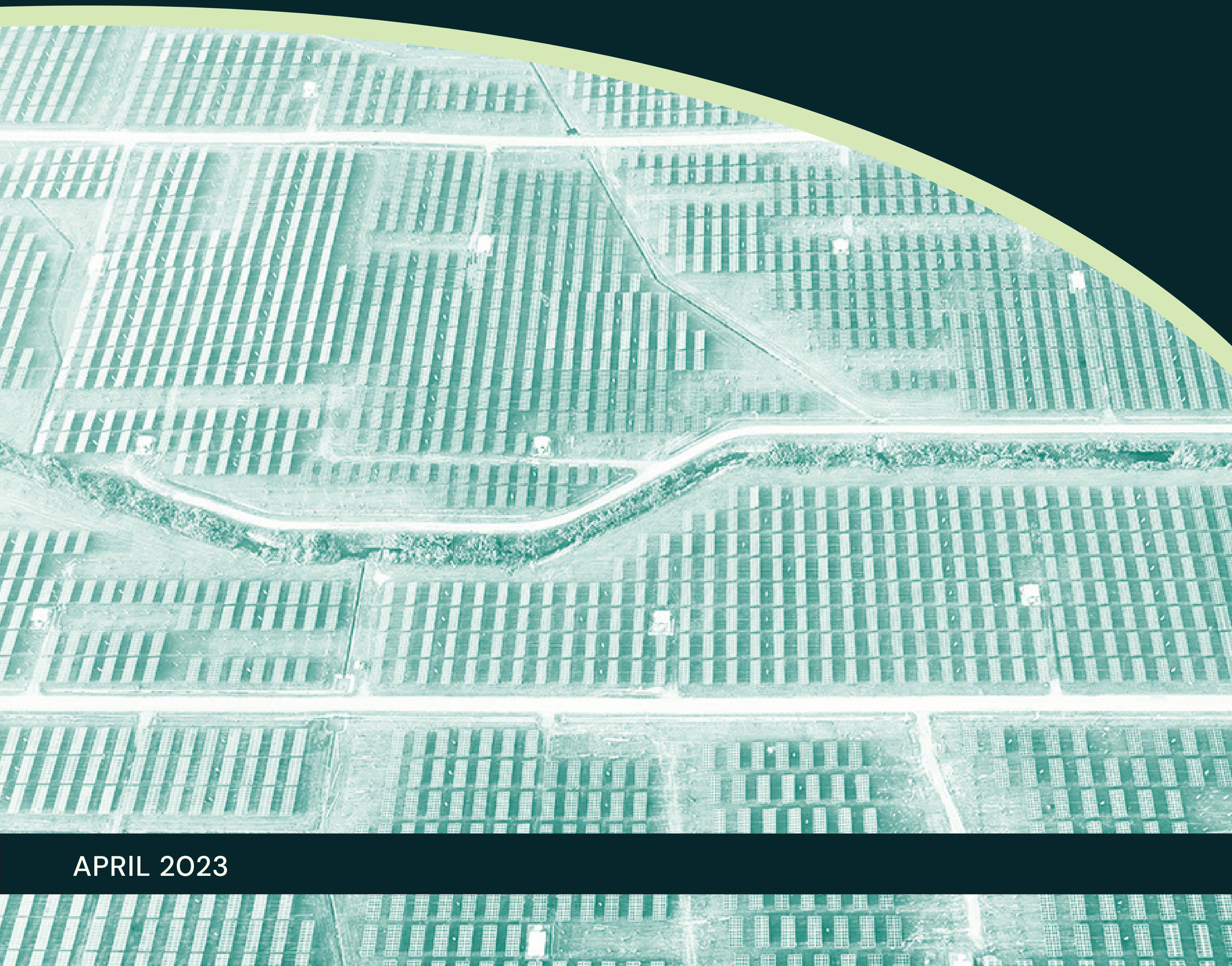
THE HAMILTON PROJECT

Principles for Public Investment in Climate-Responsible Energy Innovation

Catherine Hausman



APRIL 2023

ACKNOWLEDGMENTS

The author is grateful to Niaoniao You for outstanding research assistance. The author thanks Wendy Edelberg and the rest of The Hamilton Project team, and participants in The Hamilton Project authors' conference. The author declares that she has no relevant or material financial interests that relate to the research described in this paper.

MISSION STATEMENT

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

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

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

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

THE HAMILTON PROJECT

THE HAMILTON PROJECT

Principles for Public Investment in Climate-Responsible Energy Innovation

Catherine Hausman
University of Michigan

April 2023

BROOKINGS

Abstract

Energy markets play a key role in the US economy at both a micro and a macro level. Energy expenditures are an important—and volatile—factor in household budgets and business input costs. What is more, energy production and consumption remain the largest source of climate-damaging pollution in the US economy—amounting to $1 trillion in economic damages annually. Yet technological advances in new ways of producing and consuming energy have historically enabled economic growth.

In this proposal, I lay out the rationale for substantially increasing federal spending on clean energy research and development (R&D), along with guiding principles for how the money should be deployed. Publicly funded research in the United States has, in the past, led to valuable advances in energy technologies. But the United States has fallen behind in energy innovation, according to both measures on inputs (e.g., the portion of GDP spent on energy R&D) and outputs (e.g., clean energy patenting). Legislation including the Inflation Reduction Act, the CHIPS and Science Act, and the Bipartisan Infrastructure Law represent a move in the right direction, but more federal investment in R&D is still needed.

I propose the following foundational pillars for energy innovation policy to leverage effective investment: (1) spend triple the federal support on energy R&D; (2) prioritize clean energy, with a secondary focus on energy security; (3) leverage best practices for project selection and evaluation; and (4) draw on the expertise of the US Department of Energy, the Advanced Research Projects Agency-Energy, and the national laboratories.

In this proposal, I focus on addressing a fact of R&D funding: high risk leads to high rewards. We should acknowledge ex ante that the path to the highest return on R&D investment includes some individual project failures. Therefore, we expect the greatest return on the portfolio of projects and we should not limit evaluation as to whether individual investments succeeded. I also discuss complementary policies to ease deployment of new technologies and to support legacy fossil fuel communities. I argue that this approach will jump-start innovation, correct market failures, enhance energy security, and enable a more cost-effective transition to a climate-responsible economy.

Contents

Introduction 1

The Challenge 2
- Highlights 2
- Energy Is a Key Input and a Major Source of Pollution 2
- The United States Lags in R&D Funding for Energy 3
- Current Energy Policies Are Insufficient 5

The Proposal 7
- Highlights 7
- Pillar 1. Triple Federal Energy R&D, Scaling Up over Ten Years 7
- Pillar 2. Prioritize Clean Energy and Enhanced Energy Security 7
- Pillar 3. Use a Portfolio Approach to Evaluation: Allow for Risk-Taking in Project Selection, and Expect (and Learn From) Some Project Failures 8
- Pillar 4. Leverage Expertise at the DOE, ARPA-E, and the Energy-Focused National Labs. 10
- Incorporate Policies to Complement the Four Pillars 12

Questions, Concerns, and Additional Guiding Principles 15

Conclusion 18

Endnotes 19

References 20

Introduction

Recent decades have seen large swings between analysts' optimism and pessimism about the state of US energy markets. The shale revolution unlocked huge tracts of oil and gas extraction, lowered consumer energy prices, and made the United States a world leader in oil production. Analysts simultaneously heralded the revolution for *reducing* greenhouse gas emissions by displacing coal and criticized it for *increasing* greenhouse gas emissions by unlocking additional oil and gas supplies and slowing the deployment of low-carbon energy technologies. More recently, the global COVID-19 pandemic initially brought sharp decreases in fuel prices (notably, negative oil prices for a brief period). Russia's invasion of Ukraine subsequently sent global oil and gas prices soaring to historic levels. At the same time, there have been major swings in US climate policy. For example, in 2020 the United States withdrew from the Paris Agreement on climate change, but then in the fall of 2022 Congress passed new climate policy of historic magnitude in the Inflation Reduction Act (IRA).

A constant amidst the changes? The underfunding of the US energy innovation system. The United States has a history of public support for energy research and development (R&D) leading to commercial successes. These efforts have been enabled by R&D programs at the US Department of Energy (DOE), at the Advanced Research Projects Agency-Energy (ARPA-E), at the national laboratories (labs), and via partnerships with universities and the private sector. But the current combination of federal and private funding levels is not up to the challenges posed by decarbonization goals and energy security concerns. The United States has fallen behind countries ranging from Norway to Japan to China in the portion of GDP dedicated to federal support for energy R&D. And proposed decarbonization efforts rely on technologies that are not yet commercially viable.

To address these challenges, I propose strengthening federal support for energy innovation. This proposal emphasizes that the increase in funding for energy innovation should be mission-oriented, and should address two key national challenges—climate change and energy security:

- First, the portfolio of funded projects should be climate responsible. Funded projects should not increase the flow of carbon dioxide to the atmosphere and could help reduce the stock of atmospheric carbon dioxide concentrations. The economic damages from climate change are simply too large for the country to continue along a business-as-usual energy path.
- Second, by diversifying our fuel supply mix, energy innovation should enhance energy security. Research shows that clean energy innovation can improve resilience both by transitioning away from fossil fuels and by diversifying the supply mix within clean tech, alleviating potential security issues such as supply constraints for critical minerals.

Using evidence on the best practices for innovation subsidies will help an innovation program be effective and will help it do energy R&D investment well. Central to this proposal is a set of principles that enable high-risk, high-reward research: a diversified, portfolio approach to both investment and evaluation. Putting eggs in many baskets rather than going for a single moonshot diversifies risk and allows for risk taking across a broad range of projects. Successful venture capitalists use a portfolio approach to evaluation, and expect some project failures while leveraging the chance to learn from those failures. Additional principles include ensuring that funding is stable and that it supports a growing workforce while enabling collaboration across agencies and sectors.

The IRA and other federal, state, and local initiatives are putting the United States on a path toward a clean energy transition while providing safety nets for communities that would otherwise be left behind. The innovation policy in this proposal would complement—and indeed even accelerate—these existing efforts to enable a low-cost transition that benefits the planet and the economy.

The Challenge

Highlights

- The United States spends $1 trillion on energy each year.
- Nearly half of Americans are worried "a great deal" about the availability and affordability of energy.
- Energy expenditures are more volatile than the expenditures on other major categories of consumer goods and services.
- Millions of US households spend 20 percent or more of their income on energy goods and services.
- Over 80 percent of US greenhouse gas emissions are from energy sectors; those emissions are also key sources of local health-damaging pollutants.

Energy Is a Key Input and a Major Source of Pollution

Energy is a key input in the economy, affecting every household's budget and the input costs of all businesses in the nation. The United States spends $1 trillion on energy each year (US Energy Information Administration [EIA] 2023, table 1.7, p. 18). Energy consumption is spread across residential, commercial, and industrial end users, suggesting energy prices impact every aspect of the US economy (EIA 2023, table 2.1a, p. 38).

Households spent more than $500 billion on energy goods and services in 2021 (Bureau of Economic Analysis [BEA] 2023). Not surprisingly, then, with energy prices rising in 2022, energy expenditures are front-of-mind for many. According to a March 2022 Gallup poll, nearly half of Americans are worried "a great deal" about the availability and affordability of energy, which is by far the highest level of concern in a decade (Gallup News Service 2022a).

