“The Political Economy of American Clean Energy Innovation”

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Abstract

The Political Economy of American Clean Energy Innovation

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Why have American inventors produced so much technological innovation in clean energy technology while American policymakers' record on climate policy has generally been considered underwhelming? Under what circumstances does the US federal government act to foster technological change and what form do such policies typically take? The central topic of this dissertation is American innovation policy, specifically in the context of clean energy technology. I investigate and theorize the circumstances under which federal institutions engage in innovation policy, provide a novel analysis of such policies in the context of clean energy technology, and investigate the political effects such policy has had over recent decades.

Chapter 1 of this dissertation opens by identifying and demonstrating that American inventors remain the most prolific source of technological innovation in clean energy technology. While USPTO patent records suggest that the rest of the world caught up in the 1990s, the percentage of all patents granted to American inventors in key technology areas increased again in the 2000s. I contrast this reality with the prediction of the environmental policy literature's focus on pollution-pricing as providing key incentives for private actors to innovate. The American state has ostensibly not created a public policy environment conducive to technological innovation in alternative energy technology. I provide a detailed discussion of the specific market failures that are assumed to challenge the creation, development, and diffusion of alternative energy technologies. Further, I

discuss different approaches to solving these market failures.

I then argue that the American political economy faces a set of enduring institutional barriers to the implementation of innovation policy. In doing so, I make several theoretical and conceptual contributions. I argue that the institutional barriers to federal innovation policy are typically only overcome in the context of enduring socio-economic challenges or war. When federal innovation policy is implemented, it remains subject to ongoing Congressional pressures, which have often halted or curtailed it. I suggest that this institutional structure creates American innovation policy that typically involves dedicated federal agencies with considerable R&D budgets but limited bureaucratic capacity. This results in policy efforts that are highly decentralized, and in which federal agencies primarily play a coordinating role, while major R&D tasks are outsourced to universities and firms. Further, federal innovation policy heavily focuses on providing R&D and funding for desired technologies rather than directly regulating the use of technologies. I draw on four historical cases of federal innovation policy to demonstrate these points. I also provide an account of the role of federal agencies within the contemporary American innovation ecosystem.

Chapter 2 proposes that concerns over energy security and demand for alternative energy technology by the Department of Defense (DoD) in the early 2000s have been crucial drivers of American innovation policy related to clean energy technology. In doing so, I document the close connection between military-related research and American clean energy innovation. I show that federal policy related to clean energy has focused on investments in basic science and R&D by the Departments of Energy and Defense, which have often been conducted in close cooperation with private companies and universities. Federal agencies have also conducted public demonstration projects, and DoD has been an important source of demand for clean energy technologies. Yet, federal efforts have overwhelmingly focused on the creation and improvement of new technology. There have been comparatively few dedicated efforts to raise the domestic uptake and diffusion of these technologies.

To make this case, Chapter 2 presents two empirical approaches that demonstrate the impact of federal innovation policy in clean energy. Descriptively, I present a network analysis of clean energy patent citations showing that federal agencies are the most important sources of inventions in the US clean energy ecosystem. Here, I also make a methodological contribution, as this is the first network analysis of clean energy patent citations that I am aware of.

Further, leveraging records of public-private research cooperation, I show that companies that collaborate with federal agencies increase their subsequent patenting output significantly, providing evidence for the innovation-boosting effect of recent public-private partnerships in this area.

In Chapter 3, I broaden the scope of my investigation by testing how federal R&D initiatives have affected different geographic areas across the US. I document evidence of a Matthew effect, as a small number of areas have expanded their advantages in generating new technologies over time. The clean energy R&D push by DOE and DoD in the early 2000s has been strongly focused on a small set of major innovation hubs, substantially raising the geographic inequality in clean energy innovation.

Drawing on geo-located patent records in clean energy technology from the USPTO, I show that areas receiving larger amounts of public R&D investments as evidenced by publicly funded patents also show larger numbers of private follow-on innovation. American innovation policy has thus contributed to the uneven contribution to technological innovation of different regions of the country.

In Chapter 4, I use the case of the dedicated energy research agency ARPA-E, implemented in 2009, to gain additional empirical traction on the impact of federal R&D investment. I leverage data on the geography of ARPA-E participant organizations to estimate a Difference-in-Differences model with staggered treatment adoption, demonstrating that areas hosting ARPA-E partners have raised their patenting rates in clean energy technology significantly more than comparable areas. I provide novel evidence from an original dataset demonstrating both the effectiveness of ARPA-E, as investigation of how federal initiatives reinforce the innovation advantages of some regions over others.

In Chapter 5, I investigate the political effects of the geographical concentration of innovative activity in clean energy in the United States. I create a novel dataset of political campaign donations of entrepreneurs and workers in the clean energy industry. This analysis of the political donation behaviour of clean energy industry insiders is the first to my knowledge.

I show that US clean energy entrepreneurs and workers have become increasingly more ideologically aligned with the Democratic party while also being overwhelmingly physically located in innovation clusters. I thus provide new evidence showing that the American clean energy industry has so far been mostly concentrated in high-technology clusters, and that Democrats have politically benefitted from their embrace of climate policy. Yet, the political constituency represented by this industry remains concentrated in a small number of areas, which undermines its political influence.

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Dedication

Für meine Eltern, denen ich alles zu verdanken habe.

Chapter 1: Climate Change and Innovation Policy in the American Political Economy

1.1 Introduction

The development of new technologies is often described to suffer from a variety of market failures. In this framing, profit-oriented private actors undersupply socially desirable technological innovation. Alternatives to fossil fuel energy technologies are a particularly acute and salient case (Nordhaus, 1992; Acemoglu et al., 2012). When the environmental effects of fossil fuel use first became widely appreciated in the 1970s, no commercially viable technological alternatives existed. In part, fossil fuels were artificially cheap because market exchanges did not internalize the present or future costs of emitting carbon. To reduce the costs of alternative energy technologies would require sustained investment in basic science, R&D, and diffusion of new technologies. In the presence of cheap fossil fuels, private actors lack the requisite market incentives to conduct the necessary investments to create, develop, and diffuse such technologies. Arguably, the present situation retains many of the same challenges. While clean energy technologies have become substantially cheaper, they have yet to diffuse widely, especially so in the United States.

Arguably, the United States is structurally unlikely to implement public policy aimed at boosting alternative energy technologies. In the US, incumbent fossil fuel industry groups have gone to great lengths to undermine political support for climate policy in support of clean energy (Farrell, 2016; Hacker et al., 2016). Oreskes and Conway (2010) chronicle how industry incumbents have leveraged public relations campaigns to obscure research findings on environmental externalities. Stokes (2020) describes the strategies and policy networks employed by fossil fuel industry groups to undermine clean energy policy in state legislatures, explicitly seeking to undermine the emergence of economic competitors. Mildenberger (2020) argues that incumbent fossil fuel interests enjoy amplified political power through “double-representation” by combining support from typically left-leaning industrial workers and unions, as well as organized business interests represented by the political right. It is thus typically assumed that the American political economy features a lack of policy support for clean energy industries in addition to active efforts to suppress the growth of competition from fossil fuel industry incumbents (Hacker et al., 2022).

In this Chapter, I explicate the microeconomics of the specific market failures related to technological innovation and how these relate to the creation of alternative energy technologies. I define and discuss innovation policy as the governmental practice of deliberately providing solutions to these challenges. I further connect this discussion to the concrete policies that existing scholarship has propagated to generate alternative energy technologies. Further, I analyse the specific institutional ramifications within the American political economy for the prospects of implementing federal innovation policy. I suggest that the American political economy faces a set of enduring institutional barriers to the implementation of innovation policy. These barriers are typically only overcome in moments of sustained national crisis or war. When federal innovation policy is implemented, it remains subject to ongoing congressional pressures, which have often halted such policies. I suggest that this institutional structure creates American innovation policy that typically involves dedicated federal agencies with sizable R&D budgets but limited bureaucratic capacity and authority, as well as looming threats of future budget cuts. This results in innovation policy efforts that are highly decentralized, and in which federal agencies play a primarily coordinating role and major R&D tasks are outsourced to universities and private firms. Further, federal innovation policy heavily focuses on providing R&D and funding for desired technologies rather than directly regulating the use of technologies, as such regulation is often outside of their legal purview.

Then, I turn to the historical record to provide two cases of successful federal innovation policy and two cases of failure. I additionally provide an account of the influence of the American state in the contemporary US innovation ecosystem.

1.2 Climate Policy and Innovation in Clean Energy

The 2022 Inflation Reduction Act (IRA) implemented a variety of production incentives for electric vehicles and clean energy technologies. Before this, the US had little federal policy intended to explicitly raise domestic renewable energy capacity. In contrast, Japan and Germany implemented policies like feed-in-tariffs as early as the 1990s (Nahm, 2021). In 1998, Germany passed the Renewable Energy Sources Act (EEG), which created the largest market for renewable energy at the time (Nahm, 2021). The Chinese government has actively subsidized the manufacturing of solar panels, electric vehicles, and batteries (Nahm, 2021; Nahm and Allen, 2024).

Aside from lacking federal schemes of similar scale to encourage the uptake or production of renewables, the US also failed to pass federal policy to comprehensively regulate greenhouse gas emissions. In contrast, the European Union implemented a broad emissions trading scheme as early as 2005. The US Senate instead pre-empted joining of the Kyoto Protocol in the late 1990s[1]. In 1997, the Senate unanimously adopted the Byrd-Hagel Resolution[2], which expressed the Senate's opposition to the Kyoto Protocol. President Bush ultimately decided not to join the scheme in 2001. After that, there was no serious attempt to pass comprehensive domestic regulation of carbon emissions until 2009. The 2009 Waxman-Markey bill would have established an emissions trading scheme at the federal level, but the bill was not put to a Senate vote as Republicans threatened to filibuster. As a result of this record, several scholars have labelled the US a climate policy laggard (Rabe, 2004; Victor, 2011; Harrison and MacIntosh, 2010).

At the same time, American inventors are highly innovative in clean energy technologies. While the 2022 IRA substantially increased federal investment in clean energy R&D projects, US actors produced innovations in clean energy for some time before this.

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[1] In the American Political system, international treaties are negotiated and signed by the President, but they require the advice and consent of the Senate to be ratified. Specifically, two-thirds of the Senate must vote in favor of any international treaty. By passing resolutions that signal that there is not enough support in the Senate to meet this threshold, Senators can effectively block treaties from moving forward in the legislative process.

[2] The resolution, passed by a vote of 95-0, stated that the United States should not sign any international agreement on climate change that would mandate new commitments to limit or reduce greenhouse gas emissions.

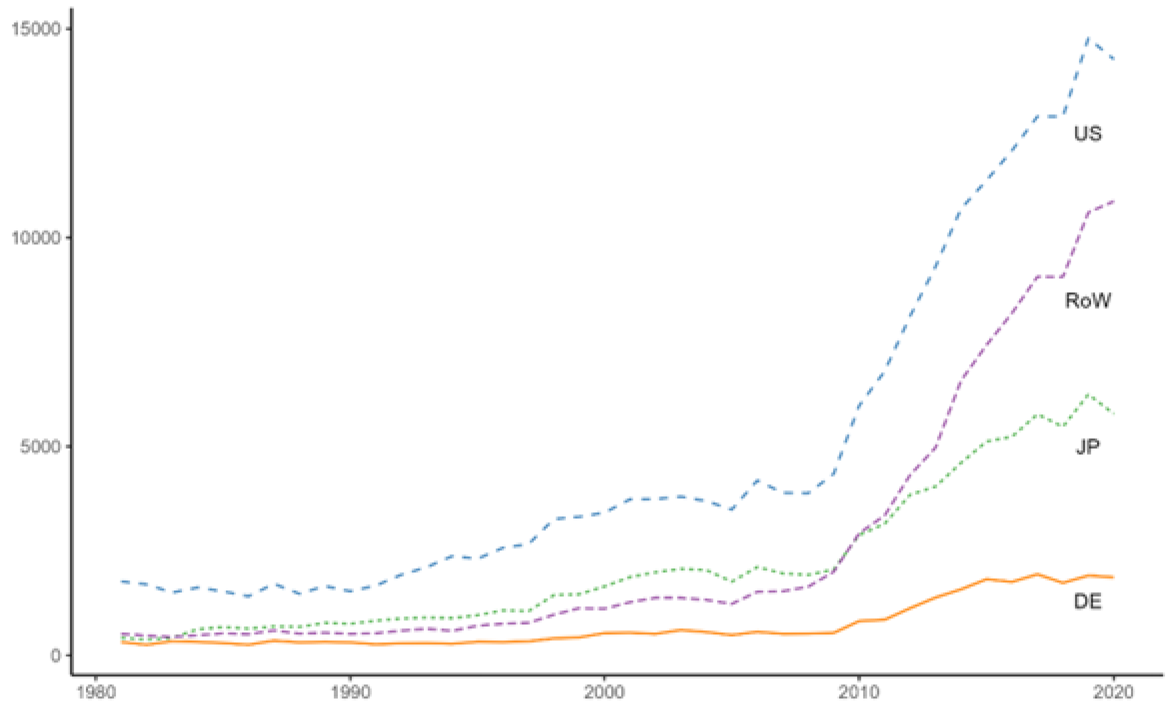

Figure 1: Patents in CPC Class Y02 Granted by USPTO Over Time for the US, Japan, Germany, and the Rest of the World (ROW).
Notes: This graph displays the number of Y02 patents granted and assigned to organizations each year, aggregated by the declared home country of the organization, between 1980 – 2022. The US in blue, Japan in green, Germany in yellow, and the rest of the world in purple.
Data Source: USPTO.

Figure 1 shows that US actors were granted considerably more patents than any other country in technologies related to clean energy and related technologies (CPC Y02[3]) throughout the 1990s and 2000s (also see Nahm 2021, Nemet 2019). Remarkably, the US did not lose this early lead in innovation. While many European countries, Japan, and China implemented a variety of climate policy tools, US actors substantially increased their number of granted patents in the apparent absence of similar policy action at the federal level.

In the United States, patents are legal protections granted by the federal government to inventors for their inventions. The number of granted patents is often used by

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[3] The Cooperative Patent Classification Category Y02 is defined by the USPTO as technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reduction technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

scholars as an indicator of innovative activity (Acemoglu, Moscana, and Robinson 2016; Xu, Watts, and Reed, 2019; Gross and Sampat 2020; Menaldo and Wittstock, 2024). Patenting rates in different locations strongly correlate with other measures of innovation, such as R&D spending, making them a good indicator of innovation activity (Acs, Anselin, and Varga 2002)[4].

While Figure 1 indicates that American inventors are generally more innovative, this might be driven by a secular advantage in technology generation of American firms, rather than an advantage in clean energy specifically. To provide a more nuanced picture, and to demonstrate an important pattern, Figure 2 instead shows the percentage of patents granted by the USTPO to American and foreign inventors in select technology classes. This allows for a comparison of the relative innovative activity of American and foreign inventors. I also provide the average, which shows that there has been a slow decline in the percentage of patents granted to American inventors since the mid-1990s. While overall rates of patenting have increased over the same timeframe, this pattern indicates that the rest of the world is catching up in their science and technology capacities.

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[4] In the US, patent records can identify technologies developed by both individuals, universities, governmental agencies, and firms. Patents are neither perfect nor complete measures of innovation. For one, not all technical inventions are patented, as firms may prefer to hold them as trade secrets instead. Some inventions might enter the public domain as open-source ideas. Also, not all patented inventions are commercialized, and inventions can vary dramatically in their impact. Finally, while patenting rates are a good approximation of the location of inventive activity, they do not necessarily provide a good indication of where commercialized technologies are implemented.

