Quadrant.*

71. Atkinson, "Innovation-Based Agenda," 6.

72. Ibid., 7.

73. Ibid., 8–9.

74. Richard K. Lester and David M. Hart, *Unlocking Energy Innovation: How America Can Build a Low-Cost Low-Carbon Energy System* (Cambridge, MA: MIT Press, 2012), 107–120.

75. National Academies of Sciences, Engineering, and Medicine, *Power of Change*.

76. Atkinson, "Innovation-Based Agenda," 9.

77. David M. Hart, "Don't Worry About the Government? The LEED-NC 'Green Building' Rating System and Energy Efficiency in U.S. Commercial Buildings" (working paper 09-001, MIT Industrial Performance Center Energy Innovation Project, Cambridge, MA, March 2009), https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1406683.

78. Secretary of Energy Advisory Board (SEAB), Task Force on Federal Energy Management, *Draft Report* (Washington, DC: SEAB, September 14, 2016), http://energy.gov/seab/downloads/draft-report-task-force-federal-energy-management.

79. Lester and Hart, *Unlocking Energy Innovation*, 57–76.

80. Maggie Molina, Patrick Kiker, and Seth Nowak, "The Greatest Energy Story You Haven't Heard: How Investing in Energy Efficiency Changed the US Power Sector and Gave Us a Tool to Tackle Climate Change" (American Council for an Energy Efficient Economy, August 19, 2016).

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