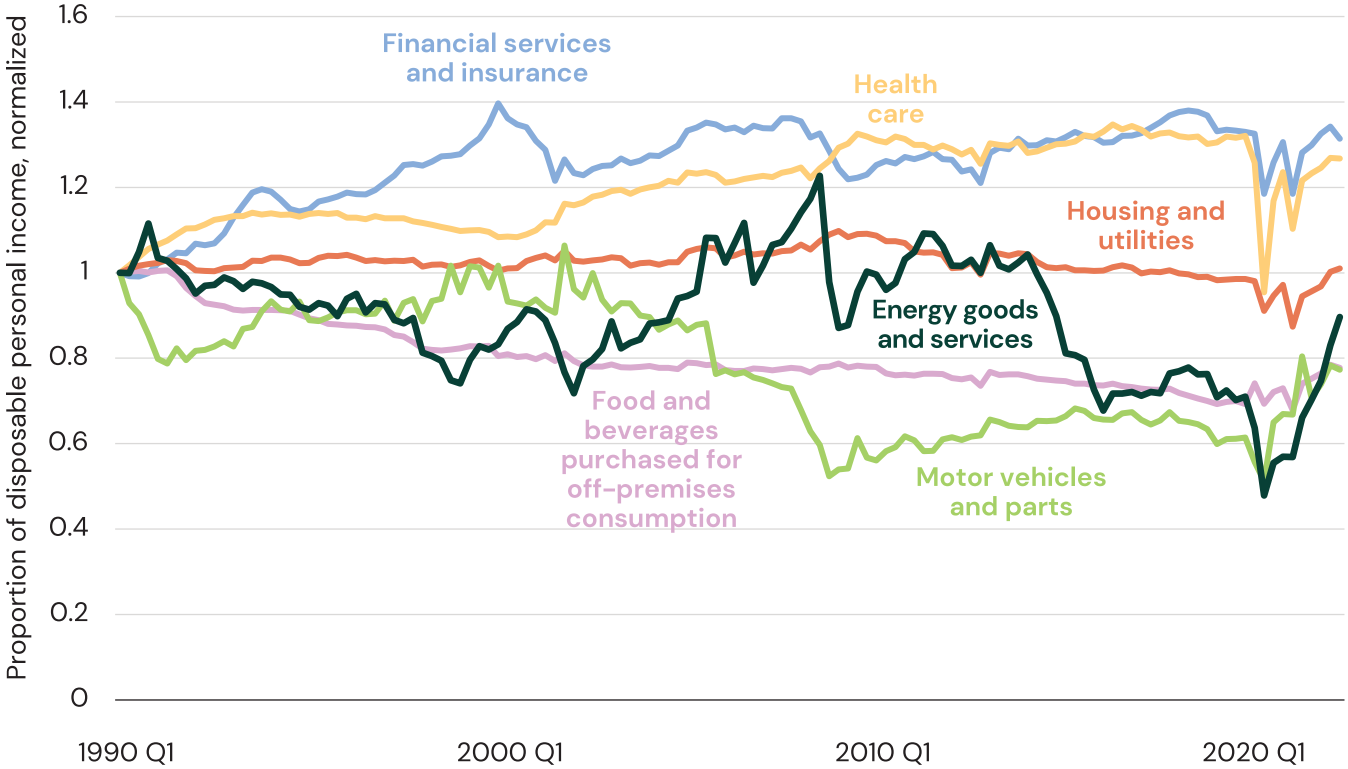
Figure 1 shows how personal consumption expenditures on energy goods and services (dark green line) have evolved over the past two decades, relative to other several other major categories of personal expenditures such as housing and health care. Each category is calculated as a portion of disposable personal income and is normalized to one in the first quarter of 1990. Readily apparent is the volatility of energy expenditures.[1] Notably, between 2000 and 2019 energy goods and services as a share of disposable personal income had the largest range of year-on-year changes—with both large increases and large decreases—among a number of other major product categories. Among the large expenditure categories shown in figure 1, only spending on motor vehicles as a share of income comes in a close second to energy. This highlights that, while there are times when energy expenditures are low, there are also frequent periods with unexpectedly very high expenditures, and this volatility implies costly uncertainty for both firms and households.

Consumer energy expenditures as a share of disposable personal income have been roughly 3 to 6 percent over the past several decades. Between 2016 and 2019, however, millions of households reported spending 20 percent or more of their aftertax income on energy goods and services.[2] Furthermore, roughly one in five households reports not being able to pay at least one of their energy bills in full,[3] which affects not only household budgets, but also household well-being. Chirakijja, Jayachandran, and Ong (2019) show that lower heating prices (resulting from fuel price decreases) reduce winter mortality. As they write, "High heating costs impose a difficult trade-off on households: They have to keep their home uncomfortably cold to save on heating or forgo other spending to afford their high heating bill (p. 1)." Similarly alarming reports come up when electricity bills are high, whether because of extreme weather or because of exorbitantly high prices (Leber 2022).

More broadly, recent price swings as well as Russia's invasion of Ukraine have reinvigorated public discussions of energy security, which Metcalf (2014) defines as "the ability of households, businesses, and government to accommodate disruptions in supply in energy markets (p. 156)." Issues in energy security can include household vulnerability, aggregate macroeconomic effects, and national security and/or military expenditures to protect the energy supply (Borenstein 2012; Löschel, Moslener, and Rübbelke 2010; Metcalf 2014; Portney et al. 2003).[4] Another framing of

FIGURE 1

Select Personal Consumption Expenditures, 1990–2022



Source: Bureau of Economic Activity n.d.; author's calculations

Note: Each category is calculated as a portion of disposable personal income and normalized to 1 in Q1 of 1990.

THE HAMILTON PROJECT BROOKINGS

the problem separates energy security concerns into three categories: "robustness (sufficiency of resources, reliability of infrastructure, and stable and affordable prices); sovereignty (protection from potential threats from external agents); and resilience (the ability to withstand diverse disruptions) of energy systems" (Cherp et al. 2012, 327).

At the same time, because of their large scale, energy sectors are a key contributor to climate change. Energy sectors produce the majority of US carbon emissions, releasing billions of tons of carbon dioxide every year, and contributing to economic damages in both the near term and the long term (Environmental Protection Agency [EPA] 2022). In 2020 alone, over 80 percent of US greenhouse gas emissions came from the energy sector.[5] Recent estimates of the economic damages from greenhouse gas emissions put a price tag of $1 trillion per year on US energy sector emissions alone.[6] These emissions are a function of economic activity across all sectors. Total emissions are roughly equal across transportation, electric power, and industrial sources. Energy sectors are also important sources of local pollution, such as health-damaging particulate matter and nitrogen oxides (EPA 2017).[7]

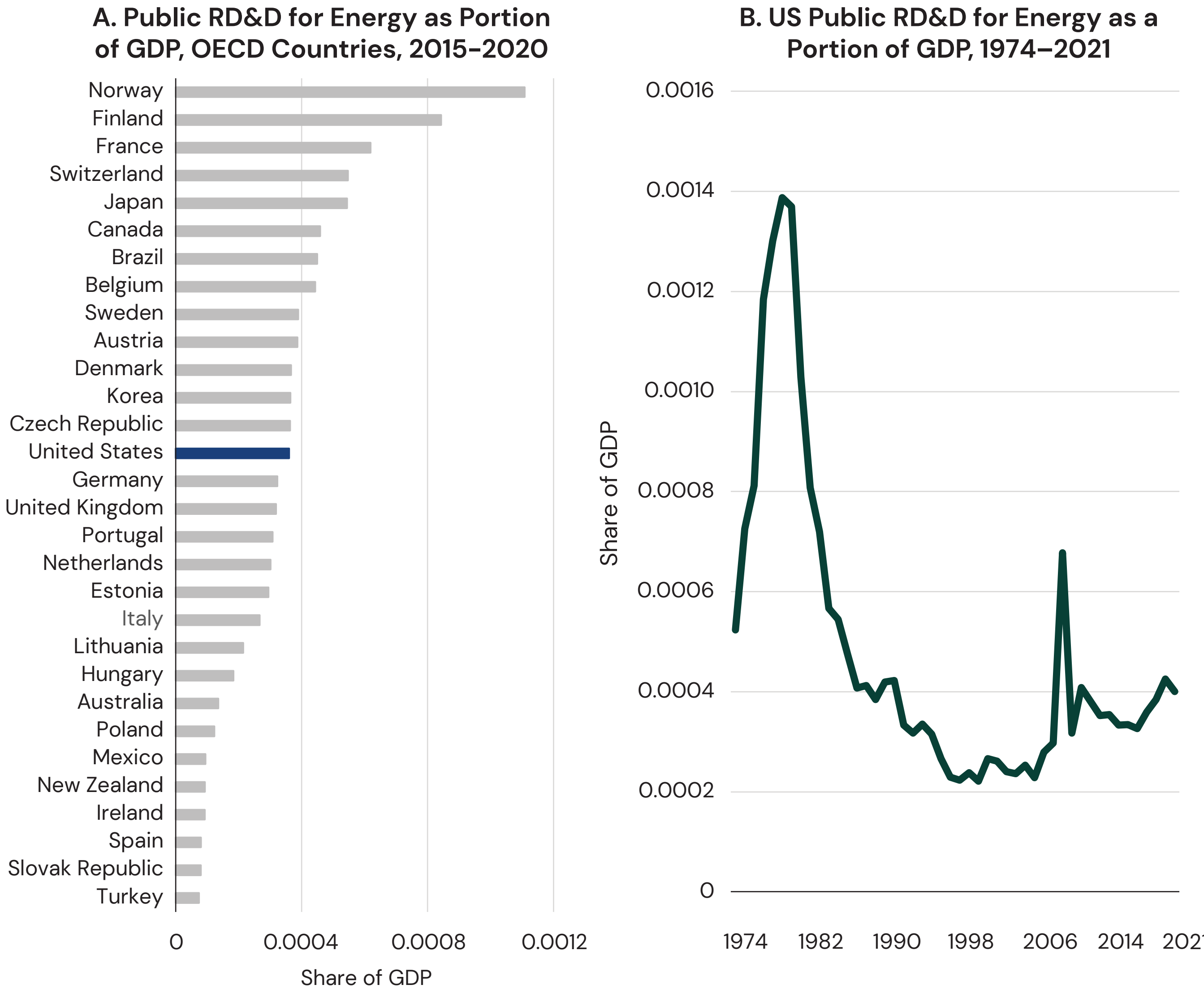
The United States Lags in R&D Funding for Energy

A whopping 93 percent of the American public reports believing that it is "very important" (69 percent) or "somewhat important" (24 percent) for the United States to be a world leader in scientific achievements (Funk et al. 2020). And indeed, the United States has long been a leader in technology development, consistently spending 2.5 to 3.5 percent of its GDP on R&D.[8] However, a crucial area where the US has slipped is government R&D funding for energy. According to International Energy Agency (IEA) data, the United States now ranks well behind numerous Organisation for Economic Co-operation and Development (OECD) countries in the portion of GDP spent on public energy RD&D (research, development, and demonstration) support (figure 2a).[9] Outside the OECD, public spending for energy RD&D in China is also ahead of the United States as a portion of GDP (IEA 2022).

In fact, apart from American Recovery and Reinvestment Act (ARRA) funding in 2009, US public energy RD&D spending has been flat for decades (figure 2b). In contrast, other countries are already operating

FIGURE 2

Public Research, Development, and Demonstration for Energy



Source: International Energy Agency n.d.

THE HAMILTON PROJECT
BROOKINGS

ambitious energy RD&D programs, especially in low-carbon and other clean energy development. For example, Norway's Energi21 strategy, announced in 2008, focuses on climate-friendly energy research, development, and commercialization. And innovation, especially related to low-carbon technologies, is a key component of China's 14th Five-Year Plan (2021–25), which comes on the heels of that country's ambitious RD&D spending during its 13th Five-Year Plan (IEA 2022).

The CHIPS and Science Act (CHIPS Act) of 2022 and the Bipartisan Infrastructure Law of 2021 provide some additional funds for R&D for energy, but more funds need to be made available over the longer term. Of the CHIPS Act's $280 billion in authorizations, $174 billion is aimed at science and technology. Not all of that sum targets clean energy innovation, but it does include budget increases for the DOE over five years, from $30.5 billion to $67.5 billion, with specific funds designated for the DOE's Office of Science, for ARPA-E, and for infrastructure and maintenance spending at the national labs. The Bipartisan Infrastructure Law contains more than $20 billion for R&D and DOE demonstration projects in areas such as carbon capture, clean hydrogen, batteries, and more, although the bulk of the law's spending is aimed at physical infrastructure projects (e.g., public transit, electric vehicle charging, electrical grid infrastructure, etc.).

What remains to be done, then? First, we need to ensure that Congress appropriates the necessary funds: importantly, the CHIPS legislation authorizes but does not appropriate funds. Second, we need to ensure that these funds are deployed toward clean energy innovation. Finally, we need to ensure that long-term funding is available and that CHIPS-authorized funds do not represent just a one-time injection of funds.

The problem with small and/or only temporary public R&D support is that, as a large body of evidence shows, federal investment in R&D has big payoffs for the economy. Broadly speaking, federal innovation spending does not crowd out private innovation; on the contrary, it can stimulate business outcomes (as measured by revenue, patents, etc.) as well as overall economic growth (Bloom, Van Reenen, and Williams 2019; Bryan and Williams 2021; Howell 2017; Jones and Summers 2022; Jones and Williams 1998).

Moreover, the private sector in the United States also lags in funding energy R&D. As one example, most electricity and natural gas utilities—two of the larger US energy sectors—have regulatory schemes that can disincentivize private-sector innovation (Costello 2016; Schwartz 2022; Sivaram et al. 2020). Indeed, Costello (2016) reports that, in 2013, while all industries spent around 3 percent of their net revenue on R&D, utilities spent 0.1 percent. For comparison, pharmaceuticals and medicines; and computer and electronic products each spent more than 10 percent, which is two orders of magnitude more than utilities spent.

Perhaps not surprisingly, given the anemic US funding—both public and private—of recent decades, US patenting in clean energy is falling, and is now behind clean energy patenting in China (IEA n.d.; International Renewable Energy Agency n.d.).

Current Energy Policies Are Insufficient

The primary reason that economists support government funding for R&D is that private markets, left to their own devices, undersupply new technological developments. If a company or an individual invents a promising technology, other companies and individuals can learn from this development, invent related products, and capture some of the profits. As a result, the private economic incentive for innovation is too low, even in the presence of patent protections. Sometimes this dampening of incentive is because patent protections are not profitable enough, and sometimes it is because simply *demonstrating* project feasibility can give valuable information to other companies. By subsidizing R&D, the government corrects this market failure.