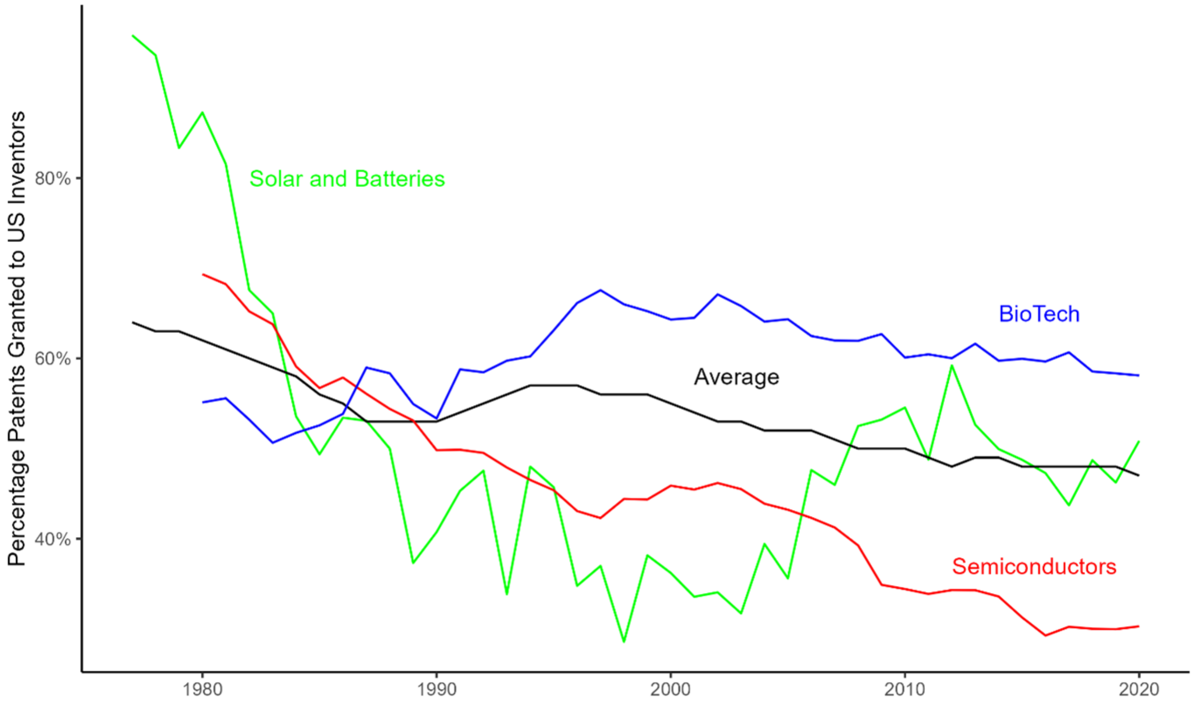

Figure 2: Percentage of Patents Granted to US Inventors in Select Technologies
Notes: Average refers to all patents. Biotech (CPC class C12), Semiconductors (CPC subgroup H01L), Solar and Batteries (CPC sub-classes Y02E10/50, Y02E 10/52, Y02E 10/541, Y02E 60/10, Y02E 10/56, Y02E 60/1, Y02E 60/14, Y02E 10/60, Y02E 10/549, Y02E 10/548, Y02E 10/547, Y02E 10/546, Y02E 10/545, Y02E 10/544, Y02E 10/543, Y02E 10/542).
Data Source: USPTO

Figure 2 also indicates that there exists considerable variation across different technology classes. The blue line shows that American inventors retain an enduring albeit diminishing advantage in biotechnology, as the domestic share of granted patents has remains considerably above the average. Further, the red line shows that patents in semiconductor technology are granted to foreign inventors more often than the average patent, suggesting that while American innovators may still be granted many patents in this technology class, this is no longer an area of technology that American inventors are extraordinarily innovative in compared to the rest of the world. Additionally, Figure 2 graphs the percentage of patents granted to American inventors in solar and battery technology, as an important set of technologies within the clean energy technology class. The green line shows that American inventors dominated this technology class in the late 1970s and early 1980s (see Nemet, 2019; Nahm, 2021). However, while American inventors raised their number patents in the late 1980s and 1990s as shown in Figure 1, Figure 2 shows that the rest of the world caught up considerably, as US inventors were granted a lower share of patents in these technology class than on average during that time. Interestingly, this trend was reversed beginning in the early 2000s.

The consistent lead of American inventors in absolute numbers of clean energy patents displayed in Figure 1 and the increase in relative patenting rates by American inventors in key clean energy technology classes beginning in the 2000s evident from Figure 2 are puzzling in the face of lagging federal climate policy. Scholars have generally argued that environmental policy is necessary to create incentives for companies to invest in clean energy R&D (Acemoglu et al, 2012, Popp 2002; Ambec, 2013). In the absence of regulation that changes relative factor prices, companies will not invest in clean technology R&D if existing “dirty” technologies remain cheaper (Acemoglu et al, 2012, Popp, 2002). Further, environmental regulation forces companies to identify waste in their production processes, which can itself spark innovation (Porter and Linde, 1995; Lim and Prakash, 2014).

Indeed, Figure 3 showcases that cross-nationally there is a clear link between the stringency of climate policy and innovation in clean energy[5]. The figure also shows that among advanced capitalist democracies, the US is a clear outlier in that it features both high levels of clean energy innovation and relatively low levels of climate regulation. Of course, the literature does not suggest that innovation is impossible in the absence of climate policy. Yet, the innovation performance of American inventors raises the question of why a country commonly associated with neglect of environmental policy and the strong political influence of fossil fuel groups has hosted so many of the inventors creating technological alternatives to fossil fuel energy production.

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[5] Climate policy stringency refers to the stringency of environmental policy, specifically with respect to the degree to which public policy is employed to put an explicit or implicit price on environmentally harmful behavior (OECD, 2024).

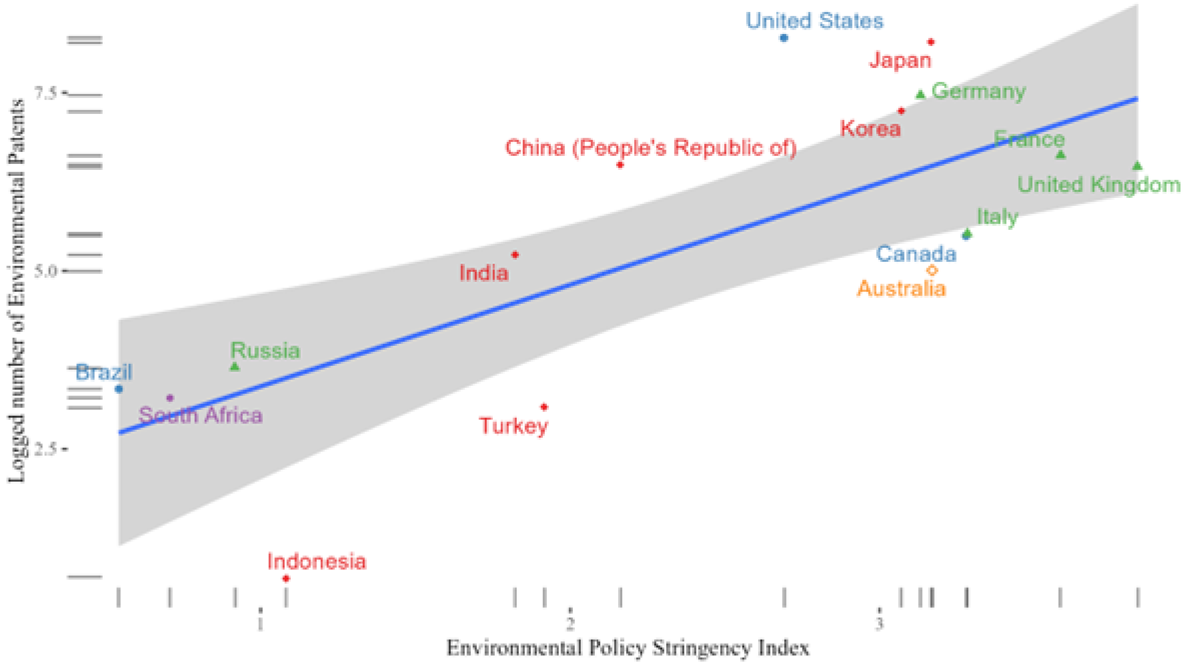

Figure 3: Environmental Policy Stringency Index and Logged Number of Environmental Patents in 2015 for Select OECD Countries.
Notes: The Environmental Policy Stringency Index includes various measures related to climate policy, including fuel economy and emission standards, intended the extent to which public policy penalizes environmental pollution. The patent measure is the annual number of patents filed under the International Patent Cooperation Treaty. I display this metric on a logged scale.
Data Source: OECD Statistics

Scholars have generally located the main engines of American climate policy action in state governments (see Bergquist and Warshaw, 2023 for a discussion). Due to hesitancy, reversal, and gridlock at the federal level, many state governments have stepped in to pass regulations on carbon emissions (e.g. California's Cap-and-Trade program in 2013) and various provisions intended to increase domestic renewable energy capacity (e.g. Renewable Portfolio Standards, Net-metering laws) (Bergquist and Warshaw, 2023).

Thus, one explanation for high aggregate US clean energy innovation is that individual state governments have created regulatory environments that incentivize local firms to invest in energy-related R&D (Popp, 2019; also see Rabe, 1999). While there is convincing evidence that this is indeed part of the story (see Popp, 2019), this explanation ignores that companies often have access to global markets. Hence, local regulations are not the only reason why firms decide to invest in R&D and commercialize technologies that may be profitably sold elsewhere. Indeed, Herman and Xiang (2022) show that innovators respond to changes in global demand for clean energy technologies – rather than just local demand. Changes in environmental policy in one place can induce innovation in other jurisdictions because the relevant technology products can often be traded. Anecdotally, SunPower and First Solar – two highly innovative US solar energy companies - have had longstanding contracts with energy producers in Europe and Latin America, selling cutting-edge solar energy generation systems to utilities and private energy producers located in regulatory environments that create markets for renewables in line with the predictions of existing environmental policy scholarship[6].

Further, the domestic market for renewable energy has been extended substantially in more recent years, as indicated by Figure 4. After stagnating throughout the 1990s, the total production of renewable energy in the United States more than tripled between 2000 and 2015.

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[6] There is ample precedent for innovative American companies selling licenses to their technologies or products into markets with larger consumer demand. Microsoft licensed its basic interpreter for microcomputers to Japanese firms. Intel has licensed its semiconductor manufacturing technology to several foreign companies. This includes licensing deals with companies in Taiwan and South Korea, which helped these countries develop their semiconductor industries. In clean energy technology, California-based start-up Innovalight licensed its technology for a new material in solar PV production to Chinese panel manufacturer JA Solar (Nahm, 2021).

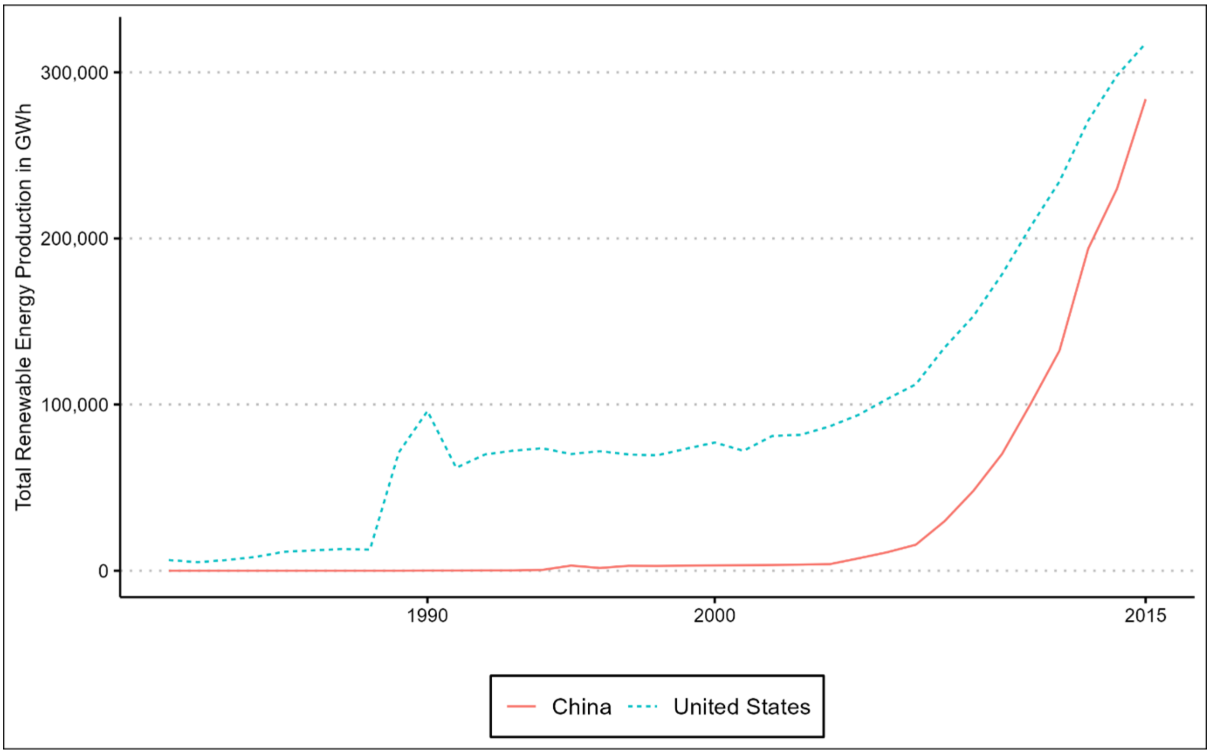

Figure 4: Renewable Energy Production in the US and China in Gwh, 1960 – 2015.
Notes: The measurement provided here excludes hydroelectric energy.
Data Source: World Bank

American state-level climate policy has unquestionably created incentives for firms to invest in clean energy R&D. That said, as a general explanation for US innovation performance in this technology class, state-level climate policy ignores the fact that globally focused companies need not exclusively sell technologies to domestic producers of energy. Further, as I will explore below, this explanation for US clean energy innovation ignores the considerable role that federal institutions play in influencing the direction and rate of innovation in the American political economy. The assessment that state-level climate policies have to some extent substituted for federal policy is accurate on balance. As an explanation of US innovation as such though, this explanation overlooks the crucial role of federal science and technology policy in driving innovation.

While scholars have sometimes attributed the inventive activity in clean energy to long-held American strengths in science (see Nahm, 2021) and R&D investments of the late 1970s (Nemet, 2019), the political economy of more recent federal innovation policies related to clean energy has been underexplored. In the following section, I take a step back to discuss the microeconomics of technological innovation, and the logic behind climate policy and its connection to innovation in alternative energy.

1.3 Market Failures in Technological Innovation

Scholars of Environmental Politics and Economics commonly argue that economic production produces environmental “externalities” which impose costs on third parties that are not part to the initial transaction (Popp, Newell, and Jaffe, 2010). Environmental policies aim to address this issue by creating incentives for firms to reduce externalities. These policies typically work in one of two ways: either by internalizing environmental costs financially, pushing polluters to manage their environmental impacts independently, or by setting limits on pollution levels (Popp, Newell, and Jaffe, 2010).

A related and complementary approach to environmental externalities is the creation of technologies that allow for avoiding pollution altogether or to clean up pollution more effectively after the fact. In the context of the use of fossil fuels, environmental policy scholars have often identified technological change as a key tool to enable effective abatement of pollution from fossil fuels and the creation of alternative energy technologies that avoid pollution (Popp, Newell, and Jaffe, 2010).

Environmental policy scholars have widely appreciated that there exist a set of challenges in the creation, development, and diffusion of clean energy[7] technologies necessary to address through policy.

Solving Social Problems Through Technological Change

Innovation encompasses the invention, development, and diffusion of new tools, techniques, goods, services, or production processes (Bryan and Williams, 2021). Tech-

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[7] Below, I will use the term ”clean energy” to refer to those technologies that are alternatives to fossil fuels and produce power without emitting greenhouse gases into the atmosphere. These energy sources are considered environmentally friendly and sustainable, helping to reduce the impact of energy production on climate change and air quality. Clean Energy technologies commonly include solar energy, wind, geothermal, hydropower, biomass, and tidal energy, as well as attendant technologies like batteries or smart grids.

nological change is the main driver of long-term economic growth (Solow, 1957; Schumpeter, 1934), and advances in science can yield profoundly beneficial returns for society (see Bush, 1945; Edler and Fagerberg, 2017). Neoclassical Economists have argued that private provision of innovation suffers from market failures primarily related to the public goods nature of knowledge (Nelson, 1959; Arrow, 1962).

The market failure view of innovation policy has been widely criticized and, in many instances, does not fit the empirical evidence or misses important dimensions of innovation policy[8] (Edler and Fagerberg, 2017; Nelson, 2017). One source of such criticism has been a school of thought broadly described as "Innovation Systems"[9], which is itself closely related to Evolutionary Economics (see Schumpeter, 1934; Nelson and Winter, 1982). Neoclassical Economics assumes the existence of a natural equilibrium state of an economy, which changes according to well-understood processes (Schumpeter, 1934 calls this a "circular flow economy"). In contrast, Evolutionary Economics conceptualizes the economic environment as much more chaotic and subject to constant and drastic change that is unpredictable for individual agents (Nelson, 2017). Enabling, guiding, and managing this constant evolution of the economy is a critical dimension of innovation policy. Nelson (2008) sees the evolution of legal, social, and political institutions related to the technological innovation process as an integral part of the dynamic process of economic change. The successful creation and diffusion of new technologies requires institutional adaptation and thus includes dynamic adjustment of public policy on top of changes in the organization of business (also see Perez, 2010).

The Innovation Systems approach identifies several challenges associated with the creation and diffusion of new technologies which are not necessarily incompatible with the "market failures" pointed out by Neoclassical Economics (Freeman, 1987; Nelson, 1985).

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[8] For example, debates over innovation policy can encompass questions over the distribution of benefits of new technologies, security of new developments, the need to create new legal frameworks for new technologies, the weighting of civil and political rights in the adoption of new technologies, as well as idiosyncratic debates related to specific technologies, like the ethics of patenting alterations of human, animal, or plant DNA for example. Analyzing these issues from a market failure perspective can be either unproductive or miss the more important dimensions of the issue.

[9] Edler and Fagerberg (2017) suggest that this school of thought should best be considered a synthesis of empirical insights from a larger number of academic disciplines on the phenomenon of technological innovation.

The Innovation Systems approach generally sees innovation taking place within different institutional frameworks that influence the provision of basic science, incentivize R&D, support creating skilled workforces, aid in the commercialization of prototypes, provide education and demonstration to society, provide early demand for new technologies, and coordinate actions between different actors relevant to the innovation process. This school of thought notes that the analytical frame of "market failures" is strained in that innovation in practice never takes place within a "pure" market in the Neoclassical sense but is rather always influenced by a range of non-market institutions, like universities, patent systems, and different forms of regulation (Nelson, 2017).

I suggest that it is most instructive to consider that the process of solving social problems through technological innovation faces a variety of practical challenges that societies attempt to meet in different ways. These challenges include investment in basic science and R&D necessary to create and improve new technologies, issues in finding and connecting relevant knowledge and information, coordinating actions across various involved actors, providing for education and a skilled workforce, credit constraints, short-term demand constraints, and various technical and social barriers to technology diffusion. These challenges need not be considered "market failures" in the Neoclassical sense, although I will use this language below. Market actors may provide solutions to some of the challenges mentioned below[10]. I do not seek to provide an endorsement of government action over private choice. Rather, my goal is to explicate the basic challenges to technological innovation that may present themselves generally, and in the context of clean energy in particular.

Underinvestment in Basic Science and R&D

According to Neoclassical Economics, basic science that is without any clear goal is undersupplied by private actors (Arrow, 1962). The main output of investments in basic science is assumed to be ideas and knowledge, which are goods that are difficult

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[10] Google for example, in its massive R&D efforts has published contributions to basic science in fields from neuroscience to theoretical physics. The company even made much of its work related to large-language machine learning models publicly available.

or impossible to exclude others from using and are non-rivalrous in consumption (public goods) (Arrow, 1962).

Hence, while the social benefits of basic research might be large, private actors cannot appropriate them sufficiently to willingly invest in its provision (Bryan and Williams, 2021). In the context of the creation of technological alternatives to fossil fuels, private actors will eschew investing in the basic research necessary to build alternative energy technologies, in important part because private investors cannot appropriate the spillover benefits from their basic research (Schneider and Goulder, 1997).

Beyond basic science, Research and Development (R&D) refers to the process of building on existing knowledge to produce commercially viable applications to some social problem or consumer need. Private actors are assumed to invest less in R&D than socially optimal because they cannot capture all benefits of their investments here either (Bryan and Williams, 2021). While property rights to ideas through tools like patents or trademarks might allow private actors to appropriate some of the returns to their R&D investments, knowledge spillovers are almost always present, providing positive externalities to those who do not foot the bill for R&D costs (Arrow, 1962).

The underinvestment in basic science and R&D in the context of alternative energy R&D is an especially pertinent issue because fossil fuels are relatively cheaply available. Hence, private actors may act myopically, preferring the cost-savings of presently cheap fossil fuels over uncertain future payoffs of investments in alternative energy technologies (Popp, Newell, and Jaffe, 2010).

Several scholars have criticized the Neoclassical “market failure” approach to innovation policy that heavily focuses on issues of appropriating returns as conceptually flawed and empirically unsupported (Edler and Fagerberg, 2017; Mazzucato and Semieniuk, 2017). Firms are often willing to exchange knowledge with customers and even competitors, and the innovation process often necessitates cooperation (‘Open Innovation’). Firms seem often unconcerned about the appropriation of returns (Cohen 2010). Often, there exist barriers to effective competition due to high levels of specialization, capital barriers to commercial exploitation of knowledge, and complementarities where innovations only gain value in combination with other factors of production or skills that may be unique to a small set of actors (Cohen, 2010).

Further, market "failures" do not suggest that government "intervention" necessarily improves outcomes (Bach and Matt, 2005; Karna, Karlsson, and Engberg, 2020). Governmental agencies have their own informational shortcomings. They may also have political incentives that lead them to allocate resources inefficiently as firms in declining industries might lobby for support (Karna, Karlsson, and Engberg, 2020).

That said, the innovation process faces the core challenge that basic science and considerable investments in R&D must be provided by someone. There are unquestionably instances in which profit-seeking actors are systematically disincentivized to provide such investments. To wit, given the widespread availability of cheap fossil fuels, firms have no direct commercial incentive to invest in costly R&D in alternative energy (Acemoglu et al., 2012).

In addition to concerns over spillover benefits of R&D, it is also the case that the returns to R&D are inherently uncertain. To illustrate, Figure 5 below presents a schematic of how three imagined technology products might move from a conceptual stage toward commercial viability in response to R&D investment.

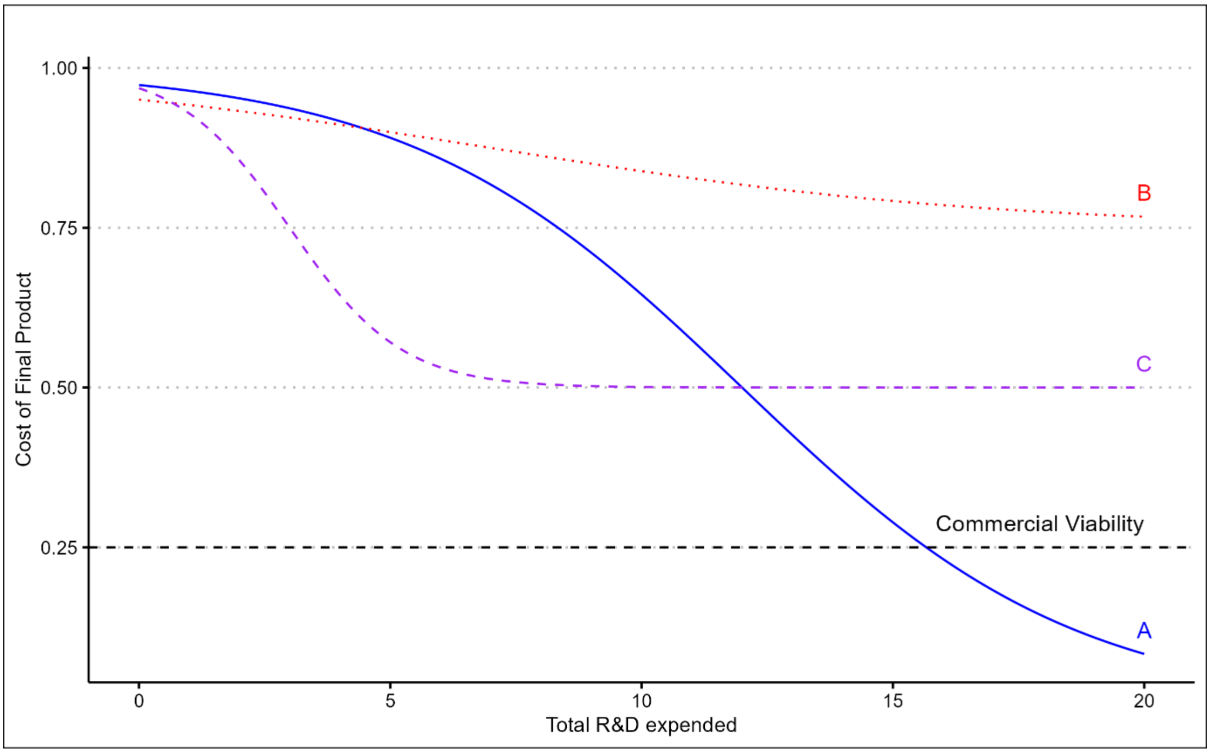

Figure 5: Cost Curves of Products Based on Different Returns to R&D.
Source: Author's Illustration.

All three technologies begin as equally expensive, but at least theoretically feasible. It is unclear which technology can be improved sufficiently to bring it to commercial viability. Technologies A, B, and C all react positively to R&D investments, in that they become cheaper as firms understand the technology better and make incremental improvements. However, only technology A can be improved sufficiently to become commercially viable over the graphed timeframe. It is not possible to ascertain what kind of improvement path any given technology will follow ex-ante. As a result, companies might be deterred from investing in any significant R&D in speculative and unproven technologies. As I will elaborate below, technologies that initially appear promising might experience unforeseen challenges later in their development (analogous the the path taken by technology C in Figure 5).

Issues of Finance and Cash-Flow

Due to uncertainty about the utility and capacities of new technologies, their development and diffusion often suffer from credit shortages (Stiglitz and Weiss, 1981). Investors and firms lack adequate information about the potential success and profitability of new technologies, leading them to undersupply credit to firms who want to undertake R&D. Also, firms that want to bring new technologies to market often struggle to attract funding because investors cannot easily distinguish between high-quality and low-quality projects, as they lack experience with the new technology (Stiglitz and Weiss, 1981).

In addition, in the context of cheap fossil fuels, new technologies might struggle to find enough early customers to create cash flow for ongoing R&D investments. As a result, innovative firms, especially startups, may face difficulties accessing sufficient funding due to the high risk and long-time horizons associated with R&D. While venture capital can provide funding for early-stage technologies, it may not be sufficient to cover the extensive R&D costs needed to bring a new technology to market (Hall and Lerner, 2010).

Further, actors that invest in early R&D might have to bear higher costs than those who invest later in the development process. Figure 1 graphs the development of the cost curve as a non-linear process, as the incremental costs of further R&D investments might decline over time. It is intuitive to assume that R&D in the early stages of a technology might be especially expensive in the sense that they are the least certain to yield usable results and have the least amount of information to go on. As more R&D is spent on a given technology, further knowledge is created which can reduce the cost of follow-on innovation spending. Because of such dynamics, private actors might especially avoid investing in the early stages of R&D which are the most expensive. This implies that insufficient investment exists to move these technologies down the cost curve in the first place (Hall and Lerner, 2010). Thus, if investments are more likely to be made in technologies closer to commercial viability, investors will systematically avoid investing in bringing longshots down the cost curve.

Relatedly, firms may not have the right time horizons in their investment decisions to invest in certain technologies. In the context of clean energy technologies, some technical solution might be decades away from commercial viability. Investors and company executives will likely have shorter time horizons in their investment decisions.

Especially related to energy technology, firms as well as consumers might also be myopic and prefer the cost-savings from presently cheap fossil fuels over the speculative long-term benefits from alternative energy technologies. Hence, given the artificially low price of fossil fuels that do not factor in the environmental price of carbon emissions, R&D money might be spent inefficiently (Acemoglu, et al., 2012, Popp, Newell, and Jaffe, 2010). Moreover, market incumbents might be averse to investing in the commercializing of alternative technologies before the costs of past investments in existing product lines have been amortized. Hence, fossil fuel companies continue to invest in related R&D because large amounts of their capital is tied up in related investments (Christophers, 2021).

Finally, companies often require co-specific investments in related technologies by other companies. Some new technologies require complementary innovations or infrastructure to be viable. An example in the context of solar energy are batteries or charging stations in the context of electric vehicles. Private actors might struggle to coordinate their own R&D efforts with others in a way that allows them to commercialize a new technology successfully.

Issues of Diffusion and Education

Even once new tools have been sufficiently developed to be cost-competitive with existing technologies or provide an affordable solution to a social or consumer problem, they may still face issues of diffusion or consumer adoption. People might hesitate to adopt new technologies, either due to ignorance, inability to pay for them, or insufficient education in using them effectively. In fact, Schumpeter (1934) suggested that diffusion of new technologies was one of the most profound challenges in the innovation process.

Consumers and investors may lack sufficient information about the benefits and performance of clean energy technologies, which might slow adoption rates. Private finance may lack sufficient information to adequately price new solar energy generation projects and thus be too risk averse.

Related to these issues of adoption are potential problems of standards and interoperability (Hawkins, Mansell, Skea, 1995). The lack of common standards in new technologies can prevent or delay the widespread adoption of new technologies, as firms and consumers may be reluctant to invest in technologies that could become obsolete or incompatible with other systems. Lack of standards in parts of a solar system might deter consumers from adopting them as they worry that exchange parts will be expensive, or that later versions will not be interoperable.

Clean energy technologies may have higher initial costs and may not benefit from economies of scale until there is significant market penetration, which will make early adoption more expensive. Fossil fuels, on the other hand, already benefit from established infrastructure and economies of scale. Some technologies may not find enough early adopters to generate the cashflow necessary to build the infrastructure necessary to gain economies of scale.

1.4 Approaches to Solving Innovation Challenges in Clean Energy

Government policy related to managing market failures in innovation is variedly referred to as "science and technology policy" or "innovation policy" as I will refer to it here (Edler and Fagerberg, 2017).

Through innovation policy related to alternative energy, governments can provide for basic science and either conduct R&D themselves or provide subsidies (Popp, Newell, and Jaffe, 2010). Governments can also provide subsidies and tax incentives for alternative energy technology projects directly and thereby lower their effective costs. Further, mandating renewable energy use or setting emissions standards can change relative prices sufficiently to induce private investment (Popp 2002; Acemoglu, 2012, Popp, Newell, and Jaffe, 2010).

Governments can guarantee demand for the technologies created by firms by pledging future purchases through procurement policy. Governments can also directly encourage the uptake of technologies in industry or by consumers, spurring the creation of market demand. Government investments in infrastructure, such as charging stations for electric vehicles, can reduce barriers to adoption. Providing information about the benefits of clean energy can help overcome information asymmetries or reduce myopic behavior by consumers. This may include education campaigns, labelling schemes, and transparency requirements. Further, governments may also finance the education of workers who are needed to work with new technologies, which may reduce operating costs of companies. Government investment in specific technologies and demonstration projects might reduce uncertainty sufficiently for private actors to coordinate around new standards and invest in complementary technologies.