In fact, the history of energy development is full of examples of energy innovations that spilled over across firms, with impacts that reached far beyond any single innovator. For example, the expansion in wind turbines in the United States is due in large part to falling costs, which is partly a function of knowledge spillovers (Covert and Sweeney 2022). Examining evidence from patenting activity, Noailly and Shestalova (2017) argue that solar, wind, and energy storage all generate knowledge spillovers. That these knowledge spillovers exist for clean energy technologies suggests that government support can have far-reaching impacts.

Moreover, government activity in clean energy has a successful track record in inducing patents, research citations, and so on (Doblinger, Surana, and Anadon 2019; Popp 2017). As a result, clean energy innovation can lower the cost of decarbonization. In particular, clean energy innovation is needed to close the gap with polluting energy industries. Acemoglu et al. (2016) show that polluting technologies have a head start: they have had more time to develop, and, as a result, "clean research must climb several steps to catch up with dirty technology and…this gap discourages research effort directed toward clean technologies (p. 100)." Government funding can help close this gap (Acemoglu et al. 2016; Aghion et al. 2016; Dugoua 2022; Noailly 2022). Relatedly, Acemoglu et al. (2012) argue that further delays in support for clean innovation widen the innovation gap between clean and polluting energy industries and impair future economic growth.

Delays can also put an economy at a disadvantage in the global marketplace. Altenburg and Rodrik (2017) focus on the developing economy case, but some of their logic applies to developed economies as well. They write, "Sticking to traditional products and processes as the worlds' dominant economic actors shift to greener goods and production techniques will drive a wedge between local and global practices. This makes it more difficult to compete in the future, considering that trade and investment treaties increasingly regulate environmental issues and that lead firms in global value chains impose progressively higher environmental standards. [Additionally], countries should avoid getting locked into unsustainable infrastructure and business practices because the costs of switching in the future will likely be disproportionally high (p. 7)."

Finally, delays in energy innovation could pose risks of energy security. Three emerging energy security risks are (1) the overreliance of our European allies on Russian natural gas, (2) future scarcity or supply chain disruptions for the rare earth elements currently used in clean energy technologies, and (3) the risks to energy infrastructure from climate change. While innovation alone is not a silver bullet for these concerns, clean energy innovation has the potential to alleviate all three concerns by diversifying energy supply chains and by slowing the pace of climate change (Cherp et al. 2012; IEA 2021; Riahi et al. 2012).

Thus, overall, R&D expenditures by the government can correct market failures, jump-start innovation, enhance energy security, and reduce the cost of a transition to clean energy (Acemoglu et al. 2016; Bohi and Toman 1993; Popp 2019). Government activity in clean energy R&D has already had many successes (Doblinger, Surana, and Anadon 2019; Goldstein and Narayanamurti 2018; Howell 2017; National Academies of Sciences, Engineering, and Medicine 2020; Popp 2017), but numerous analysts point to the urgent need to grow funding for innovation (Acemoglu et al. 2012; Blanco et al. 2022; Cunliff and Nguyen 2021; Denholm et al. 2022; Mazzucato and Semieniuk 2017; National Academies of Sciences, Engineering, and Medicine 2021; Popp 2019).

The Proposal

Highlights

- Pillar 1. Triple federal energy R&D in real terms, scaling up over ten years.
- Pillar 2. Prioritize clean energy and enhanced energy security.
- Pillar 3. Use a portfolio approach to evaluation: Allow for risk-taking in project selection and expect (and learn from) some project failures.
- Pillar 4. Leverage expertise at the DOE, ARPA-E, and the energy-focused national labs.
- Incorporate policies to complement the four pillars

Pillar 1. Triple Federal Energy R&D, Scaling Up over Ten Years

First, I recommend that the US federal government implement sustained increases in energy R&D funding. Specifically, I propose increasing federal spending by 10 percent per year in real terms, indexed to inflation. In just over ten years, this increase would imply a tripling of federal support, a level that should then be sustained (in real terms) thereafter. Other analysts have also called for comparable increases in spending (see, e.g., Costello 2016; Cunliff and Nguyen 2021; National Academies of Sciences, Engineering, and Medicine 2021; Sivaram et al. 2020).

Empirical evidence on the *optimal* level of federal funding is limited (Anadón, Baker, and Bosetti 2017). But here the perfect is the enemy of the good: an increase over current levels is well justified by the existing literature (Acemoglu et al. 2012; Blanco et al. 2022; Cunliff and Nguyen 2021; Denholm et al. 2022; Mazzucato and Semieniuk 2017; National Academies of Sciences, Engineering, and Medicine 2021; Popp 2019). Moreover, tripling R&D spending is not unprecedented: it is within the range of both historical US support and current international support (see figure 2). Committing to this steady increase over time would give innovators the confidence needed to invest in ambitious and long-term projects.

Pillar 2. Prioritize Clean Energy and Enhanced Energy Security

Second, I recommend that federal spending on energy R&D be mission-oriented. Primarily, it should prioritize clean energy and technologies that reduce pollution. Clean energy patenting in the United States has fallen, despite the ever-growing need to address climate change. New energy developments must be climate-responsible and should not lead to an expansion of the United States' carbon dioxide emissions; ideally, new technologies should even allow for a reduction in the stock of legacy concentrations. It is worth noting that most Americans are worried about climate change (Gallup News Service 2022b) and want to see more government action on it (Tyson and Kennedy 2020), which suggests the proposal could be politically feasible.

The reader may well ask *which* clean energy technologies I would recommend supporting. I make no such recommendation in this proposal, precisely because, as I argue above, technical experts in the areas of science and technology should make those decisions on the merits of specific proposals. It is neither the role of this economist nor of a politician to try to ex ante choose the winning technology. White papers have called for innovation in a broad range of technologies, including advanced batteries for electric vehicles; grid-scale electricity storage; advanced hydropower, geothermal, solar, and wind generation; small modular and other advanced nuclear reactors; hydrogen; clean fuels for air, maritime transport, and trucking; fuel cells; improved industrial sector energy technologies; carbon capture, use, and sequestration; and carbon dioxide removal (Raimi, Krupnick, et al. 2021; Sivaram et al. 2020; Third Way 2022). The potential role of these technologies in mitigating climate change is analyzed in Denholm et al. (2022) and in National Academies of Sciences, Engineering, and Medicine (2021). Returning to recommendations of which sectors to fund, it is important to note that innovation funding can also take the form of supporting basic sciences or crosscutting technologies, which can contribute to multiple energy sectors.

Note that the list of potential technologies includes both carbon capture, utilization, and storage

(CCUS), and carbon dioxide removal. Numerous studies on decarbonization highlight that CCUS is likely to play a key role, and fossil fuel infrastructure is likely to continue to be necessary in the initial stages of an energy transition. At the same time, legacy carbon pollution concentrations in the atmosphere may need to be removed. Existing CCUS R&D is being carried out by multiple national labs, which are examining a broad range of CCUS technologies for the power sector and industrial facilities, as well as direct air capture.

An additional component of this mission-oriented support is to enhance energy security. Note that this goal should not come at the expense of innovation being climate responsible. Climate change itself represents an energy security threat, since the natural disasters that climate change makes more common and more severe can damage critical energy infrastructure. Clean energy innovation can enhance energy security, however. In particular, Riahi et al. (2012) examine multiple energy transition pathways and their implications for energy security, and find that the diversification of fuel supplies would improve energy security along multiple dimensions (e.g., sovereignty, resilience). One concern that could emerge in a clean energy transition is new security issues around rare earth elements and other critical elements needed for solar, wind, batteries, and so on. However, energy innovation can alleviate these concerns by diversifying the technologies used (and therefore materials required) *within* clean energy. Indeed, the IEA (2021) has the following key recommendation: "Promote technology innovation at all points along the value chain. Stepping up R&D efforts for technology innovation on both the demand and production sides can enable more efficient use of materials, allow material substitution and unlock sizeable new supplies, thereby bringing substantial environmental and security benefits (p. 18)."

Some efforts are already under way to improve energy security during a transition to clean energy, and the R&D funding I propose should expand on these initiatives. Examples of existing initiatives include funding for rare earth security activities in the Bipartisan Infrastructure Law; and the Critical Materials Institute, a DOE initiative led by Ames National Laboratory.

It is worth noting two aspects of potential supply constraints or disruptions to the critical minerals supply chain. First, clean energy technologies are indeed expected to require more minerals than past fossil-based energy systems. As the IEA (2021) notes, however, "There are significant differences between oil security and mineral security, notably in the impacts that any disruption may have. In the event of an oil supply crisis, all consumers driving gasoline cars or diesel trucks are affected by higher prices. By contrast, a shortage or spike in the price of a mineral affects only the supply of *new* EVs [electric vehicles] or solar plants. Consumers driving existing EVs or using solar-powered electricity are not affected. In addition, the combustion of oil means that new supply is essential to the continuous operation of oil-using assets. However, minerals are a component of infrastructure, with the potential to be recovered and recycled" (14; emphasis in original). Overall, additional clean energy innovation can further the goals of diversifying fuel supply and developing substitutes to prevent critical minerals supply constraints (Cherp et al. 2012; IEA 2021; Riahi et al. 2012).

Pillar 3. Use a Portfolio Approach to Evaluation: Allow for Risk-Taking in Project Selection, and Expect (and Learn From) Some Project Failures

To maximize the benefits of energy R&D funding, it is important to plan in terms of project selection and evaluation. The academic literature has pointed to best practices in these areas, which I outline below. A common theme throughout is that high-risk projects can bring high rewards—and therefore the government should be seeking out risky projects to fund. With this approach inevitably come some project failures—but these should be more than offset by the rewards from the projects that succeed. Program evaluation, therefore, should seek both to learn from failures and to evaluate successes of the program's portfolio rather than limiting evaluation to individual projects.

Eggs in Many Baskets

Evidence supports an R&D funding approach that puts eggs in many baskets within the clean energy space, rather than going for one big moonshot (Rodrik 2014). There are several reasons for this approach.

First, if the government is funding a limited number of exceptionally large projects, it must be responsible for choosing a winner—that is, deciding which technology, which company, and which scientific approach to that technology are most likely to succeed. There is no evidence to support that the government has special skill in making this decision, and so it runs the risk of funding a spectacular failure (Henderson and Newell 2011b; Hepburn, Pless, and Popp 2018). There is also related evidence that government attempts to drive the direction of innovation too narrowly can stymy alternatives (Arora and Gambardella 2011).

Second, selecting a small number of projects at an exceptionally large scale leaves the funding project open to graft: it is simply too tempting for industry to try to capture the selection and evaluation processes.

If the selection and evaluation processes are open to corruption, the R&D program will be less valuable for the economy, and also puts in jeopardy the social license to continue the program at all.

Third, there is evidence from multiple US industries spanning many decades that accumulated, crosscutting innovative developments can lead to large leaps forward in technological change. Fracking is one notable example. What unlocked large new tracts of oil and gas development in the United States was not one singular technology, but the realization that multiple technological improvements—in underground sensing, directional drilling, and new fracking fluids—could be combined in innovative and cost-effective ways. Related evidence supports this idea for a wide variety of technologies—from the steam engine (Yanosek 2012), to synthetic rubber in World War II (Arora and Gambardella 2011), to recent biomedical advances (Cockburn, Stern, and Zausner 2011).

Relatedly, but on a more macro scale, Hausmann et al. (2013) argue that the *complexity* of an economy—its diversity of ideas, capabilities, organizations, and products—is a driver of economic growth. Again, this points toward the development of multiple directions of innovation, rather than toward a narrow focus that locks us into one industry or technology.

Finally, the complexity of energy markets points to the need to advance innovation along many fronts rather than relying on a single moonshot. Energy security issues, for instance, involve multiple markets (e.g., oil, natural gas, precious minerals) and multiple geopolitical challenges. A core principle of energy security is diversification of energy technologies and supply chains, and *not* the reliance on a single technology. As Popp et al. (2022) write, "The climate problem is too expansive and complex for a one-size-fits-all solution, and so is the energy system on which solving the climate problem depends (p. 240)."

How to Select Projects: Allowing for Risk-Taking and Expecting Some Failures

The current system for project selection varies across federal R&D programs. One common approach is using peer review via external experts. Researchers have examined the success of existing project selection for a subset of DOE programs, highlighting approaches that seem particularly successful.[10]

In general, researchers have argued that government R&D programs should be supporting riskier initiatives than they currently do (Franzoni, Stephan, and Veugelers 2022). As those authors write, "Society needs scientific breakthroughs to tackle many of the challenges it faces. Because many of the paths to such breakthroughs are risky, its science system, and particularly its public science funding system, needs to ensure that risk-taking is encouraged or, at a minimum, that the system is not biased against risky research (p. 122)."

Related to this principle, researchers have argued that technical experts should drive project selection and monitoring (Cockburn, Stern, and Zausner 2011; Goldstein and Kearney 2020). As Chan et al. (2017) write, "Active scientists are better placed than managers to spot bold but risky opportunities (p. 26)."

Overall, project selection can be a complicated undertaking, but the existing research on innovation does provide guidance, and some of the existing DOE models appear to have been successful. Peer review by external experts provides useful guidance, but internal flexibility—within broad mission-oriented programmatic guidelines—for program staff and internal researchers is advisable. Bin-Nun et al. (2017) offer additional bureaucratic details on how project selection at DOE could continue to be improved.