The academic literature on climate policy commonly distinguishes between market push, market-pull, and technology-push policy. I will explain these approaches in turn.

Market-Push or Carbon pricing

Since one key reason for private underinvestment in alternative energy technology is the cheap availability of existing fossil fuel energy carriers, many environmental policy approaches propose regulations that raise the price of pollution, thus forcing private actors to “internalize” the costs of the externalities their actions create (Popp, Newell, and Jaffe, 2010). Policy approaches like carbon taxes, technology bans, cap-and-trade systems, and variations on these tools seek to raise the effective cost of using fossil fuels, thereby incentivizing firms to instead use energy alternatives, implement abatement techniques, or otherwise create ways of minimizing fossil fuel pollution (Popp, Newell, and Jaffe, 2010).

Policy tools of this approach seek to push the supply curve of polluting technologies inward (Market-Push), by raising their price, to reduce the total amount of pollution. Some programs of carbon pricing use the proceeds to either invest in clean energy R&D or to subsidize the adoption of existing alternative energy technologies. Several analyses find that these kinds of interventions indeed raise private investment in R&D (see Lim and Prakash, 2014; Lanjouw and Mody, 1996; Popp, 2006, Jaffe and Palmer, 1997).

Market-pull: Subsidizing Desirable Technologies

Policy tools that fall under this category approach the issue from a different vantage point. Instead of making polluting technologies more expensive, market-pull policies seek to make desirable alternatives cheaper instead (Popp, Newell, and Jaffe, 2010). Policies like feed-in tariffs, renewable portfolio standards, or subsidies seek to pull the supply curve for desirable products out. In doing so, market-pull policies aim to conversely reduce the demand for "dirty technologies" (Acemoglu et al., 2012).

By subsidizing the production of a particular energy alternative, market pull technologies create a market for alternative technologies. Hence, these policy approaches create certainty over future demand for private actors. Further, as market-pull policies induce the creation of growing capacity in alternative technologies, they help to reduce the associated costs as companies experience learning-by-doing. Market pull policies can also be seen as a governmental attempt at diffusing desirable technologies.

Technology-push policies

Climate policy scholars refer to "technology push" policies as those that are "R&D-focused" (West, 2014). This broad policy bundle aims at pushing the supply curve of alternative technologies out by directly investing in the creation and improvement of cheap alternatives, which also reduces demand for fossil fuels. These policy approaches are also sometimes referred to as falling under the rubric of "R&D induced technical change" (Popp, Newell, and Jaffe, 2010).

Technology push policies are typically thought to include the provision of basic science and R&D with the goal of either directly creating technology alternatives or at least contributing to their development. These policies also include R&D subsidies and tax breaks for private actors who invest in the "right" R&D (Acemoglu et al., 2012).

However, technology-push policies typically do not include provisions that penalize the use of existing technologies (market-push) or directly subsidize the use of new tools (market-pull). In practice, environmental policy often combines elements of all three of the distinct categories outlined here. That said, technology-push policies are distinct in that they target the creation of knowledge and technology directly, often through government directed research programs or public funding for private R&D.

Defining Innovation Policy

While "Technology-Push" policies are closest to my definition of innovation policy, I will use this term to describe it. Innovation policy encompasses all policies that government wield deliberately to create, develop, and diffuse technologies.[11] Further, the literature on environmental policy has strongly focused on policies that are intended to reduce demand for fossil fuels through taxation (market push), or incentivize clean energy deployment (market pull). Innovation policy might include combinations of the different approaches discussed above to actively organize the creation, development, and diffusion of alternative energy technologies.

Further, scholarship on solving market failures related to the creation and diffusion of new technologies is often related to wider considerations of industrial policy. Some scholars of environmental and energy policy have noted that recent policy approaches implemented in the European Union, United States, and China have veered into industrial policy (Allan and Nahm, 2024).

I want to distinguish conceptually between 'innovation policy' and 'industrial policy'. Innovation policy seeks to encourage and support the creation, development, and

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[11] Discussions of technology-push policies by Climate Policy scholars have paid relatively little attention to public demonstration projects and facilities that teach people about new technologies, the creation of common technology standards, and the provision of investment in the education of consumers, as well as a complementary workforce. Such efforts are all potentially part of innovation policy in the way that I define it here.

diffusion of new tools and techniques to increase general economic productivity or to find technological solutions to specific public policy problems. Innovation policy encompasses governmental investment in basic and advanced education and vocational training, the undertaking of institutions like patent systems, governmentally organized scientific installations, tax policy related to R&D undertaken by firms, but also efforts to coordinate R&D on specific technologies or problems through research consortia, public-private partnerships, competitions, or prizes, the setting of common standards, as well as efforts to diffuse new knowledge and tools and encourage their use in a variety of ways.

Industrial policy, however, seeks to harness specific industries by cultivating competitive domestic firms through deliberate governmental support (Juhász, Lane, and Rodrik, 2023). This might take the form of tariffs or other import restrictions, favored access to finance, subsidies, currency devaluation to encourage exports, or comprehensive governmental programs that leverage multiple policy tools to facilitate the creation and growth of firms in desired industries.

In practice, innovation and industrial policies can blur, and specific governmental initiatives might have dimensions of both. Industrial policy will often have elements of innovation policy, as governments might heavily invest in education and vocational training to provide a specialized workforce to be employed in a desired industry (Juhász, Lane, and Rodrik, 2023). Further,governments might invest in basic science and R&D to generate technologies that raise the productivity of domestic firms. Governments might coordinate technology transfer schemes from government laboratories or universities to industry for the same reason. They might also organize the travel of foreign inventors, industrialists, or skilled workers to organize knowledge and skill transfers (Menaldo and Wittstock, 2021; Menaldo, 2020). Finally, in their endeavour to build competitive industries at home, governments have often engaged in various forms of industrial espionage (Menaldo and Wittstock, 2021).

That said, innovation policy as such need not be part of industrial policy. Governments might observe that the profit motive does not direct private investment toward solving specific social problems through technological means. This is easiest to consider in the case of rare diseases. In this case, private investment will be undersupplied if expected profits from creating a cure are the only assumed drivers of private investment in necessary basic science and R&D. Hence, governments might act (out of enlightened concern, or reacting to public pressure or that of an interest group), not to create a competitive domestic industry necessarily, but simply to solve a social problem through technological means. Innovation policy is thus conceptually separate from industrial policy, in that it is primarily concerned with enabling and managing the creation, development, and diffusion of technical solutions to social problems, not with ensuring the creation of a competitive domestic industry.

Incentives for Government

Governments are not necessarily incentivized to provide effective innovation policy. There is no reason to believe that time horizons of politicians are longer than those of business executives, and the benefits of innovation policy might be diffuse or in the far future (Edler and Fagerberg, 2017). Investments in basic science are unlikely to yield clear payoffs to politicians soon but constitute a present investment of tax money that might be unpopular. In some cases, political returns to innovation policy might be more immediate, as when a constituency lobbies for governmental provisions to solve some issue through investments in innovation (Karna, Karlsson, and Engberg, 2020). An example is the social movement ACT UP that demanded accelerated R&D of drugs to treat AIDS in the late 1980s and 1990s (Schulman, 2021). Yet, it is not obvious ex ante that governments are willing or capable to provide such R&D. Further demands for government provision of R&D subsidies or other innovation support might also come from declining industries, which could result in socially costly rent-seeking (Karna, Karlsson, and Engberg, 2020).

In the US, scholars have generally identified rent-seeking efforts by the incumbent fossil fuel industry as the main reason for lacking federal efforts at implementing policies like carbon taxes, emissions trading schemes, or other deliberate efforts at birthing a clean energy industry (see Farrell, 2016; Hacker et al., 2016). Mildenberger (2020) contends that fossil fuel interests wield significant political influence through “double representation.” This dual support comes from left-leaning industrial workers and unions, combined with backing from business interests typically aligned with the political right. Stokes (2020) outlines the strategies and policy networks employed by fossil fuel industry groups to undermine clean energy policies in state legislatures, aiming explicitly to stifle potential competition.

While these arguments have considerable merit, I add to these arguments by focusing on a related but separate issue. I argue that providing effective innovation policy either constitutes an exercise of federal regulatory authority or includes measures that expand the scope and power of the federal government and invariably raise needs for federal tax revenue.

Pro-climate innovation policy might create a new federal agency to assume responsibility for basic science and R&D. Further, federal programs might finance private R&D or even subsidize the uptake of developed technologies. Federal programs might coordinate the demonstration and diffusion of new technologies, or even act as consumers of new technologies themselves. In the American political economy, there exist substantial institutional barriers to the expansion of federal power and hence in some way barriers to solving market failures related to innovation in the ways just described. These barriers have historically only been overcome in very specific contexts. Even then, these institutional barriers have considerably shaped the character of American innovation policy.

1.5 The Prospects of American Innovation Policy

Given that the US has been an integrated national market for many goods since 1850 at the latest, effective regulation to solve market failures must in many cases be national. This is not to suggest that there are not some areas where state governments can effectively implement innovation policy at the state level. Yet, an effective innovation policy aimed at creating, developing, and diffusing new energy technologies would ideally be federal. Federal policy would eliminate the issue of free-riding or counterproductive behavior by some states, federal regulation would also reduce administrative costs and create uniform standards, and benefit from economies of scale.

Various factors might spur federal action to solve market failures, and I will draw on specific cases to illustrate these below. The federal government might intervene to solve market failures due to lobbying by an interested party, its enlightened concern for public welfare, or it might be urged to solve market failures by creating technologies it deems necessary for defending and administrating the Union. However, I suggest that historically it is less instructive to debate the general incentives the federal government might have than to analyze the institutional constraints imposed on federal action. I focus on the extraordinary circumstances under which these constraints have been overcome historically to implement comprehensive federal innovation policy in the pursuit of solving various markets failures. Historically, institutional constraints on federal power have either prevented, delayed or shaped the form of federal action to solve market failures.

The Impediments to Active Federal Innovation Policy

Following Migdal (1988) and Friedman (2000), I will use the term "American state" to refer to the executive branch of the federal US government, including the President and subordinate federal agencies.[12] Federal innovation policy is an exercise of central authority, which would necessitate the creation of new agencies, powers, and raise needs for federal taxation.

In some recent scholarly work on *industrial* policy in the United States, several authors have described the obstacles to federal action as predominantly ideological (many of which also connect to innovation policy) (see Wade 2017, Mazzucato 2012, Block, 2008, also see Lichtenstein and Stein, 2023). While many scholars have identified institutions and policy practices that can be described as industrial policy in the US, these practices

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[12] Nettl (1968) includes the legislative branch in the definition of the American state. I suggest that it is more instructive to consider the legislative branch an institutionalized instrument to "shackle" the federal Leviathan created by the US Constitution (see Acemoglu and Johnson, 2020; also see Friedman, 2000). While Congress is a part of the federal government, the American state is the executive body, and Congress is the institution that makes use of, funds, and directs the state.

must be "hidden" from public recognition, due to the intense American aversion to statism and wholesale embrace of "market solutions" by both major political parties since the Reagan and Clinton Presidencies (Lichtenstein and Stein, 2023; Wade, 2017; Negoita, 2015). Some scholars have pointed to the policy influence of business interest groups (Oreskes and Conway, 2023), while others have focused more specifically on the impact of academic economists[13] (Mirowski and Plehwe, 2015; Lichtenstein and Stein, 2023).

The recognition of the American intellectual bias against government in economic matters has given rise to a long scholarly tradition seeking to debunk the proposition that American capitalism developed free from state direction (Baptist, 2016; Lind 2012; Friedman, 2000; Mazzucato, 2012; Vallas, Kleinmann, and Biscotti, 2011).

More fundamentally, Friedman (2000) argues that "anti-statism" is deeply rooted in American political culture, typically identified as the "Jeffersonian" political tradition, which stresses limited federal government and emphasizes states' rights and individual liberties. Bailyn (1967) argues that fear of centralized power was an essential part of American political culture at its founding and permeated every decision in the creation of the American Constitution. This element of the American political tradition remains a durable character of political debate and in effect functions as a cultural constraint on the exercise of political authority at the federal level. Friedman (2000) points out that even Federalists like Alexander Hamilton who advocated a stronger central government chose to frame their argument in favor of such policies as enabling greater security from governmental violence toward individual rights, thus paying significant homage to the traditional American skepticism towards centralized political power captured by Jeffersonianism.

Nonetheless, it is uncontroversial that states and the federal government in the early years of the Republic were engaged in a variety of projects that can be broadly described as industrial policy (Lind, 2012; Friedman, 2000; Wallis, 2006). State governments took financial stakes in canal and road works, chartered companies, repeatedly

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[13] Commenting on the influence of academic economists on debates regarding the developmental role of government, Michael Lind writes, "*It would be easy to get a thousand PhD economists [trained in the Anglo-American tradition] to sign a manifesto insisting that we should ignore history whenever it conflicts with theory … about generic firms competing in abstract markets*" (Lind, 2012: 348).

sold lands for specific uses, or otherwise financially supported the development of specific industries. The 19th century featured ongoing debates and political struggles over federal investment in such “internal improvements”, the threats of attendant corruption, and the constitutional balance between state and federal government on regulation of the national economy (Wallis, 2006; Friedman, 2000).

By the end of the 19th century, the class of American businesspeople had largely embraced laissez-faire economic doctrines, albeit often with opportunistic exceptions (also see Oreskes and Conway, 2023). Hartz (1955) described this as a “spiritual conversion”, as the American business class that had benefitted substantially from governmental actions subsequently presented the United States as having always and exclusively relied on private enterprise (also see Friedberg, 2000 and Lind, 2012). The economy was now increasingly conceived as something separate from politics. A powerful private lobby emerged purportedly opposed to governmental “intervention” of any kind into the matters of private enterprise (Oreskes and Conway, 2023), exemplified by the rise of the National Association of Manufacturers (NAM, founded in 1895), the Chamber of Commerce (founded in 1912), and the Business Roundtable (founded in 1972) as strong lobbying influences on state and federal levels. These business interests have done much to cultivate the connection between the Jeffersonian streak in American political culture with laissez-faire economics, including the active popularization of economists like Friedrich Hayek and others, as well as radio and television programs, worker education seminars, and active attempts to influence social science curricula.[14] Later, the connection between Christian values and free-market capitalism, which has successfully aligned Evangelicals with the economic right-wing and contributed to the increasing obscurity of Christian Socialism in American politics (Moreton, 2010; Oreskes and Conway, 2023). As a result of the association of American anti-statism with laissez-faire economics, opponents of initiatives to expand federal authority often attack such efforts with politically potent slogans that resonate widely (see Wade, 2017; Negoita, 2015; Friedman, 2000).

The fact that in American political debate, any exercise of governmental power is

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[14] See Oreskes and Conway (2023) for an extensive treatment of this fascinating intellectual and cultural history.

almost inherently suspect is undoubtedly crucial to appreciate the extraordinary barriers placed in the way of the exercise of federal innovation policy. That said, below I will focus on institutional representations of this culture and make little reference to American political culture directly.

Effective innovation policy would often entail economic regulation that would necessarily have to encompass the entire market in question, which is constitutionally impeded by the strong decentralization of the US polity. Innovation policy, or the solving of national market failures, typically requires some form of state building. There is a need to either regulate nationally or to create federal agencies that will coordinate innovation policy, which requires the empowerment or expansion of the federal government at least to some degree. The American Constitution intentionally constrains such initiatives. The American state thus faces comparatively high institutional obstacles to solving market failures.

Institutional Barriers to Federal Political Action

The American Constitution establishes a "*system of dual sovereignty between the States and the Federal Government*" (Gregory v. Ashcroft, 501 US 452, 457, 1991). The Constitution grants the federal government enumerated powers over a defined number of policy areas, while the political authority of the states is indefinite in covering all areas not explicitly granted to the federal government ("reserved powers") (US Constitution Article 1, §8). In practice, the American form of federalism creates an exceptionally decentralized polity in which the power over key areas of taxation, economic regulation, and education policy are devolved to the states (Lacey and Soskice, 2015; Hacker et al., 2022).[15]

Further, the US Constitution places essential capacities for state-building in the hands of the Legislature, not the executive branch (Friedman, 2000). It is Congress that levies tax, borrows and coins money, and regulates foreign commerce. While the President

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[15] That said, the Supreme Court has interpreted the Constitution's Commerce Clause to grant the Federal Government authority to regulate economic activities if they substantially affect interstate commerce (Sabel, 2010).

is the commander in chief, Congress has the power to "raise and support armies" and has the right to declare war (US Constitution, Article 1, section 8).

Hacker et al. (2022) thus describes the American political economy as an exceptionally fragmented institutional landscape, in which public authority is both vertically and horizontally divided to an extraordinary extent compared to other capitalist democracies (also see Stepan and Linz, 2011). Substantial governing authority is devolved to states, cities, and localities, while federal power is separated to an extreme extent (Hacker et al., 2022). Federal legislation depends on political support from two houses of Congress, as well as the President in most cases, which creates three separate electorally generated veto points over federal political action (Friedman, 2000; Stepan and Linz, 2011; Hacker et al., 2022). Within the Senate, the filibuster has developed into an additional check on federal action.[16]

In addition, courts can veto federal legislation and influence how policies and laws are implemented (Hacker et al., 2022; Friedman, 2000). Huntington (2006) describes the US as possessing a "Tudor-style" political system, in which the legislative and judicial functions of courts have remained connected (also see Hacker et al. 2022). Finally, this institutional configuration is comparatively difficult to reform given the high barriers to constitutional change.

The institutional barriers to federal action thus reinforce the American cultural bias against the exercise of central political authority. Historically, this has often prevented the creation of federal schemes to solve market failures of various kinds, also those unrelated to innovation policy. Given the highly fragmented nature of American political institutions, it is difficult for voters to hold politicians accountable, and more organized actors are in much more influential positions (Oreskes and Conway, 2023; Hacker et al., 2022). In many cases, this has amplified the power of market incumbents, who can move across political venues more easily and can durably invest in legal and other campaigns (see

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[16] While this piece of Senate procedure has been criticized widely in recent debates regarding partisan gridlock, it is important to note that there have been multiple periods in American history during which Senate filibusters prevented federal action. In 1917, President Wilson requested that merchant ships should be armed, which was approved by the House but then successfully blocked by a small number of Senators (Friedman, 2000).

Stokes, 2020; Oreskes and Conway, 2023, Hacker et al., 2022).

Further, Congress also disciplines the actions of federal agencies through its power over the federal budget. While the Constitution does not explicitly grant Congress this power, the Supreme Court has generally held that Congress can use its Article 1 lawmaking powers to create, staff, and fund federal agencies (Garvey and Stiff, 2023). Congress also controls federal agencies through its legislative rights, while the exercise of its powers to regulate, fund, or terminate federal agencies requires acts of legislation (Garvey and Stiff, 2023). Historically, Congress has disbanded federal agencies multiple times due to a variety of reasons, thus exercising a disciplining role on the exercise of federal power.

While the institutional features described above exist as real constraints on federal political authority, it remains the case that the American state has been the most powerful geopolitical force since the late 19th century (Novak, 2008). Hence, despite the considerable institutional barriers to the growth of federal power, there have been considerable expansions. Scholars have typically pointed to crises, especially war, as providing the extraordinary impetus for federal action that expands the American state.

Historical Expansions of the American state – The Role of War and Crises

While the American state was minuscule at the beginning of the 19th century, it has grown substantially since (Higgs, 2012; Porter, 2002; Friedman, 2000). The expansion of the American state has been broadly in line with the political logic most memorably described by Charles Tilly, with his idiom that "War made the state, and the state made war." The "Military Revolution" in Europe in the 16th and 17th centuries was driven by the intense Tillyan dynamic of the Eurasian state-building model in which states competed for control over territory, building extensive administrative apparatuses in the process (Roberts, 2018; Parker, 1988; Black 1991). Roberts (2018) argues that a series of changes in military strategy and technology beginning in the 16th century induced durable changes in governmental structures in Europe. These changes enabled new tactics, which then necessitated large standing armies, raising the necessity to tax, administer, and police populations through effective bureaucracies with capable central states (also see Parker, 1996 and Black 1991).

A key issue that amplified the Tillyan impetus for state-building was the physical proximity in Europe of several strong states. Key American statesmen were acutely aware that the US was in a unique geographic position that was the complete inverse of Europe (Porter, 2002). George Washington referred to America's "detached and distant situation" (Gilbert, 1965: 145), and Alexander Hamilton argued in Federalist 24 that due to the weak position of European powers in the Western hemisphere, "Extensive military establishments cannot, in this position, be necessary to our security." (Hamilton, 1961: 151). Hence, the Jeffersonian ideal of a weak central state was based on American geographic isolation, which allowed it to remain removed from the Tillyan political dynamic for a long time (Mearsheimer, 2001; Porter, 2002). Figure 1 below demonstrates the difference between the American state and those in Europe during the 19th century by displaying the percentage of the population that is employed as military personnel.

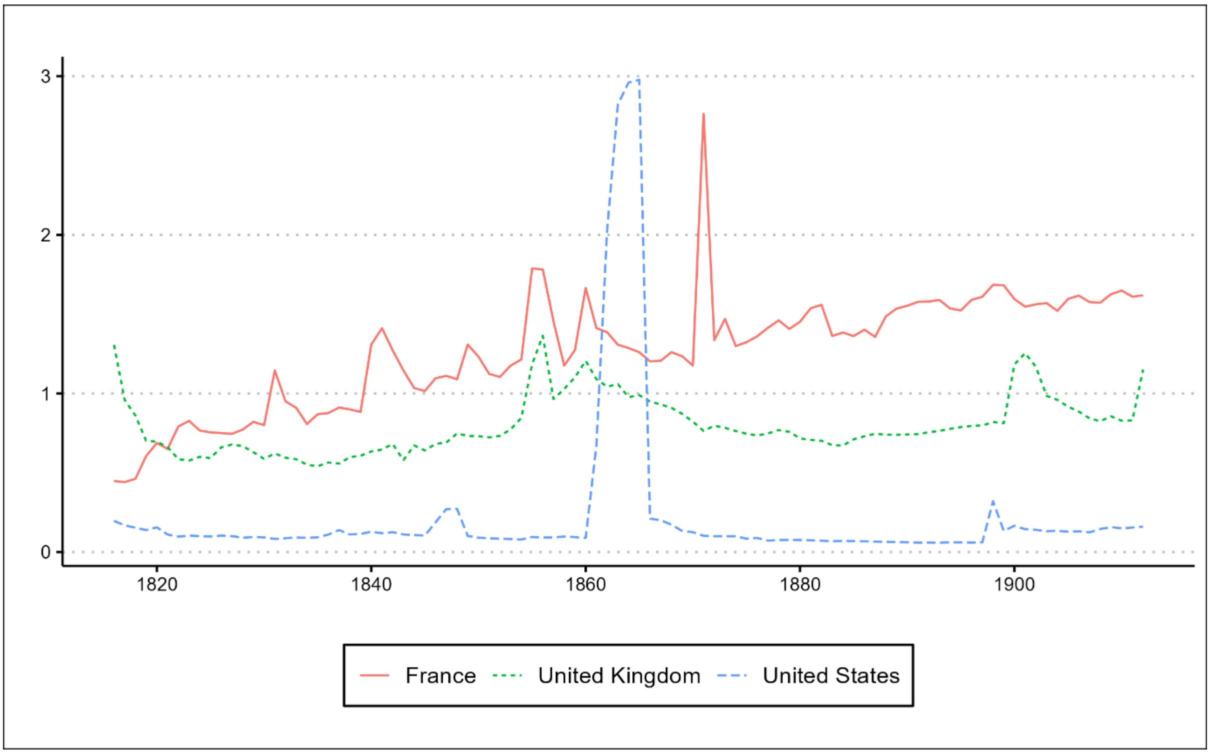

Figure 6: Military Personell as Percent of the Population.
Data Source: World Bank.

Figure 6 shows that both France and Britain left the Napoleonic Wars with durably high conscription numbers, which were dramatically above those in the United States. During the Revolutionary Wars, France pioneered the mass mobilization of citizen armies (*Levée en Masse*), which ultimately induced other European powers to build larger standing armies themselves. While the US was able to mobilize enormous shares of its population during the Civil War, this notably did not result in a large standing army (or a comprehensive federal bureaucracy for that matter) after the end of hostilities, in stark contrast to European countries (Porter, 2002). The Union did create a capable administrative state. While many of the attendant institutions were deconstructed after the Civil War ended, this period was nonetheless an important juncture in American state-building (Porter, 2002).

Higgs (2012) and Friedman (2000), as well as Brownlee (2004) and Porter (2002) all focus on the role of national crises in explaining the historical trajectory of American federal state building. Wars and other prolonged national crises have provided the impetus for federal legislative action to expand the American state. Table 1 showcases some of the more important federal agencies and programs that were created in response to major crises or wars throughout US history.

One important institutional innovation of the Civil War was the National Academies of Sciences (NAS), the first institutionalized scientific advisory body to the federal government. The proposal to create the NAS was introduced in the Senate and hurried through the House of Representatives during the Civil War in 1863. Relatedly, in 1917, President Wilson crated the National Research Council as an additional scientific advisory body during WW1. Both institutions survived the wars that forged them.

Period	**Institutions Created**
Early Republic (1776-1789)	Departments of War, State, Navy, and Treasury, Department of Justice (1789-)
Civil War (1861 - 1865)	USDA (1862 -), Internal Revenue Service, National Academy of Sciences (1862 -), National Banking System
Progressive Era (1890 - 1914)	Food and Drug Administration (1906 -), Federal Reserve System (1913-), Federal Trade Commission (1914-), Federal Farm Loan Board (1916), Department of Commerce and Labor (1903 -1913), US Bureau of Mines (1910 - 1996)
World War 1 (1916 - 1919)	War Industries Board (1917 - 1919), Committee on Public Information (1917 – 1919), Fuel Administration (1917 - 1919), War Labor Board (1917 - 1919), United States Shipping Board (1917, later US Maritime Commission in 1936), Aircraft Production Board (1917 - 1919), National Research Council (1916 -)
New Deal (1933 - 1939)	Federal Security Agency (1939), Farmer's Loan Program (1937), Social Security Administration (1935 -)
World War 2 (1941 - 1945)	Office of Scientific Research and Development (now NSF) (1941), Office of Strategic Services (now CIA) (1942), Civil Air Patrol (1941), War Production Board (1941, disbanded), National War Labor Board (1942, disbanded), Defense Plant Corporation (1940 - 1945), Manhattan Project (1942 -1946)
Early Cold War (1945 - 1960)	Atomic Energy Commission (1946 - 1976), Central Intelligence Agency (1947 -), Department of Defense (combining Army and Navy) (1947 -), Air Force (1947 -), National Institutes of Health (1948 -), National Science Foundation (1950 -), National Security Agency (1952 -)
Great Society (1964 - 1968)	Department of Housing and Urban Development (1965 -), Department of Transportation (1967 -)
Late Cold War (1977 - 1989)	Department of Energy (1977 -), Department of Education (1980 -)
War on Terror (2001 -)	Department of Homeland Security (2002 -), Transportation Security Administration (2001 -), Customs and Border Protection (2003 -)

Table 1: Major Extensions of the US Federal Government
Sources: Friedman (2000), Higgs (2012), Brownlee (2004), Author's additions.

War and American Innovation

One line of explanation of how the American state has overcome institutional barriers to federal innovation policy is war[17]. Indeed, the federal agencies engaged in national defense have played an important role in the history of American innovation. Even before the massive mobilization of WW2 and the complex technological system that was the Manhattan Project, the US Army and Navy were critical actors within the American innovation system.

World War 1 and its associated mobilization of manufacturing resources induced the creation of industrial research labs in France, Germany, and Britain, but also in the United States (Hughes, 2004). At the end of WW1, Hudson Maxim, brother of famed inventor Hiram Stevens Maxim and member of the US wartime Naval Consulting Board surmised that "*this is an age of specialists, and it is necessary for any inventor, scientist, or engineer to devote a large amount of time and attention to the special requirements of naval and military matters before he can qualify himself to be of much use...*" (cited in Hughes, 2004: 125). Maxim summarized the increasing professionalization of inventive and innovative activity, as WW1 dramatically demonstrated the value of science to American industrialists, but simultaneously ushered in a change in the industrial organization of inventive activity, both within government and in industry (Rabbitt, 1989, Hughes, 2004).

During the prior age of "Independents", as professional and amateur inventors like Thomas Edison, Reginald Fessenden, Elmer Sperry, and the Wright brothers had been labelled, federal agencies had already developed into critical funding sources and early customers for some of the most important inventions of the time (Hughes, 2004). In 1905, the Wright brothers proposed to the US War Department to build airplanes for the military, which after several rejections finally accepted the Wright's proposal in 1908 (Hughes, 2004). The Wright's concluded that there was simply no other institution that

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[17] Two recent studies of WW2 and Cold War US innovation policy find substantial and long-lasting effects of federal R&D on regional productivity and rates of innovation (Gross and Sampat, 2023; Kantor and Whalley, 2023). Vernon Ruttan (2006) dedicated an entire book to the question whether war was necessary for economic growth and answered largely in the affirmative. Mazzucato (2012), Weiss (2014), and O'Mara (2019) have focused on the role of the Cold War on recent American technological innovation.

was interested or financially capable of buying their new technology that was still far away from being commercially viable in civilian use[18] (Hughes, 2004).

It was the US Navy that was the main source of demand for Elmer Sperry's gyrostabilizers[19]. The British-German naval armaments race did not pass the US Navy by completely, which was in its own naval competition with Japan[20]. Sperry's gyrostabilizers promised to provide the US with a strategic edge, as stabilized ships would be able to fire with greater accuracy (Hughes, 2004). Incidentally, the US Navy was also a key funding source and customer for the work of Reginald Fessenden and Lee de Forest on wireless communication[21](Hughes, 2004).

During WW1, the federal government created the Naval Consulting Board and the National Research Council to connect the federal war-fighting forces with the "Independents", to work on some of the specific technical issues of war (Hughes, 2004). This initial foray created the prototype for the more institutionalized employment of scientists in federal scientific installations for the specific purpose of war-related research. The creation of industrial research labs that provided long-term employment to scientists was also taken up by private industry.

It is thus easy to conclude that the American state is especially capable of providing effective innovation policy in the context of technologies necessary for war, or dual-use technologies (Weiss, 2014). Concerns over national security are strong animators of federal policy, because they can overcome some of the institutional barriers against the exercise of federal authority. The federal government has significant economic regulatory

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[18] The Wrights explored building airplanes for the British military as well (Hughes, 2004).

[19] Gyrostabilizers are devices that reduce the rolling motion of ships and aircraft. They consist of a rapidly spinning flywheel that generates a stabilizing force against the movement of a vessel as a result of waves for example. Gyrostabilizers substantially increased the size and capacity of cargo ships as well as military vessels. Some aircraft also use gyrostabilizers to reduce unwanted motion during flight (Hughes, 2004).

[20] On the contrary, under President McKinley, the United States went so far as to annex Hawaii in 1898, in important part due to concerns that the Hawaiian monarchy might foster closer ties with Imperial Japan (Kinzer, 2006). Due to Hawaii's strategic location in the Pacific Ocean, control of the islands was crucial for American naval supremacy in the Pacific, a fact that came to a head during the Japanese attack on Pearl Harbor in 1941.