The good news for program design is that selecting projects for funding in the perfectly optimal way is not necessary for the program to be effective. Even with less-than-optimal design, government support for R&D can significantly lower the costs of a transition to cleaner energy sources (Acemoglu et al. 2016).

A Portfolio Approach to Evaluation

Paradoxically, the sign of a high-quality government R&D program is that some projects fail. If every chosen project succeeds, it is a sign that the program is not taking enough risk in its project selection. Of course, if every chosen project fails, that is also a sign of a flaw in the selection process.

As a result, there is ample evidence that government R&D funding programs should be evaluated using a portfolio approach (Hepburn, Pless, and Popp 2018; Mazzucato and Semieniuk 2017; Rodrik 2014). That is, they should not be evaluated on whether any *one* project succeeded or failed in its goal, but on whether the suite of projects led to new, useful breakthroughs.

Indeed, this is the same approach venture capitalists take: They do not evaluate their performance based on one win or one loss. Instead, they expect many projects to fail but look toward whether their overall portfolio grew.

Finally, selection and evaluation ought to be transparent. As Rodrik (2014) writes, "Public agencies must explain what they are doing and how they are doing it. They must be as transparent about their failures as their successes. Accountability not only keeps public agencies honest, it also helps legitimize their activities (p. 488)."

There should be off-ramps for *individual* projects that have hit a dead end (Goldstein and Kearney 2020; Newell 2011; Rodrik 2014). Some projects that failed in highly visible ways (e.g., Solyndra) continued to be funded even as it became clear that they were problematic. One way to implement these off-ramps is to include milestones and to halt funding when projects are significantly behind on meeting milestones (Chan et al. 2017). Moreover, the metrics for off-ramps should be "consistent, comprehensive, and objective (Newell 2011; p, 40)." A similar approach is for the government agency to "fund in stages, where increasingly larger amounts of funding are allocated depending on whether interim milestones are met" (Franzoni, Stephan, and Veugelers 2022, 125). This kind of approach can give government agencies the freedom to fund riskier projects early on, knowing that there is an off-ramp if the project is not paying off.

Notably, although Solyndra failed, the overall loan guarantee program of which Solyndra was a part was actually successful (Hepburn, Pless, and Popp 2018), which highlights that, while individual projects need off-ramps, overall performance should be evaluated as a portfolio, and overall funding should remain stable even when individual projects fail. Indeed, Goldstein and Kearney (2020) argue that the DOE's ARPA-E program has already shown successes in dynamically adjusting project funding.

Pillar 4. Leverage Expertise at the DOE, ARPA-E, and the Energy-Focused National Labs.

The DOE, the ARPA-E program, and the national labs have a proven record of contributing to technological developments in many energy sectors: wind, solar, natural gas, coal, and nuclear power generation, along with fracking, energy efficiency technologies, and batteries. The labs also have a record of supporting local economies in a broad range of regions across the continental United States (figure 3). In this pillar, I give a brief overview of existing activities at ARPA-E, at DOE more broadly, and at the energy-focused national labs.

ARPA-E is a federal agency tasked with developing technological advances in energy, focusing on high-risk, high-reward projects. It began funding projects in 2009, and has supported both basic and applied sciences, with a cumulative $3 billion in R&D funding since 2009. Funded projects have supported the development of batteries, electrical grid infrastructure, electrical vehicle charging, wind turbines, energy efficiency, alternative fuels, and more. A major strength of the ARPA-E approach is its focus on risky projects with the potential for high-reward innovation; this is exactly the approach supported by best practices in innovation policy.

Another DOE initiative with successes in funding energy innovation is the Small Business Innovation Research (SBIR) program. It funds innovation at small and young firms that face greater challenges in accessing private capital. An area of success of this program has been easing early-stage financial constraints and enabling firms to eventually receive venture capital investment.

Both ARPA-E and the SBIR program have been successful at fostering quantifiable, measurable innovation successes (Feldman et al. 2022; Goldstein and Narayanamurti 2018; Howell 2017; Myers and Lanahan 2022; National Academies of Sciences, Engineering, and Medicine 2020). Those two programs' budgets are only a small fraction of the total DOE budget, and scaling up funding for both is justified by their past successes.

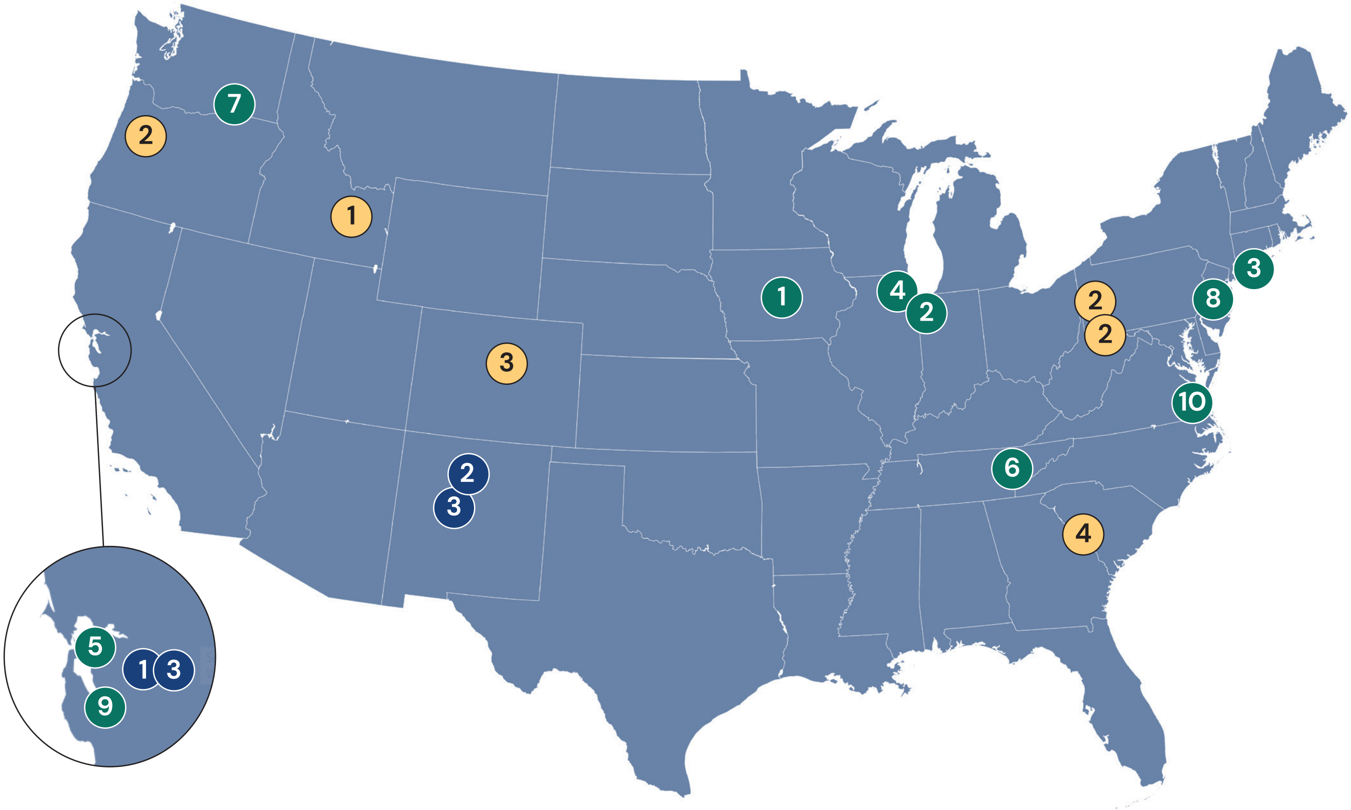
The DOE employs around 100,000 staff and contractors at national labs and related sites. The seventeen national labs in the United States had combined operating costs in 2020 of around $18 billion, most of it coming from DOE funds. The labs engage with numerous external partners, including via technology transfer programs, private industry agreements, and collaborations with universities.[11] In 2020 there were more than 10,000 university faculty, postdoctoral researchers, graduate students, and undergraduates with national lab affiliations (DOE 2021).

Almost all seventeen labs conduct research on energy, and they have played important roles in the development and improvement of wind, solar, natural gas, coal, and nuclear power generation, along with fracking, energy efficiency technologies, and batteries (Glauthier et al. 2015). National labs with significant clean energy programs include Idaho National Laboratory (nuclear energy); the National Energy Technology Laboratory (carbon capture), with sites in Alaska, Oregon, Pennsylvania, Texas, and West Virginia; the National Renewable Energy Laboratory in Colorado; Oak Ridge in Tennessee (wind, solar, energy efficiency); and the Pacific Northwest National Laboratory's new Energy Sciences Center in Washington State (DOE 2021).[12]

Collectively, the DOE, ARPA-E, DOE's SBIR program, and the national labs have a history of success. Broadly, government-generated clean energy patents are more likely to be cited than are patents from other institutions, which Popp (2019) argues shows the quality of government-driven clean energy innovations. Individual programs from the DOE also have proven to be successful. For instance, projects funded by the ARPA-E have been particularly likely to contribute to a new patent or scientific publication (Goldstein and Narayanamurti 2018). And DOE's SBIR grant program has been quite successful at spurring innovation with commercial success (Feldman et al. 2022; Howell 2017; Myers and Lanahan 2022). Myers and Lanahan (2022) estimate that, "for every patent produced by [SBIR] grant recipients, three more are produced by others who benefit from spillovers (p. 2393)." The labs also have a record of success in terms of research output. For instance, the Nature Index of scientific publications ranks five US

FIGURE 3

Department of Energy National Laboratories



Office of Science Laboratories

1. Ames Laboratory
   Ames, Iowa
2. Argonne National Laboratory
   Argonne, Illinois
3. Brookhaven National Laboratory
   Upton, New York
4. Fermi National Accelerator Laboratory
   Batavia, Illinois
5. Lawrence Berkeley National Laboratory
   Berkeley, California
6. Oak Ridge National Laboratory
   Oak Ridge, Tennessee
7. Pacific Northwest National Laboratory
   Richland, Washington
8. Princeton Plasma Physics Laboratory
   Princeton, New Jersey
9. SLAC National Accelerator Laboratory
   Menlo Park, California
10. Thomas Jefferson National Accelerator Facility
    Newport News, Virginia

Other DOE Laboratories

1. Idaho National Laboratory
   Idaho Falls, Idaho
2. National Energy Technology Laboratory
   Morgantown, West Virginia
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. National Renewable Energy Laboratory
   Golden, Colorado
4. Savannah River National Laboratory
   Aiken, South Carolina

NNSA Laboratories

1. Lawrence Livermore National Laboratory
   Livermore, California
2. Los Alamos National Laboratory
   Los Alamos, New Mexico
3. Sandia National Laboratory
   Albuquerque, New Mexico
   Livermore, California

Source: Department of Energy n.d.

national labs in its list of the twenty most productive government research institutions worldwide (Nature Index 2021). While there have been criticisms of the national labs specifically, suggestions for how to continue to modernize them are already available (e.g., Anadon et al. 2016; Bin-Nun et al. 2017; Glauthier et al. 2015).

Finally, the national labs can be a valuable source of local economic benefits for the regions that host them. Using government labs as place-based policy is not limited to direct employment effects (i.e., government jobs),[13] but rather is also about adding to an industry base, thus attracting firms and workers more generally—so-called localization effects and agglomeration spillovers (Feldman and Kogler 2010). For instance, empirical research for Soviet-era innovation clusters shows long-run impacts on economic development, employment, and patenting in localities hosting hubs; the authors point to agglomeration effects, local knowledge spillovers, and path dependence (Schweiger, Stepanov, and Zacchia 2022). Moreover, these regional economic development effects might also make it easier to attract political support, of the kind needed to promote stable, long-term funding.

National labs are already working on numerous clean energy technologies, and they are represented in a wide range of geographic regions. But there is room to grow. First, these are not the largest national labs in the system, which include Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and Sandia National Laboratories.

Second, there are no national labs centered in Texas, and there are only limited partnerships with Texas-based universities and companies (DOE 2021).[14] Nonetheless, Texas is a national center for numerous forms of energy production, from wind to fossil fuels, including carbon capture. (Indeed, there is no national lab anywhere on the Gulf Coast, despite that region's vital role in US energy markets.) Moreover, both Dallas and Houston are listed as promising areas for building technology hubs because of their size, residents' educational attainment, and those cities' quality of life (Gruber and Johnson 2019).[15] One option would be to expand the size and scope of the Sugarland, Texas, branch of the National Energy Technology Laboratory; another option would be to build a new national lab in Texas. For either option, collaboration with local universities and local industry could lead to a greater impact.

Funding for dedicated line items for doctoral and postdoctoral training (e.g., summer internships, multiyear postdoctoral positions) could be increased. This would allow the United States to grow its researcher workforce while also facilitating collaboration between national labs and universities.

Additional funding at national labs would provide the opportunity for greater social science and interdisciplinary research at these facilities, and indeed funding could come with dedicated line items for these activities. The labs have historically focused on engineering and basic sciences, but social science and interdisciplinary researchers could concentrate on questions such as the social license to develop and deploy innovative technologies, the equity and justice implications of modern technologies, and so on.

Incorporate Policies to Complement the Four Pillars

Just as there is widespread agreement in support of the four pillars within the main proposal, there is similarly a consensus regarding the benefits of pairing this R&D support with complementary policies (Acemoglu et al. 2012; Fischer, Preonas, and Newell 2017; Henderson and Newell 2011b; Hepburn, Pless, and Popp 2018; Popp 2017; Sivaram et al. 2020). Complementing investment with implementation support is clearest for those policies that (1) aid with deployment and adoption of new energy technologies, (2) correct environmental externalities, and (3) support communities who might otherwise be harmed by the transition to new energies.

Additional Policies to Support Deployment

Innovation policy on its own (i.e., absent complementary policies) helps mitigate climate change. Indeed, some researchers have proposed ramping up innovation policy as a second-best subsidy if climate regulations or carbon pricing are infeasible (Rodrik 2014). It is worth stressing, however, that innovation policy and other climate policy—whether market-based carbon pricing or sector-specific regulations and subsidies—are complements. Innovation policy corrects market failures that stem from knowledge spillovers and financing constraints and lowers costs of climate-responsible energy; carbon pricing or emissions regulation or abatement subsidies correct environmental externalities. Innovation will help ensure we have the right mix of cost-effective tools available, while climate policy will ensure we deploy those tools.

One way to see the need for complementary policies is by comparing energy innovations to innovations in health care or defense, two large areas of government R&D support. In the case of health care, innovations bring about improved quality of care for patients, who are then willing to pay for that improved quality. Thus, innovators can be assured that there will be a market-based demand for commercialization of their products. In the case of national defense, innovators can be assured that the government will pay for new technologies. Energy innovations, however, are different. Innovations that lower the cost of energy production or delivery are likely to be adopted. But energy innovations that bring about improved quality—particularly in the form of lower carbon emissions or other forms of improved environmental protection, such as reduced air, water, or soil pollution—reduce unpriced externalities, which individual consumers may not be willing to pay for. As a result, new innovations can be trapped in the so-called "Valley of Death," failing to commercialize at scale.

The key, then, to ensuring deployment of new clean energy is to pair R&D subsidies with complementary policies aimed at environmental protection. These policies could take the form of deployment subsidies, pollution regulations, or pollution pricing. Best practices support focusing these complementary policies where there are market failures—asymmetric information, public goods, externalities and concentrated market power that private actors do not incorporate into their production and consumption decisions. These market failures could be related to climate change, health and safety, capital market failures, or network externalities (e.g., chicken-and-egg problems in the diffusion of electric vehicles vs. charging stations).

The Role of the Inflation Reduction Act

The IRA includes many such complementary policies. The IRA, passed in August 2022, includes an estimated $369 billion in federal spending for energy security and climate change mitigation. Central provisions include tax credits for wind and solar electricity and tax credits for electric vehicles. There are also provisions for a loan program through the DOE[16] and green financing through the EPA. Moreover, there are tax credits and other incentives for battery storage, nuclear power, carbon capture and storage, hydrogen production, and energy efficiency. Finally, there is some limited pollution pricing in the form of methane fees.

Indeed, the IRA contains aspects of all the complementary policies described above—with provisions aimed at deployment, at environmental protection, and at capital market failures. All these are areas where market failures justify federal policy. However, three limitations remain: First, the IRA is not primarily innovation policy, and its financing programs will not do enough to support the development of new energy technologies. Second, implementation details for many IRA provisions must still be worked out.[17] Finally and most importantly, the IRA is a carrots policy. Sticks are still needed, as described in depth in the next section.

The Need for Sticks: Beware Energy Additions Rather Than Transitions

Another lens through which to view the deployment problem is to note that climate-responsible energy policy requires not only adopting clean new energies, but also phasing out heavily polluting energy sources. Innovation policy on its own will not lead to this phase-out unless the new energy breakthroughs are so low cost that they completely displace existing sources. The world has never seen such an energy breakthrough. Newell and Raimi (2018) lay this phenomenon out starkly with two centuries worth of global fuel use data. They show (figure 4) that, as new energy technologies have been developed, they have been *stacked on top of* existing energy use. Coal boilers revolutionized industry but did not replace the global use of wood, biomass, and waste. More recently, the use of other renewables, including solar and wind, has increased dramatically—but the global use of fossil fuels has nonetheless continued.

Even when new energies are sufficiently low cost to displace some legacy sources, it is difficult to *completely* displace the legacy sources. The reason for this difficulty is that the new energy technology is lowering the cost of energy services. This is, of course, good for economic growth, but it means more energy services are demanded overall. And this means legacy energy sources are retained. One example can be seen in the energy efficiency literature, where improvements in the efficiency of vehicles or appliances lead to a rebound effect. Another example can be seen in the development of shale gas—it displaced more heavily polluting coal, but it also led to a large expansion in natural gas use, which on net increased greenhouse gas pollution (Hausman and Kellogg 2015).

Climate mitigation requires adopting new technologies and decreasing our use of fossil technologies. Decarbonization actually requires *stopping* our use of fossil technologies or developing carbon capture that is sufficiently low cost. Either of these steps would represent an unprecedented kind of energy transition, which will require complementary policies of the sort described above. Moreover, it will require regulations or pricing to drive down the use of legacy polluting industries, and not just the carrots that the IRA uses to incentivize the deployment of green alternatives such as renewables. These sticks could be sector-specific regulations on emissions—ideally through, for example, a cost-effective clean electricity standard (Borenstein and Kellogg 2022)—or they could come in the form of carbon pricing (Finkelstein-Shapiro and Metcalf 2022; Metcalf 2021; National Academies of Sciences, Engineering, and Medicine 2021).

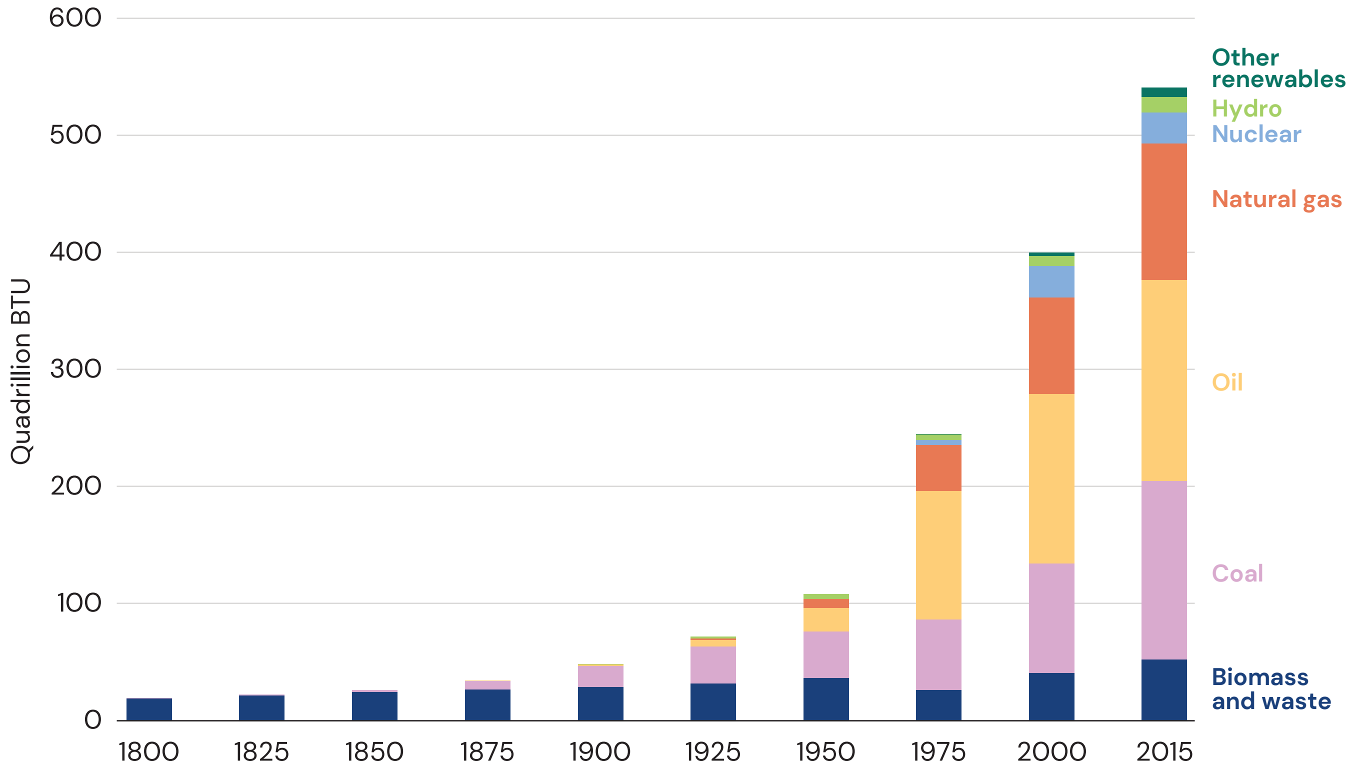
Support for Communities Left Behind

Even as the energy transitions broadly helps many communities by limiting the negative effects of climate change and bolsters local economies that are involved in the expansion of renewable energy, the energy transition described in the previous section leaves some communities vulnerable—particularly those that previously relied on fossil fuels for local economic development. Thus, an additional bucket of complementary policies is support for these communities.

One of the most common concerns about energy transitions is the job prospects in communities that are historically reliant on fossil fuels. More-recent work has examined fiscal implications for local governments (Raimi et al. 2022). Employment losses and other economic damages are a concern for coal mining communities, oil and gas extraction regions, and communities that rely on both power plants and on industrial sites that use fossil fuels. Energy transition policies could put some communities especially at risk (Raimi 2021; Raimi et al. 2022), but it is worth noting that the

FIGURE 4

Global Fuel Use, By Type, 1800–2015



Source: Newell and Raimi (2018), data shared by authors.

aggregate national impacts (e.g., on employment) are likely to be small. Many climate policy studies show that employment effects are very small (Hafstead, Williams, and Chen 2022; Marin, Marino, and Pellegrin 2018; Martin, Muûls, and Wagner 2016). Policy options for targeted support to these legacy energy communities are laid out in Raimi, Barone, et al. (2021).

Also important is environmental remediation of legacy fossil infrastructure. Orphan oil and gas wells, for instance, pose environmental hazards in the forms of air and water pollution; no company is responsible for emissions from these unplugged, abandoned wells. Abandoned mines can similarly pose hazards. Policy options for ensuring safe and environmentally friendly decommissioning of legacy fossil sites are explored in Raimi, Krupnick, et al. (2021).

Questions, Concerns, and Additional Guiding Principles

Should demonstration and deployment initiatives be publicly funded?

The conceptual justification from the economics literature for innovation funding—that is, knowledge spillovers—has historically been focused on upstream R&D. Many researchers recommend focusing the above funding primarily on basic science and technology development, rather than deployment, and argue that knowledge spillovers and capital market failures are strongest at the upstream stage. However, there are justifications for including some demonstration and deployment in federally funded R&D (i.e., expanding R&D to RDD&D).

First, it is plausible that both demonstration and deployment can exhibit knowledge spillovers. For instance, a demonstration project that shows technical and commercial potential of a project may well give information to other companies that reduces their uncertainty about the viability of their own projects. Successful commercialization of innovative technologies may also enable learning by other companies (e.g., how to reduce installation costs for rooftop solar, how to optimize operating procedures at a wind turbine site, etc.). Indeed, the National Academies of Sciences, Engineering, and Medicine (2021) argues that demonstration projects are a crucial and underfunded link between upstream basic science and commercial deployment. More empirical research is needed to understand the magnitudes of these spillovers, but it is plausible that they exist.

A second argument for expanding R&D to RDD&D is that capital market failures (described above) could apply at the demonstration and deployment stages. A third argument relates to network externalities, such as chicken-and-egg issues in complementary technologies such as electric vehicles and their charging stations.

The final argument for supporting demonstration and deployment in clean energy innovation is a second-best argument: if climate policy (e.g., pollution regulations, carbon pricing, etc.) is insufficient at a global level, then including demonstration and deployment in innovation policy is an alternative way to advance climate policy. A component of this reasoning is an *immediacy* argument—in which *rapidly* scaling up the deployment of clean energy technologies is needed for climate mitigation, and there currently is no global carbon price of the sort economists have argued for.

Should funding opportunities focus on small and young businesses?

There is high-quality evidence for prioritizing small and young businesses to receive R&D funding. Howell (2017) and Myers and Lanahan (2022) specifically examine the DOE's SBIR grant program. Both papers find that the SBIR program has been successful, but Howell emphasizes that even more success could have been found if the program were to "reallocat[e] money (i) from larger, later stage grants to more numerous small, early-stage grants; and (ii) from older firms and regular winners to younger firms and first-time applicants" (1138).