[21] Fessenden and De Forest made significant contributions to the development of wireless communication, such as the AM radio. Both men's work with the US Navy was focused on maritime communications, which allowed for permanent contact between ships and control stations (Hughes, 2004). The related technologies have since been applied and improved in telecommunications, early electronics, and computing.

powers related to defense and war, including the power to raise and support armies, provide and maintain a navy, and regulate the military. This gives the federal government the capacity to act in a way that can bypass the constitutional constraints imposed by American federalism.

Yet, these powers importantly lie with Congress. Still, war and issues of national security generally allow for bipartisan compromises, and often align Congress with the executive branch. Historically, war mobilization has created large federal agencies under operational control of the executive branch, with considerable R&D budgets that also provide demand for new technologies, but also do much to coordinate the innovation activities of a variety of actors, including university research labs, federal contractors, and government scientists. Periods of war have also generally been periods of more intensive American state building (see Tables 7 and 8 below) (also, Porter, 2002). Figure 7 shows the development of total federal tax revenue over the 20th century, showing clear jumps during wartime. Figure 8 shows the percentage of GDP expended on the military, showing a similar trajectory.

Several scholars have concluded that wartime mobilization allowed the American Leviathan to durably throw off its Constitutional shackles (Higgs, 2012). Even President Eisenhower articulated his own concern about how war had warped American institutions in his speech warning of the military-industrial complex.

Figure 7: Total Federal Tax Revenue in Logged Million USD.
Data Source: Piketty (2014)

This dynamic can be termed a “Tillyan spiral” in which the process of war mobilization empowers the state to an extent that cannot be undone once hostilities end. Fear of Tillyan spirals is communicated in varying forms, but always suggests that necessary expansions of state power during war time might make liberal-democratic governance impossible during peacetime. Such fears are often directly related to technologies created during war. In a 2019 paper, Philosopher Nick Bostrom presented his “Vulnerable World Hypothesis”, suggesting that technological progress might eventually necessitate the elimination of political and economic freedom in their entirety. Bostrom argued that technological capacities could become sufficiently advanced and ubiquitous to threaten human civilization as such. “Easy Nukes” would necessitate dramatic increases in governmental control of society to prevent nuclear proliferation. Bostrom’s line of argumentation in fact has ample historical precedent and was especially widespread at the dawn of the nuclear age in the late 1940s and early 1950s. Scientists, journalists, and the wider public alike worried that the awesome destructiveness of nuclear weapons would logically necessitate the permanent expansion of State power to ensure that the capabilities to build and

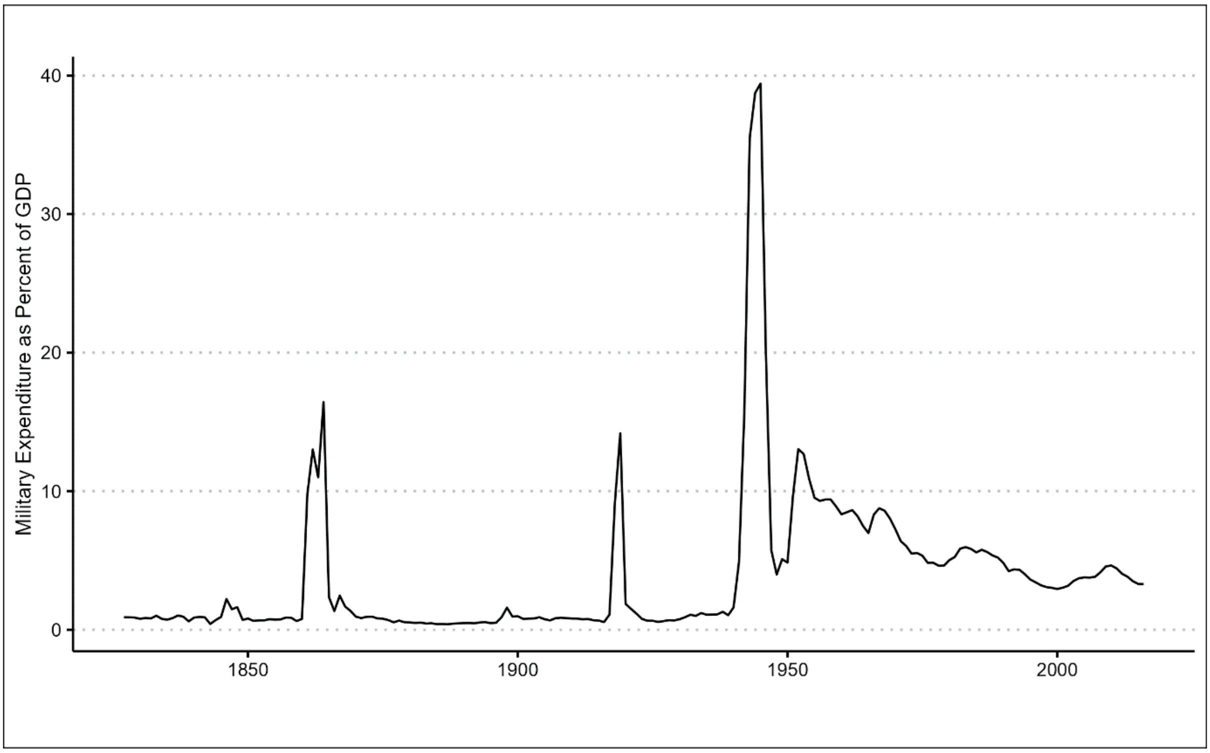

Figure 8: Military Expenditure as Percent of GDP
Data Source: Correlates of War, SIPRI, 2018

use such weapons would not diffuse (Friedman, 2000). Technology critic Lewis Mumford presented four future scenarios of human existence, none of which left much room for civil liberties, and some required humans to live underground (see Friedman, 2000). George Orwell's seminal *1984* was inspired by the large-scale military mobilization during WW2 and the fear that nuclear weapons would make attendant political measures permanent. And indeed, WW2 and the Cold War were important state-strengthening events in the US (Higgs, 2012; Friedman 2000).

Yet, while such arguments correctly stress the catalysing nature of war in American industrial and innovation policy, they miss important nuance. For one, Figure 8 shows that US military expenditure as percentage of GDP came down dramatically after WW2, as Congress aggressively curtailed efforts by elements within the American state to uphold defense spending (I will elaborate on this below). Even though the early Cold War period saw a renewed increase, this did not result in the institutionalization of a "Garrison State" as people feared at the time (Friedman, 2000), and commentators like Mumford saw as inevitable. Friedman (2000) convincingly argues that even during the Cold War which dramatically empowered the American state, US institutions and culture effectively constrained the growth of federal power. In the face of the Soviet nuclear threat, several voices within the American state called for more intense increases of federal power for war readiness that would have either matched Soviet expense or even surpassed them in percentage of GDP terms (Friedman, 2000). Yet, the American state remained institutionally constrained from metastasizing in the same way the Soviet state did (Friedman, 2000, see Figure 9 below).

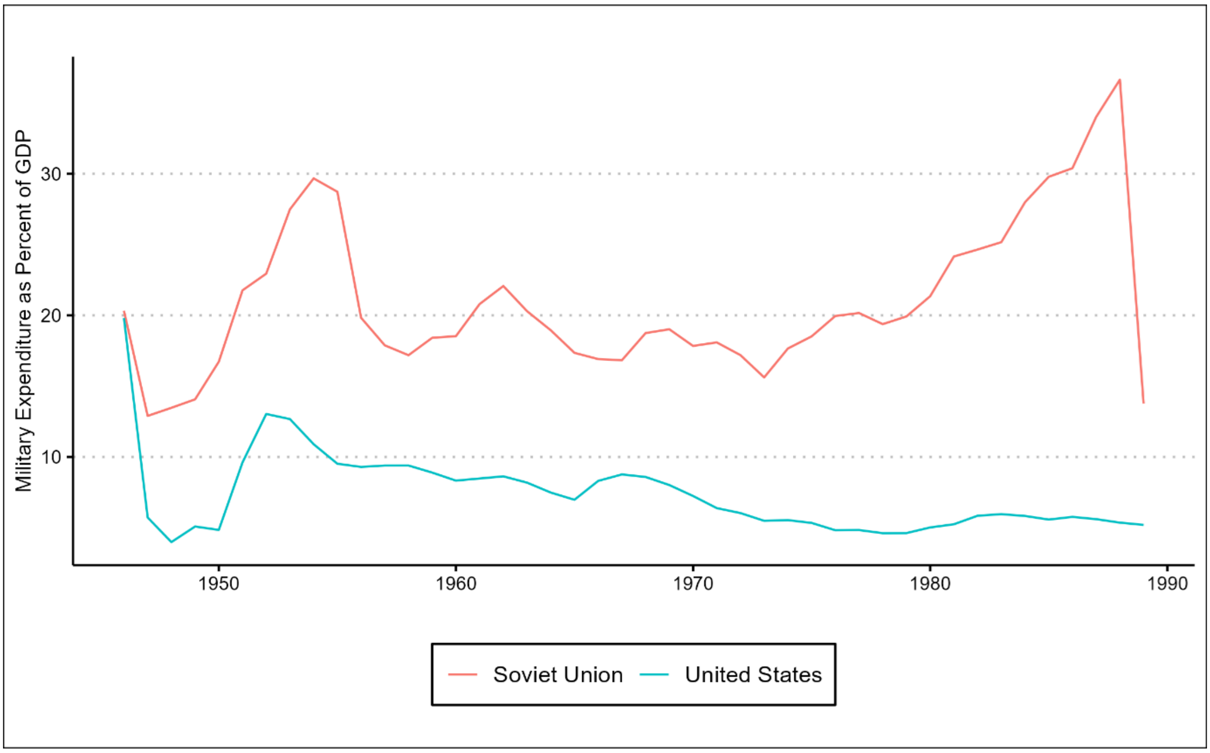

Figure 9: War Military Expenditure as Percent of GDP in the Soviet Union and US
Data Source: Correlates of War, SIPRI, 2018

There was no uncontrolled Tillyian spiral in the United States. After public protests forcing the end of the Vietnam war, the United States even stopped the draft. Throughout the entire Cold War, US military expenditure as percent of GDP was dramatically lower than in the Soviet Union (see Figure 9). Granted, Soviet GDP was considerably lower than that of the United States. Nonetheless, it was clear to American military strategists early in the Cold War that the Soviet military possessed a clear advantage in conventional forces (Weiss, 2014; Friedman, 2000). At some junctures, it was also suspected that the Soviet military had advantages in nuclear and thermonuclear weapons and delivery systems (Cooke, 2009). While there were continual attempts to expand US military spending, the institutional contours of the American polity made it virtually impossible to attain a conventional advantage over the Soviet Union (Weiss, 2014; Friedman, 2000). Instead, the American "offset strategy" sought to leverage American innovation policy to overcome the military disadvantage through technological means and lower military demands on society (Weiss, 2014, Friedman, 2000).

Nonetheless, public protests against what was perceived to be an unacceptable militarization of the American state and the conduct of the Vietnam War in the 1960 and 1970s ultimately resulted in a further reduction of military spending and a second offset strategy, in which federal agencies re-organized their strategy and R&D activities in the face of curtailed budgets (Weiss, 2014).

Subsequently, some authors have argued that federal expenditure on defense-related R&D through the Department of Defense has amounted to a covert industrial policy that boosts strategic American industries (Block, 2008; Wade, 2017). In contrast, Weiss (2014) has argued that the American state uses defense R&D to create a high-tech domestic industrial base for defense purposes, not to spawn commercially successful industries.

Extending these arguments to the issue of American innovation policy more generally, I suggest that while war has historically empowered the American state considerably, and military-related R&D is critical in the American innovation system, the exact way federal innovation policy operates is nevertheless highly impacted by the institutional constraints imposed upon it by the American Constitution. This means that it is not possible to use war or the demand for specific technologies by elements of the American state as a blanket explanation for the success of innovation policy in different technological issue areas.[22]

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[22] As I will explore below, institutional constraints on the American state contributed to the failure of the nuclear energy transition, as nuclear R&D and power generation required a level of secrecy, surveillance, and the creation and empowerment of state institutions effectively separate from the rest of society that were politically challenged and ultimately reined in by public opinion and Congress.

The Character of American Innovation Policy

Some scholars have argued that American political culture has always had a relatively positive view towards science or the solving of social and economic problems through technological solutions (Hughes, 2004). Others suggest that American political institutions featured especially enlightened provisions with respect to innovation policy from the start of the Republic (especially the creation of a federal patent system through Article 8 of the US Constitution) (Lamoreux and Sokoloff, 2001; also see Bessen, 2015; Menaldo and Wittstock, 2024). These arguments have merit. Yet, as I will explore below, the creation, development, and commercialization of technology has historically relied on considerable and deliberate additional execution of federal authority, which was often strongly resisted, and clearly failed in many instances.

President Eisenhower famously articulated his concern about the growing political ties between the American military forces and private industry emerging during the early Cold War. Many scholars have seen this as an expression of characteristically American fears of overly powerful central authority (see Friedman, 2000). Yet, it is noteworthy that Eisenhower presupposed that the American state would remain dependent on private industry to produce weapons, instead of taking more direct control over their production through nationalized armories. In many ways, this fundamental assumption of relatively restrained direct federal influence over the economy and technology development might be the more distinctly American characteristic of the view on federal authority articulated by President Eisenhower.

While the American state is militarily powerful and remains the technological vanguard in many areas, its domestic actions remain heavily circumscribed by Congress and federalism. There are extraordinary barriers to decisive federal action, large federal budgets and expenditures, the federal government often lacks authority to regulate or intervene in states policy matters (Friedman, 2000; Hacker et al., 2022). Historically, these barriers have often either prevented comprehensive innovation policy altogether, dramatically delayed it, and always shaped its form when implemented.

Creating effective federal policy that can create institutions to solve market failures, requires the acquiescence of Congress, the executive branch, and the Courts. There thus needs to be a widely perceived issue, crisis, or potential threat that allows for the consensus opinion between these institutions to emerge that sustained innovation policy is needed.[23] Even if a wide consensus over the desirability of federal action emerges, repeated and sustained efforts to pass federal policy have historically been necessary to provide effective innovation policy and overcome challenges to successful technological innovation. This situation has historically mostly occurred in the context of persistent socio-economic challenges or wartime.

Hence, it is unquestionably the case that war and the federal branches tasked with national security are key elements in US innovation policy efforts. Yet, for innovation policy to succeed, political support needs to be durable and federal programs have often been eliminated or heavily curtailed by Congress if they outlive their purpose, were perceived as unsuccessful, or otherwise raised organized opposition (see Negoita, 2015; Friedman, 2000).

In the American political economy, innovation policy typically is characterized by a system in which federal authority primarily assumes a coordinating and facilitating role. There is little direct federal technology regulation that would encroach on the reserved power of states. Rather, innovation policies often have a voluntary character, as federal institutions cooperate with state and local actors. While innovation policy has historically often included the creation of dedicated federal agencies with considerable R&D budgets, these tend to coordinate innovation policy through a network of decentralized actors. Rather than expanding the capacity of federal institutions to conduct basic science and R&D intramurally, federal agencies typically devolve the execution of research projects to actors including state research agencies, universities, and private companies. The American state has limited bureaucratic capacity to permanently oversee projects, which contributes to the strong impulse to outsource. Arguably, those within the federal government pursuing the development of new technologies also anticipate that their actions will draw political pushback in the future, and thus have an additional incentive

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[23] There are innumerable historical instances in which these conditions did not obtain and initiatives for federal action subsequently failed. I shall discuss some such cases below.

to induce outside actors to continue pursuing the development of certain technologies on their own should federal support be curtailed in the future.

Existing federal agencies will retain the capacity to solve some market failures related to technological innovation if they gain periodic permission from Congress for their funding plans. Existing federal agencies are actors with long time horizons in the fulfilment of their associated public policy missions. In many cases, existing agencies have found ways to use their budgets in ways that raise their direct impact on technology development related to areas they care about (Weiss, 2014). Most obvious in this context is DoD, the federal agency with the largest budget of all federal agencies. DoD has historically directly induced technological innovation without new acts of Congress (Weiss, 2014). While the federal agencies are overseen by the executive branch and formally funded by Congress, there are also cases in which Congress defers to them on policy details, and agencies will retain significant leeway in how they spend funds. Yet, there are also ample instances where such efforts have been curtailed (Friedman, 2000; Negoita, 2015). Hence, federal agencies conduct innovation policy under the permanent shadow of raising Jeffersonian backlashes.