Small and young businesses are attractive opportunities for government funding because they face more limitations when obtaining funding from nongovernmental capital markets (Hall and Lerner 2010; Noailly 2022; Pless 2021).[18] As a result, government funding for them is less likely to duplicate or even crowd out private funding. Howell's (2017) explanation for the decrease in crowding out is that private funding is limited when there is information asymmetry between the innovator and the potential funder—the innovator knows why a project is likely to succeed but cannot credibly communicate that reason to a potential funder. Additional research supports this premise, as well as the broader claim that funding small and new firms can lead to major breakthroughs (Noailly 2022; Noailly and Smeets 2021). Notably, the results from both Howell (2017) and Noailly and Smeets (2021) point toward these financing constraints applying to *clean* energy development, which provides another reason (beyond the need to address climate change) for directing R&D funds toward clean energy.

Are DOE, ARPA-E, and the national labs well positioned to expand their support of innovation?

A recent large-scale evaluation of the national labs found that, overall, the labs are effective and successful at inducing innovation, but that one barrier to innovation is bureaucracy and red tape (Glauthier et al. 2015). That report has specific recommendations for minimizing transactional burdens, which I recommend continuing to follow as the budget grows.

As one example of a piece of evidence, the report notes that one of the most successful programs is the Laboratory Directed Research and Development (LDRD) program. This program supports "researcher-initiated work of a creative and strategic nature. These projects might serve as proofs of concept in emerging fields, address significant technical challenges facing laboratory programs, or explore innovative concepts to address DOE missions" (Glauthier et al. 2015, 175–176. LDRD initiatives have led to significant scholarly output and have attracted follow-on outside funds (Bin-Nun et al. 2017; Glauthier et al. 2015).

More broadly, the best practices described by Franzoni, Stephan, and Veugelers (2022) support this kind of flexible funding for researcher-driven initiatives, which they describe as financial support for "loose-play, early stage ideas" (125).

I also recommend continuing flexibility at ARPA-E. As Azoulay et al. (2019) note, ARPA-E's organizational structure frees it from some of the bureaucratic barriers within the DOE. The authors also highlight that ARPA-E has four characteristics: "(1) general organizational flexibility, (2) bottom-up program design, (3) discretion in project selection, and (4) active project management. Importantly, the last three elements highlight the critical responsibility of program managers within ARPA-model agencies" (Azoulay et al. 2019, 76–77).

Why does funding need to be put in place over such a long period?

Several pieces of evidence point to the boom-and-bust nature of energy R&D programs as a key weakness of current US innovation policy (Chan et al. 2017; Cockburn, Stern, and Zausner 2011; Dechezleprêtre, Martin, and Bassi 2019; Dugoua 2022; Newell 2011). Innovations can take years to develop and then translate into commercial-ready projects, and so companies and researchers need to be able to count on future funding. As Chan et al. (2017) write, "Fluctuations in funding erode the cost-effectiveness of programmes by precluding strategic, sustained investments that are high risk but potentially high reward" (27). Similarly, highly skilled workforce training requires a sustained funding commitment. And, relatedly, Cockburn, Stern, and Zausner (2011) argue that boom-and-bust funding can be counterproductive in that it distorts investment decisions for both physical and human capital. This volatility of energy R&D funding contrasts with biomedical funding, where steady funding has contributed to tremendous advances in the life sciences (Cockburn, Stern, and Zausner 2011).

Along with stable funding, the long-term development of a scientific workforce is important to promoting innovation. Numerous authors writing about many different sectors have emphasized the need for developing human capital to drive innovation (Arora and Gambardella 2011; Cockburn, Stern, and Zausner 2011; Dechezleprêtre, Martin, and Bassi 2019; Dugoua 2022). Increasing stable funding for the national labs could provide this long-term commitment to human capital support; unlike short-term grants or prizes, such funding is closer to the best practice of "funding researchers rather than projects and for longer periods of time" (Franzoni, Stephan, and Veugelers 2022, 126).

Clearly, human capital is a key input into the innovation process. R&D funding that allows for the training of new researchers (e.g., at universities or via postdoctoral research positions), that allows for increased specialization of individual researchers, and that encourages collaborative research groups has been key in, for instance, the success of biomedical innovation in the United States (Cockburn, Stern, and Zausner 2011). The national labs have a history of supporting scholars at all stages of their careers via partnerships, internships, and joint appointments, and I recommend that this support continue.

What are the benefits of collaboration and technology transfer?

As emphasized above, the primary rationale for government support of R&D is about *knowledge spillovers*, meaning the effect of innovation multiplies as it spreads across companies in the same sector and even to other sectors. As such, technology transfer programs are critical (Chan et al. 2017), and I recommend accelerating them at the DOE, with enhanced funding for technology transfer activities.

Different researchers have emphasized collaboration across various actors. Moniz (2012) and Hepburn, Pless, and Popp (2018) emphasize collaboration between academia, national labs, and the private sector; Rodrik (2014) also emphasizes coordination between government and the private sector. Newell (2011) emphasizes collaboration across units within the DOE to ensure that the results of upstream, basic sciences projects are communicated to downstream deployment projects. Other authors argue that innovations intended for one sector can aid another sector (Myers and Lanahan 2022; Popp 2019). As one example, jet engine technology, which was funded by government R&D for military applications, led to major improvements in natural gas electricity generation (Yanosek 2012). Notably, the DOE and specifically the national labs already engage in widespread collaboration in both industry and academia (Glauthier et al. 2015), and continuing this engagement would follow best practices. As one key example, external researchers can use national lab facilities, which provide them with critical access to expensive and complex equipment that universities and private companies do not own.

What is the role for international collaboration?

While the previous section focuses on domestic spillovers across agency types and across sectors, Chan et al. (2017) emphasize the importance of international collaboration in driving energy innovation. Indeed, there is already ample evidence of international spillovers in energy development (Dechezleprêtre and Glachant 2014; Gerarden 2021; Myers and Lanahan 2022).

It is worth understanding the role of global spillovers, given the energy security concerns described above. These energy security concerns do not necessarily imply the need for domestic-only supply chains. First, one of the threats to energy security is climate change itself; given the global nature of climate change, international collaboration may especially make sense for clean energy development. Indeed, technology transfer to developing economies has been identified as a key mitigation opportunity. And, as Rodrik (2014) writes, from a climate policy perspective, "what ultimately matters is whether the global supply of green technologies expands (good) or contracts (bad). From a global standpoint, it would be far better if national competitiveness concerns were to lead to a subsidy war than a tariff war" (489).

Second, as described above, researchers have pointed toward the diversification of energy sources and supply chains to enhance energy security. Finally, collaboration with key international allies could also help further the national security goals of both the United States and its allies.

Conclusion

In energy policy, the more things change, the more they stay the same. The United States has seen decades of energy boom-and-bust cycles, with volatile energy prices and the rise and fall of different energy sectors. But there are three constants: (1) Households and companies cite volatile energy prices as a concern. (2) Energy innovations drive economic growth and well-being. (3) And the growth of the energy sector has been the primary contributor to a dangerously changing climate. As energy policy analyst Pizer (2005) noted nearly two decades ago, “There is no magic bullet for our energy problems, no single way to address our security and environmental concerns” (10). There is widespread agreement, however, that government support for clean energy innovation can bring numerous economic and environmental benefits by correcting multiple market failures.

The head of the IEA, Fatih Birol, recently sounded an alarm on supply shortages and rising prices: “The world has never witnessed such a major energy crisis in terms of its depth and its complexity” (Stringer 2022). The time to act—on energy supply and on climate change—is now. The US government recently enacted a suite of reforms to support clean energy deployment; what remains to be done is a concerted effort to kick-start energy innovation. The United States could be a world leader in clean energy if it leverages and strengthens existing energy R&D programs at the DOE, the ARPA-E, and the national labs, and if it increases funding with a mission-oriented approach that takes on risky projects knowing some will fail while, hopefully, some will succeed spectacularly.

Endnotes

1. Indeed, this figure may understate the volatility faced by a typical household: the BEA reports the data as seasonally adjusted, but both prices and quantities vary across seasons for gasoline, electricity, and natural gas.

2. Author's calculations using Bureau of Labor Statistics (BLS; n.d., categories include natural gas, electricity, fuel oil and other fuels, and gasoline and motor oil). For 2020, around 7–8 percent of households reported spending more than 20 percent of their income on energy goods and services; the range comes from treatment of outliers. The percentage was higher (roughly 10 percent) in 2016–19.

3. US Census Bureau (2021-2022), using responses for weeks 35, 40, 45, and 50 (the question was not asked for weeks 1–33).

4. The literature disagrees on whether national security concerns constitute an externality per se, although, even before 2021, there was some agreement that it applied to the case of European imports of Russian natural gas (see, e.g., Borenstein 2012; Cherp et al. 2012). For a discussion of the historical role of energy in war, see Samaras, Nuttall, and Bazilian (2019).

5. EPA (2022, table ES-3) shows that 81 percent of gross emissions (not accounting for land use–related emissions sinks) were from the energy sector. Remaining sectors were industrial processes (e.g., chemical reactions that produce carbon dioxide), agriculture (e.g., nitrous oxide emissions resulting from soil management), and waste (e.g., methane from landfills).

6. Rennert et al. (2022) estimate a social cost of carbon emissions of $185 per metric tonne of carbon dioxide, incorporating climate impacts on agriculture, mortality, energy consumption, and sea-level rise. EPA (2022, table ES-3) estimates nearly 5 billion metric tonnes of carbon dioxide-equivalent emissions from energy sectors for 2020 (and more than 5 billion metric tonnes in pre-COVID years).

7. After dust and wildfires, some of the largest sources of particulate matter are fuel combustion in businesses, power plants, and homes. The largest sources of nitrogen oxides are transportation-related.

8. "Research and development expenditure (% of GDP)—Gross domestic expenditures on research and development (R&D), expressed as a percent of GDP. They include both capital and current expenditures in the four main sectors: Business enterprise, Government, Higher education and Private non-profit. R&D covers basic research, applied research, and experimental development" (World Bank n.d.).

9. The IEA data set used for figure 2 covers research, development, and demonstration (RD&D); the World Bank series described previously in contrast covers R&D. Below, I discuss the extent to which demonstration and deployment might also be covered by federal innovation policy, leading to so-called research, development, demonstration, and deployment (RDD&D) policy.

10. Goldstein and Kearney (2016, 2020) analyze the way peer review is implemented for ARPA-E programs. External reviews are solicited, and ARPA-E program directors have significant discretion in how those reviews are used in the selection process. Program directors tend to use the qualitative comments submitted by external reviewers, in particular searching out projects that are both high risk and, potentially, high reward. Thus arises a tricky aspect of project selection: how to trade off the likelihood of success with the potential impact if the project does succeed. The ARPA-E approach is to ask, "If it works, will it matter?" This approach allows for the possibility that a project may fail by recognizing that the program is looking for potential game changers. Another DOE program that researchers argue has had a successful selection process is the Laboratory Directed Research and Development (LDRD) program. This program allocates a small portion of lab funding to projects internally selected by researchers themselves, which Chan et al. (2017) argue have been particularly successful at translating into new innovations and new patent filings. In related work, Anadon et al. (2016) argue that "its [LDRD's] potential to support high-risk, high-value innovation suggests the need for a broader view of LDRD's place in the missions of the DOE and the labs" (4).

11. Examples of those programs include Cooperative Research and Development Agreements (CRADA), the Strategic Partnership Program (SPP), and Agreements for Commercializing Technology (ACT) (DOE 2021). For further details on tech transfer programs, see Bin-Nun et al. (2017).

12. For further details on individual labs and on their organizational structure and management, see DOE (2021) and Bin-Nun et al. (2017).

13. And indeed, care should be taken to not overemphasize direct employment impacts of R&D programs, since counting up direct employment effects of grants or other R&D spending can be misleading, and it can go against the best practice of supporting initiatives that promote external partnerships (see, e.g., Lanahan, Joshi, and Johnson 2021).

14. Of the National Energy Technology Laboratory's five locations, one is in Sugarland, Texas, part of its Strategic Center for Natural Gas and Oil. This is, however, a very small fraction of the DOE's national lab system.

15. Gruber and Johnson (2019) evaluate nearly 400 metropolitan statistical areas for their size, college share, number of top graduate-level science departments, number of top undergraduate students, count of patents per worker, average house price, crime rate, and commuting times.

16. Specifically, $5 billion has been provided to support projects such as "Replacing Fossil Electricity Generation with Established Cleaner Sources" or "Retrofitting Existing Fossil Assets" (DOE 2022).

17. The Energy Innovation Policy and Technology (2022) notes, "Comparing the models' predictions of the IRA's impact to the detailed bill provisions reveals that the greatest uncertainty is execution" (28). The authors of that report note many ways that implementation details (and therefore IRA impact) will depend heavily on choices made by state-level agencies.

18. Bloom, Van Reenen, and Williams (2019) emphasize that this logic is more likely to apply to young than to small firms, although the empirical literature does not always differentiate between the two.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102 (1): 131–66.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy* 124 (1): 52–104.