Some observers have characterized the creation of relatively small, independent, and nimble bureaucracies that mainly seek to influence technological innovation through the coordination and funding of private R&D efforts, combined with the permanent threat of withdrawing funding from non-performing entities as the “DARPA-model” of innovation policy (named after the Defense Advanced Research Projects Agency) (Ruttan, 2006). In important respects, American innovation policy in general shares many of these characteristics, as the above discussion indicates.

Further, American innovation policy strongly stresses positive incentives rather than coercion in the adoption of new technologies. In many cases, federal agencies have worked actively to encourage the adoption of desired technologies through public demonstration, access to subsidies or other financial support, diffusion of educational material, or other positive inducements. Cases in which federal agencies force the adoption of technologies by banning existing technologies or penalizing their use in some ways are comparably rare. American innovation policy is often strongly focused on publicly funding basic science and R&D, less so on directly regulating the uses of specific technology. One reason for this character trait of American innovation policy is that federal agencies (especially DoD) have in many instances pursued technologies for their own mission needs, not to encourage their widespread use (Weiss, 2014). Another important reason is that regulation of technology use generally falls outside of the purview of federal agencies' authority and would require additional legislation. Of course, there are exceptions to this rule. Related to clean energy policy, the Bush administration passed provisions in the Energy Policy Act of 2005 that specified emission standards, and the Department of Energy was empowered to operate a sizable loan guarantee program for energy projects (seeking to subsidize the adoption of new energy technologies). Characteristically, these steps required acts of Congress above and beyond the regular R&D budgets of DOE. Such policies have historically been filtered in their frequency by the institutional barriers laid out above.

Overall, these factors lead to a characteristic form of American innovation policy that is somewhat pantomime rather than heavy-handed. In part because of constitutional limits to federal power expansion, American innovation policy has historically strongly relied on coordinating the actions of outside actors and strongly focused on the creation of technology, and the open diffusion of scientific insights and less on active efforts to force their use. Central coordination is typically only exerted over goals rather than concrete ways of behaviour or paths of technology development. In what follows, I will present four case histories of American innovation policy to illustrate these points.

1.6 American Innovation Policy in Historical Perspective

In American history, there have been many instances in which the federal government enacted programs to coordinate the creation, development, and diffusion of technology. Recent scholarship has produced several excellent accounts of the American state's role in providing the basic science, R&D, and continual financial and coordinating support of a host of recent technologies including the internet, GPS, semiconductors and information technologies (Mazzucato, 2011; O'Mara, 2019; Block, 2008; Ruttan, 2006). These are explicitly dual-use technologies that were based on basic science and R&D financed and directed by the American state's war-related objectives (Weiss, 2014). Later, the federal government organized standards, education, and civilian diffusion of these technologies (Mazzucato, 2011; Ruttan, 2006).

The strong institutional hurdles to federal action shape the way the American state solves market failures when it manages to do so but also pre-empts, complicates, or delays such action in many cases. I will focus here on less widely discussed cases. I have also deliberately chosen some cases that are less obviously related to military investment, while the American military will feature in these cases, nonetheless. The first two cases presented here illustrate the ways in which the American state has historically provided innovation policy, but also showcase the unique political challenges to such action in the US polity.

Success Case 1: The Agricultural Extension Program

The United States Department of Agriculture (USDA) Cooperative Extension Service is a prime example of federal action successfully solving market failures around basic science, R&D, invention, commercialization, and diffusion of agriculture-related technology. The USDA's Extension Service coordinates, conducts, and disseminates knowledge and technology through a network of land-grant universities and county-level extension service offices to agricultural producers across the country. The contemporary contours of this system were created through the Smith-Lever Act of 1914. Yet, the program must be seen in combination with the Morrill Act of 1862 which created the land-grant universities, to be coordinated by the newly established Department of Agriculture (USDA, also created in 1862)[24].

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[24] The 1862 Morrill Act was motivated by more than the goal of boosting agricultural production through the diffusion of technology and provision of education. Nonetheless, in his study of American agricultural history, Conkin (2008) credits the federal government as the key actor in raising farm productivity, highlighting especially investments in research, development, and education through the Morrill and Hatch Acts (which expanded the Morrill Act), as well as the Smith-Lever Act of 1914.

The USDA-land-grant system was to provide practical education in agriculture and the mechanical arts ((today called engineering) in every state. The 1914 Smith-Lever Act formalized the role of these universities in disseminating agricultural knowledge and innovative technologies directly to farmers through a network of experimental stations and county-level extension agents (Rasmussen, 1989). Building on these efforts, the federal government provided two major credit programs to enable farmers to upgrade their equipment.

The Agriculture Extension program is one of the most widely imitated American institutions and has been widely credited with mechanizing American agriculture and dramatically raising agricultural productivity (Rasmussen, 1989, Conkin, 2008). Moreover, Ehrlich, Cook, and Yin (2018) suggest that the Morrill Acts sufficiently boosted human capital to partly explain why US GDP overtook Britain during the Second Industrial Revolution of the late 19th and early 20th centuries. The Morrill Acts aided in the creation of considerable advantages in average schooling attainment compared to Britain, France, and Germany, which was later amplified by the high school movement of 1915 – 1940, and the GI Bill after WW2. In the wake of the Sputnik shock, Congress additionally passed the National Defense Education Act of 1958, which further expanded federal involvement in education policy. In conjunction, these federal efforts contributed to an enduring US lead in knowledge formation (Goldin and Katz, 2008).

Historical Context

Agricultural productivity in mid-19th century America remained low, and many farming practices were outdated (Conkin, 2008, Cochrane, 1993). These circumstances constituted a drag on economic growth and food security, especially in the context of an industrializing economy that drew people into cities and away from farms. Since land was abundant, US agriculture had been highly based on land mining or the practice of extracting nutrients from the ground without replenishing them[25] (Conkin, 2008, Rasmussen,

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[25] Unsustainable farming practices and environmental pollution that arose from Tragedy of the Commons dynamics both within and between states of the American Union played some role in demands

1987). In many instances, farmers attempted to use farming techniques that proved unsuitable or unsustainable in the areas they settled in (Conkin, 2008, Cochrane, 1993). Beginning in the early 19th century, Congress was increasingly concerned with finding ways to change farming practices to raise sustainability and productivity (Rasmussen, 1991).

In the late 1830s, the commissioner of the US Patent Office Henry Leavitt Ellsworth encountered new seeds and agricultural techniques but also noticed the lack of their widespread adoption (Rasmussen, 1989). Ellsworth saw the federal government in the best position to diffuse technical knowledge and thus asked Congress to federally fund agricultural education (Rasmussen, 1989). Congress allocated some funds to the Patent Office to circulate information and seeds through the US Postal Office (Rasmussen, 1989). Ellsworth also began devoting space to agricultural techniques, seeds, and new equipment in his periodical distribution of new inventions in his role as Patent Office Commissioner. Ellsworth's Patent Office thus pioneered some of the functions that the Department of Agriculture would take over in 1862 (Rasmussen, 1989).

The mid-19th century saw the introduction of mechanized farming equipment. Cyrus McCormick obtained a patent for a mechanized reaper in 1834[26]. While individuals like McCormick did much to diffuse these new technologies, using public demonstrations, warranties, and even credit to customers, farmers nonetheless were often hesitant to adopt new tools (Conkin, 2008). The growing range of improved technology and farming knowledge extended far beyond the McCormick reaper and included new tools like steam-powered tractors, but also new crop, soil, and pest management techniques, as well as new seeds. Farmers often lacked access to the latest research and innovations in agricultural science and adoption of these innovations was slow (Rasmussen, 1989). As a result, by the mid-19th century, it became increasingly clear that US agriculture was severely underperforming its potential, and that federal efforts to diffuse technologies and

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for increased federal regulatory action on multiple fronts, including the provision of agriculture-related innovation and education policy (Conkin, 2008).

[26] After legal battles over the extension of the patent, which McCormick lost in 1848 he began mass-producing an improved version of the McCormick reaper (Rasmussen, 1989). In 1851, McCormick's machine won the Great Exhibition in London, and in 1856, McCormick's factory was producing more than 4000 reapers annually (Rasmussen, 1989).

educate farmers could increase farm yields.

Morrill Acts and Land Grant Colleges

The 35th Congress (1857 - 59) introduced the first formal proposal (House Bill Number 2) for the creation of agricultural and mechanical colleges. The explicit purpose of the bill was to raise skills in the agricultural labor force, to diffuse best practices, and to conduct both basic science and R&D related to agriculture and mechanical arts (today called engineering).

At the time, proponents of the law sought to justify federal action to improve agricultural education by appealing to Jeffersonian virtues just like Hamilton had framed his agenda in those terms. Proponents also pointed to the national security benefits of improving agriculture. A report from the Committee of Public Lands from April 1858 stated: "*. . . If the intelligence of the people is the safeguard of our liberties and attachment to the soil of our birth, the guarantee of our continued independence, surely the more extended the education of the people and the more intelligently that soil is cultivated, the safer are our liberties and the stronger the guarantees of our independence*" (US House of Representatives, 1858, p. 2).

It was Justin Morrill, a Republican Representative from Vermont[27], who introduced House Bill 2 in 1857, making provisions that would establish a system of public higher education to be funded by the provision of federal lands to each state. Yet, House Bill Number 2 did not pass in the House of Representatives, in large part due to the opposition of Southern state representatives. There was intense division over the appropriate scope of federal responsibility and the balance of activity undertaken by the national and state governments which led to lawmakers' rejection of Morrill's proposal (Conkin, 2008; Abramson et a., 2014). Southern opposition to the land-grant university system was certainly also informed by their slavery-based plantation economy. While the diffusion of agricultural knowledge may have raised labor productivity in the South, education for

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[27] Morrill is often referred to as Senator Morrill, as he served as Senator of Vermont from 1867 until 1898. However, when he introduced the first proposal for the land-grant university system in 1857, Morrill served as a Member of the US House of Representatives for Vermont's second district.

enslaved farm labor in the South must have been viewed as a political danger. It was likely also the case that the mechanization of agriculture, and diffusion of new farming techniques and seeds were seen as less relevant for the mode of farming practiced in the South (Wright, 2006).

In 1860, the "Morrill" bill was reintroduced and passed both houses of Congress but was then vetoed by President Buchanan (Abramson et al., 2014). In a relatively lengthy explanation, President Buchanan argued that the creation of land-grant colleges through the sale of federal lands would be an unconstitutional incursion into states' rights[28]. Hence, the efforts by Representative Morrill to enact a land-grant university system to boost agricultural productivity failed multiple times, due to different veto points within the American political system.

Yet, the secession of Southern states in 1861 and the ensuing Civil War created a shift in the political opportunity structure. Many of those representatives who had opposed Morrill's proposals were no longer part of the Union (Conkin, 2008; Abramson et al., 2014). Moreover, President Lincoln, whose election and openness to expansions of federal power had provided the proximate cause for Southern Secession, was open to Morrill's bill (Abramson et al., 2014). President Lincoln signed the bill on July 2, 1862, and the Morrill Act of 1862 established the land-grant college system in the United States, providing federal lands to establish an agricultural and mechanical college in every state. States were required to sell the granted lands and use the proceeds to establish and fund colleges to teach "agriculture and mechanical arts" (Morrill Act of 1862, Public Law 37-108).

In the same legislative session, the Department of Agriculture (USDA) was created (Abramson et al., 2014). Through the land-grant university system and the creation of the USDA, the federal government assumed primary responsibility for R&D related to agriculture (Conkin, 2008). Soon after the first Morrill Act, several new agricultural colleges began extensive R&D efforts through a network of agriculture experiment stations (Conkin, 2008; Rasmussen, 1989). This practice was universalized through the Hatch

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[28] The original veto message can be accessed here: James Buchanan, Veto Message, Gerhard Peters and John T. Woolley, The American Presidency Project, https://www.presidency.ucsb.edu/node/203065.

Act of 1887, in which Congress authorized funds to support an agricultural experiment station in every state (Conkin, 2008; Rasmussen, 1989). The experiment stations carried out basic research and were also engaged in active cooperation with farmers to test soils for different fertilizers and provided public demonstrations of new techniques (Abramson et al., 2014). The results were published and distributed openly to farmers. While the initial federal appropriations for the Hatch Act were modest, the success of the experiment stations contributed to significant increases in the appropriations in 1906 and 1920 (Conkin, 2008).

In 1890, the Morrill Act was explicitly expanded to the states of the ex-confederacy. The statute also stipulated that federal funds would be withheld from states that failed to admit non-white students or provide "separate but equal" facilities, which resulted in the foundation of 17 black colleges in Southern states (Conkin, 2008).

Congress heavily subsidized the R&D conducted by the experiment stations and their activities were coordinated by the USDA. While this improved the dissemination of advanced farming practices, the system still often failed to reach many more remote and less educated farmers (Conkin, 2008; Rasmussen, 1989). In 1914, the Smith-Lever Act formalized a system of county-level extension agents. The Act provided that the land-grant agricultural colleges now had the legislative mandate to organize for extension agents to bring education in agriculture and home economics directly to farmers through a variety of programs (Conkin, 2008). These efforts were supported and coordinated by USDA, and the Extension Service became a sprawling network of agricultural education and the most extensive element of the bureaucracy of the USDA (Rasmussen, 1989). Adult education was further expanded through the Smith-Hughes Act of 1917, also known as the National Vocational Education Act, providing federal subsidies for vocational education (Moore, 2017).

Beyond federal investments in basic science, R&D, education, and diffusion of best practices, federal programs also addressed financial barriers in the diffusion of new farming equipment. In 1908, President Roosevelt appointed the Country Life Commission as part of a broader Progressive-era agenda to improve the economic conditions of rural America.

The report found that many farmers struggled to obtain credit, which hindered their ability to acquire new mechanized farming equipment and invest in other new farming tools and practices. (Report of the Country Life Commission, 1909).

The report stressed that a lack of access to credit was one of the major challenges faced by farmers in raising their productivity.[29] In fact, the diffusion of new agricultural technologies remained relatively slow (Rasmussen, 1982). As late as 1917, there were fewer than 80,000 tractors on American farms (Conkin, 2008). With the increasing mechanization of farming, the dependence of farmers on bankers and credit increased. Often, it was also necessary for farmers to bring more land under cultivation to economically justify the considerable investments that new harvesting machines represented (Rasmussen, 1989). Yet, increased production often reduced prices for agricultural output and resulted in substantial surpluses (Rasmussen, 1989). Fluctuations in agricultural prices often deterred farmers from making large investments in new production equipment (Conkin, 2008).

The 1908 Country Live Commission Report sparked two large credit programs for farmers. The Federal Farm Loan Act of 1916 and the Agricultural Credits Act of 1923 created regional Farm Loan banks to provide long-term credit to farmers, offering low-interest loans. The federal government provided the initial capital to establish these regional banks (Valgren, 1923).

During WW1, the federal government also conducted several public demonstration programs of agricultural equipment. WW1 together with government encouragement increased the uptake of tractors (Rasmussen, 1982). By 1921, American farmers owned more than 300,000 tractors, which was also eased by the 1917 introduction of Ford's mass-produced tractor model (Rasmussen, 1982). The New Deal Farm programs of the 1930s further enabled farmers to upgrade equipment. The New Deal programs also invested substantially in upgrading rural American infrastructure, most famously through rural

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[29] The report also stressed that inadequate education remained a major issue for many rural farmers. Due to lacking infrastructure, the existing agricultural extension services were reported to be insufficient in achieving their goal of improving education and diffusing best practices while conducting R&D in cooperation with farmers. The 1908 Country Life Report thus impacted the policy choices made in the 1914 Smith-Lever Act and the 1917 Vocational Education Act.

electrification programs like the Tennessee Valley Authority (Conkin, 2008). It took WW2, however, and the accompanying shortages of farm labor, high prices and enormous demand for farm products to convince all American farmers to turn to tractors and advanced farming machines (Rasmussen, 1982).