Aghion, Philippe, Antoine Dechezleprêtre, David Hémous, Ralf Martin, and John Van Reenen. 2016. "Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry." *Journal of Political Economy* 124 (1): 1–51.

Altenburg, Tilman, and Dani Rodrik. 2017. "Green Industrial Policy: Accelerating Structural Change Towards Wealthy Green Economies." *Green Industrial Policy: Concept, Policies, Country Experiences*, edited by Tilman Altenburg and Claudia Assmann, chap. 1. Geneva, Switzerland: UN Environment.

American Recovery and Reinvestment Act of 2009 (ARRA) Pub.L. 111–5 (2009)

Anadón, Laura Díaz, Erin Baker, and Valentina Bosetti. 2017. "Integrating Uncertainty into Public Energy Research and Development Decisions." *Nature Energy* 2: 17071.

Anadon, Laura Diaz, Gabriel Chan, Amitai Y. Bin-Nun, and Venkatesh Narayanamurti. 2016. "The Pressing Energy Innovation Challenge of the US National Laboratories." *Nature Energy* 1: 16117.

Arora, Ashish, and Alfonso Gambardella. 2011. "Implications for Energy Innovation from the Chemical Industry." In Henderson and Newell, *Accelerating Energy Innovation*, chap. 3.

Azoulay, Pierre, Erica Fuchs, Anna P. Goldstein, and Michael Kearney. 2019. "Funding Breakthrough Research: Promises and Challenges of the 'ARPA Model.'" *Innovation Policy and the Economy* 19: 69–96.

Bin-Nun, Amitai Y., Gabriel Chan, Laura Diaz Anadon, Venkatesh Narayanamurti, and Sarah Jane Maxted. 2017. *The Department of Energy National Laboratories: Organizational Design and Management Strategies to Improve Federal Energy Innovation and Technology Transfer to the Private Sector*. Cambridge, MA: Belfer Center for Science and International Affairs, Harvard Kennedy School.

Bipartisan Infrastructure Law of 2021, aka Infrastructure Investment and Jobs Act (IIJA), Pub.L. 117-58 (2021)

Blanco, Gabriel, Heleen C. de Coninck, Lawrence Agbemabiese, El Hadji Mbaye Diagne, Laura Diaz Anadon, Yun Seng Lim, Walter A. Pengue, et al. 2022. "Innovation, Technology Development and Transfer." In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* edited by Priyadarshi Shukla, Jim Skea, Raphael Slade, Alaa Al Khourdajie, Renée van Diemen, David L. McCollum, Minal Pathak, et al. New York, NY: Cambridge University Press.

Bloom, Nicholas, John Van Reenen, and Heidi Williams. 2019. "A Toolkit of Policies to Promote Innovation." *Journal of Economic Perspectives* 33 (3): 163–84.

Bohi, Douglas R., and Michael A. Toman. 1993. "Energy Security: Externalities and Policies." *Energy Policy* 21 (11): 1093–109.

Borenstein, Severin. 2012. "The Private and Public Economics of Renewable Electricity Generation." *Journal of Economic Perspectives* 26 (1): 67–92.

Borenstein, Severin, and Ryan Kellogg. 2022. "Carbon Pricing, Clean Electricity Standards, and Clean Electricity Subsidies on the Path to Zero Emissions." Working Paper 30263, National Bureau of Economic Research, Cambridge, MA.

Bryan, Kevin A., and Heidi L. Williams. 2021. "Innovation: Market Failures and Public Policies." *Handbook of Industrial Organization* 5: 281–388.

Bureau of Economic Analysis (BEA). 2023. National Data, National Income and Product Accounts. Table 2.3.5 Personal Consumption Expenditures by Major Type of Product and by Major Function." Last revised on February 23, 2023. Bureau of Economic Analysis, US Department of Commerce, Washington, DC.

Bureau of Labor Statistics (BLS). n.d. "Consumer Expenditure Surveys: Public Use Microdata." Last modified on February 23, 2023. Bureau of Labor Statistics, Washington, DC.

Chan, Gabriel, Anna P. Goldstein, Amitai Bin-Nun, Laura Diaz Anadon, and Venkatesh Narayanamurti. 2017. "Six Principles for Energy Innovation." *Nature* 552: 25–27.

Cherp, Aleh, Adeola Adenikinju, Andreas Goldthau, Francisco Hernandez, Larry Hughes, Jaap Jansen, Jessica Jewell, et al. 2012. "Energy and Security." In Johansson et al., *Global Energy Assessment*, 325–84.

CHIPS and Science Act of 2022, aka Research and Development, Competition, and Innovation Act Supreme Court Security Funding Act of 2022 Pub.L. 117-167 (2022)

Chirakijja, Janjala, Seema Jayachandran, and Pinchuan Ong. 2019. "Inexpensive Heating Reduces Winter Mortality." Working Paper 25681, National Bureau of Economic Research, Cambridge, MA.

Cockburn, Iain M., Scott Stern, and Jack Zausner. 2011. "Finding the Endless Frontier: Lessons from the Life Sciences Innovation System for Energy R&D." In Henderson and Newell, *Accelerating Energy Innovation*, 113–58.

Costello, Ken. 2016. *A Primer on R&D in the Energy Utility Sector*. National Regulatory Research Institute Report No. 16-05. Silver Spring, MD: National Regulatory Research Institute.

Covert, Thomas R., and Richard L. Sweeney. 2022. "Winds of Change: Estimating Learning by Doing without Cost or Input Data." Mimeo.

Cunliff, Colin, and Linh Nguyen. 2021. *Energizing Innovation: Raising the Ambition for Federal Energy RD&D in Fiscal Year 2022*. Report. Washington, DC: Information Technology and Innovation Foundation (ITIF).

Dechezleprêtre, Antoine, and Matthieu Glachant. 2014. "Does Foreign Environmental Policy Influence Domestic Innovation? Evidence from the Wind Industry." *Environmental and Resource Economics* 58: 391–413.

Dechezleprêtre, Antoine, Ralf Martin, and Samuela Bassi. 2019. "Climate Change Policy, Innovation and Growth." In *Handbook on Green Growth*, edited by Roger Fouquet, chap. 10. Cheltenham, UK: Edward Elgar Publishing.

Denholm, Paul, Patrick Brown, Wesley Cole, Trieu Mai, and Brian Sergi. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Report NREL/TP-6A40-81644. Golden, CO: National Renewable Energy Laboratory.

Doblinger, Claudia, Kavita Surana, and Laura Diaz Anadon. 2019. "Governments as Partners: The Role of Alliances in U.S. Cleantech Startup Innovation." *Research Policy* 48 (6): 1458–75.

Dugoua, Eugenie. 2022. "Research and Innovation Policies for the Green Transition." In *Science, Research and Innovation Performance of the EU*, chap. 10. Brussels, Belgium: European Commission.

Energy Innovation Policy and Technology. 2022. "Implementing the Inflation Reduction Act: A Roadmap for State Electricity Policy." Energy Innovation Policy and Technology, San Francisco, CA.

Environmental Protection Agency (EPA). 2017. "2017 National Emissions Inventory (NEI) Data." Last updated on December 27, 2022. Environmental Protection Agency, Washington, DC.

Environmental Protection Agency (EPA). 2022. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2020*. Report 430-R-22-003. Washington, DC: Environmental Protection Agency.

Feldman, Maryann, Evan E. Johnson, Remi Bellefleur, Savannah Dowden, and Eshika Talukder. 2022. "Evaluating the Tail of the Distribution: The Economic Contributions of Frequently Awarded Government R&D Recipients." *Research Policy* 51 (7): 104539.

Feldman, Maryann P., and Dieter F. Kogler. 2010. "Stylized Facts in the Geography of Innovation." *Handbooks in Economics* 1: 381–410.

Finkelstein-Shapiro, Alan, and Gilbert E. Metcalf. 2022. "The Macroeconomic Effects of a Carbon Tax to Meet the U.S. Paris Agreement Target: The Role of Firm Creation and Technology Adoption." Working Paper 2022-013, MIT Center for Energy and Environmental Policy Research, Cambridge, MA.

Fischer, Carolyn, Louisa Preonas, and Richard G. Newell. 2017. "Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?" *Journal of the Association of Environmental and Resource Economists* 4 (4): 959–84.

Franzoni, Chari, Paula Stephan, and Reinhilde Veugelers. 2022. "Funding Risky Research." *Entrepreneurship and Innovation Policy and the Economy* 1:103–33.

Funk, Cary, Alec Tyson, Brian Kennedy, and Courtney Johnson. 2020. "Science and Scientists Held in High Esteem Across Global Publics." Pew Research Center, Washington, DC.

Gallup News Service. 2022a. "Gallup Poll Social Series: Environment—Final Topline." March 1–18, 2022. Gallup News Service, Washington, DC.

Gallup News Service. 2022b. "In Depth: Topics A to Z: Environment." Gallup News Service, Washington, DC. https://news.gallup.com/poll/1615/environment.aspx

Gerarden, Todd. 2021. "Demanding Innovation: The Impact of Consumer Subsidies on Solar Panel Production Costs." Working Paper, Harvard University, Cambridge, MA.

Glauthier, T. J., Jared L. Cohon, Norman R. Augustine, Wanda M. Austin, Charles Elachi, Paul A. Fleury, Susan J. Hockfield, Richard A. Meserve, and Cherry A. Murray. 2015. "Securing America's Future. Realizing the Potential of the Department of Energy's National Laboratories." Technical Report. Office of Scientific and Technical Information, US Department of Energy, Washington, DC.

Goldstein, Anna, and Michael Kearney. 2016. "The Impact of Active Program Management on Innovation at ARPA-E." Consulting report to the National Academies for a study on ARPA-E.

Goldstein, Anna P., and Michael Kearney. 2020. "Know When to Fold 'Em: An Empirical Description of Risk Management in Public Research Funding." *Research Policy* 49 (1): 103873.

Goldstein, Anna P., and Venkatesh Narayanamurti. 2018. "Simultaneous Pursuit of Discovery and Invention in the US Department of Energy." *Research Policy* 47: 1505–12.

Gruber, Jonathan, and Simon Johnson. 2019. "102 Places for Jump-Starting America: Appendix to Jump-Starting America, with a Technical Description of the Technology Hub Index System (THIS)." In *Jump-Starting America: How Breakthrough Science Can Revive Economic Growth and the American Dream*. New York City: PublicAffairs.

Hafstead, Marc A. C., Roberton C. Williams III, and Yunguang Chen. 2022. "Environmental Policy, Full-Employment Models, and Employment: A Critical Analysis." *Journal of the Association of Environmental and Resource Economists* 9 (2): 199–234.

Hall, Bronwyn H., and Josh Lerner. 2010. "The Financing of R&D and Innovation." *Handbooks in Economics* 1: 609–39.

Hausman, Catherine, and Ryan Kellogg. 2015. "Welfare and Distributional Implications of Shale Gas." *Brookings Papers on Economic Activity* Spring: 71–125.

Hausmann, Ricardo, César A. Hidalgo, Sebastián Bustos, Michele Coscia, Alexander Simoes, and Muhammed A. Yildirim. 2013. "The Atlas of Economic Complexity: Mappings Paths to Prosperity." Massachusetts Institute of Technology and Center for International Development, Harvard University, Cambridge, MA.

Henderson, Rebecca M., and Richard G. Newell, eds. 2011a. *Accelerating Energy Innovation: Insights from Multiple Sectors*. Chicago, IL: University of Chicago Press

Henderson, Rebecca M., and Richard G. Newell. 2011b. "Introduction and Summary." In Henderson and Newell, *Accelerating Energy Innovation*, 1–24.

Hepburn, Cameron, Jacquelyn Pless, and David Popp. 2018. "Encouraging Innovation that Protects Environmental Systems: Five Policy Proposals." *Review of Environmental Economics and Policy* 12 (1): 154–69.

Howell, Sabrina T. 2017. "Financing Innovation: Evidence from R&D Grants." *American Economic Review* 107 (4): 1136–64.

Inflation Reduction Act of 2022, Pub. L. 117-169 (2022).

International Energy Agency (IEA). 2021. *The Role of Critical Minerals in Clean Energy Transitions*. Report. Paris, France: International Energy Agency.

International Energy Agency (IEA). 2022. *Tracking Clean Energy Innovation: Focus on China*. Report. Paris, France: International Energy Agency.

International Energy Agency (IEA). n.d. "Energy Technology Patents Data Explorer." Last updated September 2, 2022. International Energy Agency, Paris, France.

International Renewable Energy Agency (IREA). n.d. "The Patents Evolution Data Set." Last updated November 1, 2022. International Renewable Energy Agency, Masdar City, United Arab Emirates.

Johansson, Thomas B., Nebojsa Nakicenovic, Anand Patwardhan, and Luis Gomez-Echeverri, eds. 2012. *Global Energy Assessment: Toward a Sustainable Future*. New York, NY: Cambridge University Press.

Jones, Benjamin F., and Lawrence H. Summers. 2022. "A Calculation of the Social Returns to Innovation." In *Innovation and Public Policy*, edited by Austan Goolsbee and Benjamin F. Jones, 13–60. Chicago, IL: University of Chicago Press.

Jones, Charles I., and John C. Williams. 1998. "Measuring the Social Return to R&D." *Quarterly Journal of Economics* 113 (4): 1119–35.

Lanahan, Lauren, Amol M. Joshi, and Evan Johnson. 2021. "Do Public R&D Subsidies Produce Jobs? Evidence from the SBIR/STTR Program." *Research Policy* 50 (7): 104286.

Leber, Rebecca. 2022. "The US Could Stop One Cause of Heat Wave Deaths Tomorrow." *Vox.com*, August 3, 2022.

Löschel, Andreas, Ulf Moslener, and Dirk T.G. Rübbelke. 2010. "Indicators of Energy Security in Industrialised Countries." *Energy Policy* 38 (4): 1665–71.

Marin, Giovanni, Marianna Marino, and Claudia Pellegrin. 2018. "The Impact of the European Emission Trading Scheme on Multiple Measures of Economic Performance." *Environmental and Resource Economics* (71): 551–82.

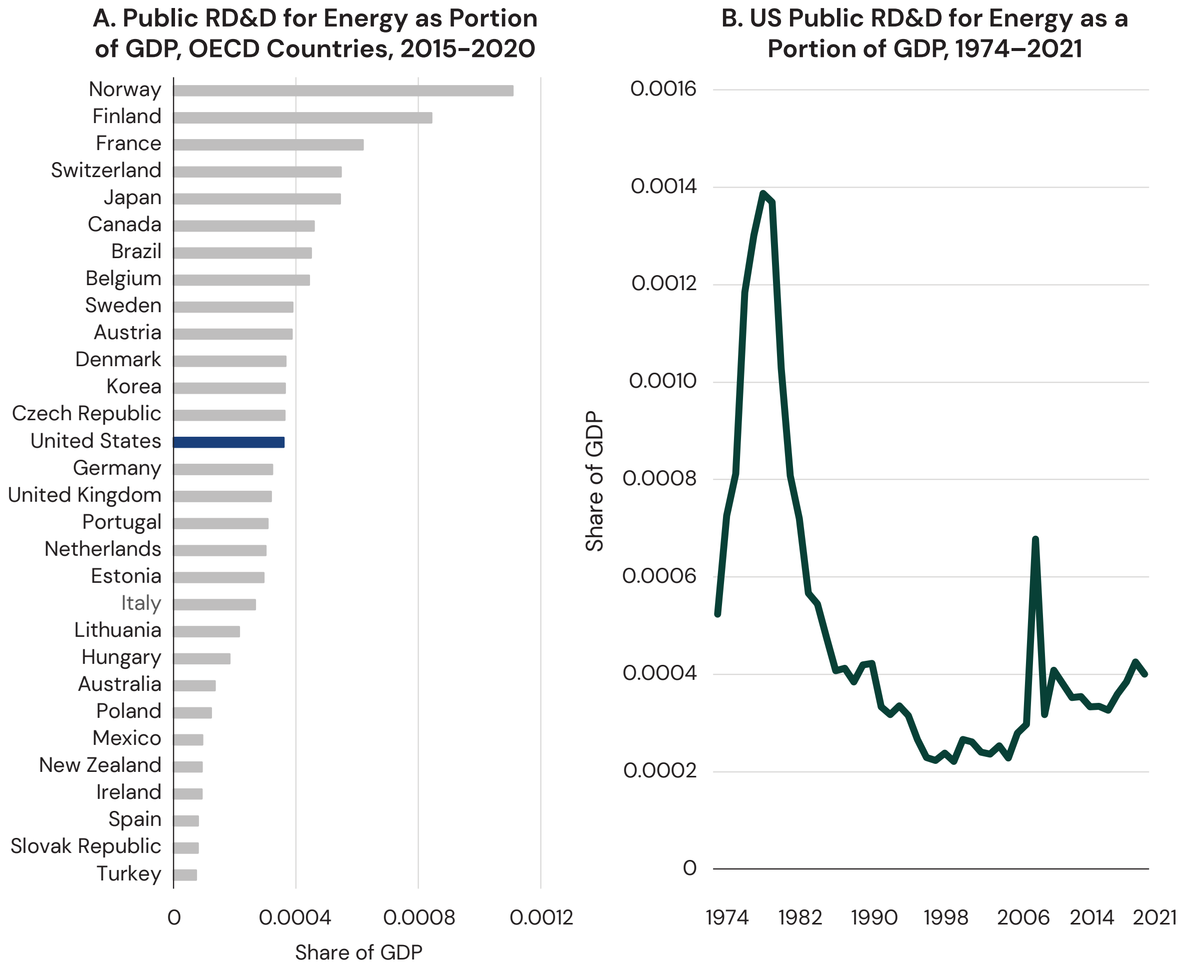
Martin, Ralf, Mirabelle Muûls, and Ulrich J. Wagner. 2016. "The Impact of the European Union Emissions Trading Scheme on Regulated Firms: What Is the Evidence after Ten Years?" *Review of Environmental Economics and Policy* 10 (1): 129–48.
Mazzucato, Mariana, and Gregor Semieniuk. 2017. "Public Financing of Innovation: New Questions." *Oxford Review of Economic Policy* 33 (1): 24–48.
Metcalf, Gilbert E. 2014. "The Economics of Energy Security." *Annual Review of Resource Economics* 6: 155–74.
Metcalf, Gilbert E. 2021. "Carbon Taxes in Theory and Practice." *Annual Review of Resource Economics* 13: 245–65.
Moniz, Ernest J. 2012. "Stimulating Energy Technology Innovation." *Daedalus* 141 (2): 81–93.
Myers, Kyle R., and Lauren Lanahan. 2022. "Estimating Spillovers from Publicly Funded R&D: Evidence from the US Department of Energy." *American Economic Review* 112 (7): 2393–423.
National Academies of Sciences, Engineering, and Medicine. 2020. *Review of the SBIR and STTR Programs at the Department of Energy*. Washington, DC: National Academies Press.
National Academies of Sciences, Engineering, and Medicine. 2021. *Accelerating Decarbonization of the U.S. Energy System*. Washington, DC: National Academies Press.
Nature Index. 2021. "Ten Rising Stars of the Nature Index Annual Tables 2021." Listings. *Nature Index*, May 20, 2021. Accessed August 17, 2022.
Newell, Richard G. 2011. "The Energy Innovation System: A Historical Perspective." In Henderson and Newell, *Accelerating Energy Innovation*.
Newell, Richard G., and Daniel Raimi. 2018. "The New Climate Math: Energy Addition, Subtraction, and Transition." Issue Brief 18-09, Resources for the Future, Washington, DC.
Noailly, Joëlle. 2022. "Directing Innovation towards a Low-Carbon Future." Economic Research Working Paper 72, World Intellectual Property Organization, Geneva, Switzerland.
Noailly, Joëlle, and Victoria Shestalova. 2017. "Knowledge Spillovers from Renewable Energy Technologies: Lessons from Patent Citations." *Environmental Innovation and Societal Transitions* 22: 1–14.
Noailly, Joëlle, and Roger Smeets. 2021. "Financing Energy Innovation: Internal Finance and the Direction of Technical Change." *Environmental and Resource Economics* 83: 145–69.
Pizer, William A. 2005. "Setting Energy Policy in the Modern Era: Tough Challenges Lie Ahead." *Resources Magazine* (Winter).
Pless, Jacquelyn. 2021. "Are 'Complementary Policies' Substitutes? Evidence from R&D Subsidies in the UK." Working Paper 2021-006, MIT Center for Energy and Environmental Policy Research, Cambridge, MA.
Popp, David. 2017. "From Science to Technology: The Value of Knowledge from Different Energy Research Institutions." *Research Policy* 46 (9): 1580–94.
Popp, David. 2019. "Promoting Innovation for Low-Carbon Technologies." Policy Proposal 2019-14, The Hamilton Project, Brookings Institution, Washington, DC.
Popp, David, Jacquelyn Pless, Ivan Haščič, and Nick Johnstone. 2022. "Innovation and Entrepreneurship in the Energy Sector." In *The Role of Innovation and Entrepreneurship in Economic Growth*, edited by Michael J. Andrews, Asron Chatterji, Josh Lerner, and Scott Stern, 175–248. Chicago, IL: University of Chicago Press.
Portney, Paul R., Ian W. H. Parry, Howard K. Gruenspecht, and Winston Harrington. 2003. "The Economics of Fuel Economy Standards." *Journal of Economic Perspectives* 17 (4): 203–17.
Raimi, Daniel. 2021. "Mapping County-Level Exposure and Vulnerability to the US Energy Transition." Working Paper 21-36, Resources for the Future, Washington, DC.
Raimi, Daniel, Aurora Barone, Sanya Carley, David Foster, Emily Grubert, Julia Haggerty, Jake Higdon et al. 2021. "Policy Options to Enable an Equitable Energy Transition." Report 21-09, Resources for the Future, Washington, DC.
Raimi, Daniel, Emily Grubert, Jake Higdon, Gilbert Metcalf, Sophie Pesek, and Devyani Singh. 2022. "The Fiscal Implications of the US Transition Away from Fossil Fuels." Resources Working Paper 22-3, Resources for the Future, Washington, DC.
Raimi, Daniel, Alan J. Krupnick, Jhih-Shyang Shah, and Alexandra Thompson. 2021. "Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers." *Environmental Science and Technology* 55 (15): 10224–230.
Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon et al. 2022. "Comprehensive Evidence Implies a Higher Social Cost of CO2." *Nature* (September).
Riahi, Keywan, Frank Dentener, Dolf Gielen, Arnulf Grubler, Jessica Jewell, Zbigniew Klimont, Volker Krey, et al. 2012. "Energy Pathways for Sustainable Development. In Johansson et al., *Global Energy Assessment*, 1205–305.
Rodrik, Dani. 2014. "Green Industrial Policy." *Oxford Review of Economic Policy* 30 (3): 469–91.
Samaras, Constantine, William J. Nuttall, and Morgan Bazilian. 2019. "Energy and the Military: Convergence of Security, Economic, and Environmental Decision-Making." *Energy Strategy Reviews* 26: 100409.
Schwartz, Lisa C. 2022. "Executive Summary." In *The Role of Innovation in the Electric Utility Sector*, edited by Lisa C. Schwartz. Future Electric Utility Regulation Report No. 13. Grid Modernization Laboratory Consortium. Washington, DC: US Department of Energy.
Schweiger, Helena, Alexander Stepanov, and Paolo Zacchia. 2022. "The Long-Run Effects of R&D Place-Based Policies: Evidence from Russian Science Cities." *American Economic Journal: Economic Policy* 14 (3): 322–51.
Sivaram, Varun, Colin Cunliff, David Hart, Julio Friedmann, and David Sandalow. 2020. *Energizing America: A Roadmap to Launch a National Energy Innovation Mission*. New York, NY: Columbia University SIPA Center on Global Energy Policy.
Stringer, David. 2022. "Worst of Global Energy Crisis May Still Be Ahead, IEA Says." *Bloomberg*, July 11 2022.
Third Way. 2022. "Spending Smart: High-Priority Appropriations for Energy Innovation at DOE." Third Way, Washington, DC.
Tyson, Alec, and Brian Kennedy. 2020. "Two-Thirds of Americans Think Government Should Do More on Climate." Pew Research Center, Washington, DC.
US Census Bureau. n.d.. "Household Pulse Survey." US Census Bureau, Washington, DC, 2022. Accessed January 2023.
US Department of Energy (DOE). 2021. *The State of the DOE National Laboratories: 2020 Edition*. Report. Washington, DC: US Department of Energy.
US Department of Energy (DOE). 2022. "#DeployDeployDeploy: 2. The Energy Infrastructure Reinvestment (EIR) Program." US Department of Energy, Washington, DC.
US Energy Information Administration (EIA). 2023. *Monthly Energy Review* February. OE/EIA-0035(2023/2). US Energy Information Administration, Washington, DC.
World Bank. n.d. "Metadata Glossary; Research and development expenditure (% of GDP), Data series GB.XPD.RSDV.GD.ZS." World Bank, Washington, DC.
Yanosek, Kassia. 2012. "Policies for Financing the Energy Transition." *Daedalus* 141 (2): 94–104.

THE HAMILTON PROJECT

ADVISORY COUNCIL

Energy markets play a key role in the US economy at both a micro and a macro level with technological advances in new ways of producing and consuming energy have historically enabled economic growth. In this proposal, Hausman lays out the rationale for substantially increasing federal spending on clean energy research and development (R&D), along with guiding principles for how the money should be deployed. Hausman proposes the following foundational pillars for energy innovation policy to leverage effective investment: (1) spend triple the federal support on energy R&D; (2) prioritize clean energy, with a secondary focus on energy security; (3) leverage best practices for project selection and evaluation; and (4) draw on the expertise of the US Department of Energy, the Advanced Research Projects Agency-Energy, and the national laboratories. In this proposal. She argues that this approach will jump-start innovation, correct market failures, enhance energy security, and enable a more cost-effective transition to a climate-responsible economy.

Public Research, Development, and Demonstration for Energy



Source: International Energy Agency n.d.