The mechanization of American agriculture and the dramatic increases in farm yields over the 19th and 20th centuries have thus been accompanied by deliberate federal innovation policy. The land-grant university system invested in basic science and created a network of institutions conducting agricultural R&D. The Hatch Act began to create a system direct R&D and demonstration cooperation with farmers through the extension program, which was expanded considerably through the Smith-Lever Act of 1914. The Agricultural Extension Program actively deployed agents to diffuse knowledge and best practices, but also inform the basic science and R&D programs of USDA and the network of land-grant universities by engaging directly with farmers. Finally, federal programs aided considerably in overcoming capital market shortcomings in providing American farmers credit to upgrade their equipment.

Reasons for Federal Action

Scholars have often argued that the policies described above were the result of lobbying by farmers, as well as the Populist movement that emerged in the late 19th century (see Conkin, 2008). In the mid-to-late 19th century growing numbers of Americans had settled on the plains, but dry weather and above-mentioned unsustainable farming practices led to a series of crop failures (Conkin, 2008). Farmers began to organize into political groups called Granges, forming the Greenback party in the 1870s. In the 1890s, they formed the Independent People's or Populist Party to challenge the Republican and Democratic parties in Presidential elections (Kazin, 1998). Farmers political parties variously demanded price control schemes, a bimetallic monetary standard[30] that

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[30] The novel Wizard of Oz, written by L. Frank Baum and published in 1900, has often been interpreted as a metaphorical treatment of the cause of farmers' political movements and demands against the urban industrial elite of the day. Typically, the character of the Scarecrow is seen to represent the struggling American farmer, the Tin Man the American industrial worker. The "yellow brick road" is interpreted to be a reference to the gold standard, while "Oz" is supposedly a reference to the measurement of

would inflate the monetary supply and thereby reduce farmers' debts in real terms, higher wealth taxes, nationalization of the railroads, antitrust measures, and direct election of Senators (Conkin 2008, Kazin, 1998). The Populist party identified the divergence in political interests between industrializing urban centres and rural areas as the most important political cleavage of the time. Politicians like William Jennings Bryan asserted that federal policy was beholden to a monopolized industrial elite that took economic advantage of average Americans (Kazin, 1998).

Indeed, it is difficult to overstate the impact of the Agrarian Populism that gripped American Politics in the late 19th century. The aggressive agitation for economic Populism contributed to a party realignment, as Republicans, previously the party of big business *and* state intervention soured on this policy mix and henceforth aligned themselves with a business class that itself had become more oriented towards laissez-faire (see section 1.5 above). Further, many of the policies advanced by the Populist party were later implemented to some extent. Most famously, the 16th Amendment ratified in 1913 implemented a federal income tax, the 17th Amendment ratified in the same year provided for the direct election of US Senators, and the Sherman Antitrust Act of 1890 and the Clayton Antitrust Act of 1914 were significant steps against industrial monopolies.

While the political organization of farmers certainly played a role, the assessment that it was farmers' lobbying that drove federal innovation policy in agriculture is not entirely persuasive. Many of the policy demands that were directly targeted at farmers were ignored or went nowhere (Kazin, 1998). Also, innovation policy that was implemented, for example in the form of the Agricultural Extension Service, ultimately did much to euthanize the farmer as a political force. While growing education of farmers and the diffusion of mechanical tools and techniques drastically raised agricultural productivity, this did not unequivocally raise the economic prospects of farmers and if anything, further enabled the reduction in the agrarian labor force (Rasmussen, 1989). Rasmussen (1989) goes so far as to suggest that the increase in agricultural output was achieved at the expense of the individual farmer's fortunes. Of course, these developments are clear

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precious metals in ounces, and the Wizard represents bankers who are opposed to a bimetallic monetary standard.

in hindsight and may have been perceived differently at the time.

Yet, the record of Congressional debates surrounding the Smith-Lever Act of 1914 suggests that even at the relative height of the Populist party's strength, other concerns were at least as important for the Congressional Representatives who debated the Act. The Congressional record suggests that members of Congress actively compared US farm yields with those of Germany and other countries they deemed to be at the technological cutting edge (US House of Representatives, 1959). It was clear to policymakers that US agriculture was less productive and continued to face issues related to the creation and diffusion of knowledge and technology. Representatives were keenly aware of the importance for the United States to produce enough food as they observed the increasingly worsening diplomatic relationships in Europe (US House of Representatives, 1959). Hence, the 1914 Smith-Lever Act must also be seen in the context of pre-WW1 military build-up.

Further, Representatives repeatedly noted that populations in cities were increasing much faster than agricultural productivity made sensible (US House of Representatives, 1959). Cities were especially attractive due to the growing demand for manufacturing labor at the time, which was itself in part spurred by increasing US, exports to Europe. Most contemporary farming methods remained highly labour-intensive which limited the amount of acreage that farmers could bring under cultivation as they had to compete for workers.

Representative Townsend of New Jersey's 10th district relayed in 1914 that because New Jersey has experienced considerable industrialization and urbanization, the acreage under cultivation in the state had declined over the prior 20 years, as well-paying jobs in cities like Newark drew people away from farms (US House of Representatives, 1959). Agricultural output, the number of farms, as well as acreage under cultivation declined in New Jersey between 1880 and 1910 (US House of Representatives, 1959).

Thus, Representatives argued that industrialization, which many of them thought desirable, necessitated the dramatic increase in agricultural productivity, which they thought to support through federal innovation policy. The Congressional record thus reveals that federal politicians saw improvements in agricultural technology and education as critical in supporting the ongoing industrialization of the economy. The fact that these policies could be advertised as pro-farmer policies certainly made them more politically palatable in the Populist political climate.

Simultaneously, increased federal efforts to improve educational outcomes also dovetailed with the demands of growing manufacturing firms. The National Association of Manufacturers (NAM), founded in 1895 publicly advocated for a federal role in coordinating education policy. Influential educators like Booker T. Washington and John Dewey publicly advocated for changes to the American education system to meet the needs of a technologically changing society (Wirth, 1972). Education for manufacturing workers was covered by the 1917 vocational training program (Moore, 2017).

Finally, while the political influence of farmers certainly made a difference at the margins, it is important to note that the federal government largely ignored calls for production subsidies, price floors, or the creation of centralized export marketing boards. Such policies were actively demanded by both farmers' organizations and the Populists but would have improved farmers' economic conditions at the expense of their consumers. Such policies would have likely sparked more intense pushback either from the courts or complicated compromises between Congress and the executive branch. The policies that were implemented focused strongly on innovation policy, with strong reliance on state governments as the executive organs, and a comparably loose coordinating role of federal agencies.[31]

While I have described the Agricultural Extension Service as a success case of American innovation policy, it should be noted that this case also demonstrates the difficulty of implementing such policy in the American political economy. The need to centrally coordinate policies in aid of agricultural technology upgrading and diffusion was widely appreciated since at least the 1840s (Rasmussen, 1989). President Washington, in his last annual presidential address to Congress in 1796 had proposed that some federal office be established to promote agriculture through the collection and diffusion of related infor-

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[31] Note that the Morrill Acts effectively just gave states money to create their own educational institutions.

mation (Rasmussen, 1989). Representative Morrill himself worked on this issue for 20 years and either Congress or the President struck down the idea multiple times. The legislative creation of the foundational land-grant university system and USDA was almost a historical accident, as the secession of the Confederacy opened sufficient legislative space for the passage of the Morrill Act in 1862 (Rasmussen, 1987). The system of policies to support agricultural productivity described here thus proceeded in fits and starts despite considerable interests advancing them and broad benefits to be reaped.

Success Case 2: Exploration and Development of Minerals and Fossil Fuels

At the end of the 19th century and early 20th century, the United States became the largest economy and the technological vanguard by pioneering drilling technologies and extraction techniques leading to cheap oil and its use in the internal combustion engine, and combining related technologies in manufacturing (Perez, 2010). David and Wright (1997) argue that this wave of innovation emerged from the US rather than elsewhere in important part because the country made much more intensive use of its natural resource endowment. Both the federal and state governments played an active role in facilitating this economic development through innovation policy. David and Wright (1997) note that the exploration of mineral and oil deposits can suffer from similar appropriability issues as the insights from basic science and R&D investments. Extracting minerals or oil involves costly search activity with high uncertainty over appropriability (David and Wright, 1997; Menaldo, 2016). The rapid pace of American development of mineral resources, petroleum, and attendant technologies and processes was in important part the direct consequence of federal investments in basic science, R&D, technical education, and their diffusion (Wright and Czelusta, 2002; David and Wright, 1997).

The US government provided land grants to actively encourage the development of natural resources, including oil. The General Mining Act of 1872 facilitated the acquisition of land for mining and extraction purposes. Yet, the largest initial challenge for the fledgling US fossil fuel industry in the mid-19th century was the lack of geological information and significant uncertainty around the availability of mineral and oil reserves within the country (David and Wright, 1997). Hence, the federal provision of geological information through a variety of programs and efforts mainly coordinated by the US Army was one of the most important early steps in American discovery and exploitation of minerals and oil (David and Wright, 1997). These explorations provided the institutional groundwork for the US Geological Survey (Rabbitt, 1989).

The US Geological Survey (USGS) was created by an act of Congress in 1879, as part of the Department of the Interior. This new institution was almost immediately engaged in active efforts at network building between the growing number of mining schools and companies, publicly providing maps and other results from basic science and R&D (Rabbitt, 1989). The US funded these efforts generously. Before WW2, Britain spent 70,000 GBP on geological surveys annually, while the US spent the equivalent of 1Mn GBP (David and Wright, 1997).

The US Bureau of Mines (USBM), established in 1910, played a significant role in advancing R&D in the mining and petroleum sector. Through the USBM, the federal government indirectly created an educational institution that diffused insights from basic science to practitioners. USBM researched drilling techniques, safety measures, and refining processes (Powell, 1922). It also provided technical assistance to the industry, helping to disseminate best practices and innovations, through a network of experimental stations, and conducted targeted R&D in coordination with Universities and state institutions, in a manner comparable to the Agricultural Extension Service discussed above (Powell, 1922).

The initial creation of the USGS and USBM were connected to the sale of public lands by the federal government. However, the activities of these agencies were expanded considerably during WW1 and later WW2, as federal interest in the access to mineral resources increased. Especially in the case of oil, federal R&D investment as well as demand emanating from the Department of War increased substantially during WW1 and later WW2. It was the combination of increased demand for resources, motorized vehicles , government investment in infrastructure and R&D, that contributed decisively to the widespread uptake of oil as the primary energy source (Johnston and McLeish, 2020).

Historical Context

While the United States has often been described as uniquely blessed with abundant natural resources, these resources remained substantially underdeveloped until the last third of the 19th century (David and Wright, 1997). US coal production did not pass Germany's until 1880 and surpassed that of Britain only in 1900 (David and Wright, 1997). The exploration, discovery, and access to new minerals and oil required the deliberate search, extensive investment in infrastructure, as well as the development and diffusion of new technologies to extract and process these natural resources (David and Wright, 1997). Several federal innovation policy steps contributed considerably to this process.

Public Provision of Geological Information

One of the major impediments to the exploitation of natural resources in the United States throughout the 19th century was the large amount of mostly unchartered territory. This was not unique to the US, as David and Wright (1997) point out, Australia, Chile, and many other countries and European colonial possessions remained largely unexplored. Yet, the effective provision of publicly funded geological and topographical surveys was a key factor in the creation and diffusion of scientific knowledge and skill that allowed private American prospectors to rapidly exploit minerals and petroleum reserves as extraction techniques improved and demand expanded (David and Wright, 1997, Yergin, 2011).

Scientific research and "internal improvements", sometimes called "public works", were generally within the realm of states' rights; and federal efforts to conduct such activities often resulted in heavy Congressional resistance, typically from Southern states (see above). Hence, it was primarily the states that initially financed and sponsored local explorations of topographies (Rabbitt, 1989). North Carolina sponsored a geological survey in 1823, Massachusetts in 1830, followed by 14 other states during the 1830s (Rabbitt, 1989). The states supported not only the fieldwork of geologists but also the publication of their findings. These initial surveys were primarily made in support of agriculture, as farmland in many Eastern and Southern States lost fertility and induced residents to move westward (also see above) (Rabbitt, 1989).

The military engaged in some scientific endeavors related to the mapping of US territories, but Congress did not authorize explorations for civilian use until 1807 when the Coast Survey was established, which provided navigational information to private actors (Rabbitt, 1989). The federal government's interest in more accurate mapping of internal land derived in important part from the fact that Congress was in the process of selling lands that the federal government formally possessed because of westward expansion, seeking to be able to distinguish between agricultural and mineral lands (Rabbitt, 1989). In 1824, Congress authorized the Army Engineers to create topographical surveys for the creation of roads, canals, military, and postal purposes (Rabbitt, 1989). Further, in 1834, Congress authorized the Army to use $5,000 of its appropriation for geological investigations and the construction of a geological map of the United States (Rabbitt, 1989).

The head of the responsible Army Bureau justified this expense in reports mainly by reference to the potential economic benefits that would come from the "*development of these great resources of wealth and commercial intercourse, which now lie inert and buried in the bowels of the earth.*" (Abert, 1833). Because the Army would make its findings public, it was thus clear that the Army's topographical mapping efforts were part of a federal "internal improvement" effort. At the time, the Army was the only organ of the federal government with sufficient capacity to conduct such projects. In 1838, the Army established the Army Corps of Topographical Engineers (Rabbitt, 1989) and the various topographical surveys subsequently produced and publicly circulated by the Army allowed American geologists to study lands in the American West (Rabbitt, 1989).

In 1848, President James Polk asked Congress to fund a geological survey of regions where gold had been discovered (Rabbitt, 1989). President Polk argued that such a survey was necessary to either preserve the lands that contained valuable minerals or for the federal government to dispose of public lands in a manner that would maximize returns to the Treasury (Rabbitt, 1989). In 1849, Congress established a new federal agency, the Department of the Interior (DOI), which was to have a range of responsibilities, including the exploration of the Western parts of the country. Further, to connect the gold-rich Western regions to the Eastern US, in 1853, Congress appropriated funds to map the best route for railroads from the Mississippi River to the Pacific Ocean, utilizing the Army Corps of Topographical Engineers (Rabbitt, 1989; David and Wright, 1997).

American industrialization accelerated during, and especially after the Civil War (Lind, 2012; Rabbitt, 1989), aided also by the considerable public investment in the expansion of railroads. Several American iron manufacturers imported technologies and know-how from Europe, including the rights to use the Bessemer process in making steel, which began in 1865 (David and Wright, 1997). Accelerating industrialization created increasing demand for all manner of minerals. Commissioner of the DOI's General Land Office John Wilson argued in his annual report that the development and exploration of natural resources was critical to continued American economic development.

In 1867, Clarence King approached the Army Corps of Engineers, asking to fund a Geological exploration of the 40th parallel (Rabbitt, 1989). Congress for the first time authorized Western explorations of the geology and natural resources along the route of the transcontinental railway (Rabbitt, 1989). The subsequent exploration which was led by Clarence King created the institutional foundation for further government coordination of science that combined geology and technology (David and Wright, 1997; Rabbitt, 1989).

While these initial forays into topographical and geological mapping were made by the federal government, by the time of King's exploration, the federal government held title to 1.2bn acres of land, of which only 200m had been surveyed (Rabbitt, 1989). Hence in 1878, the National Academy of Sciences (NAS) had been tasked by Congress to ascertain the most cost-effective way to survey the territories of the United States (Rabbitt, 1989). The Committee appointed by the NAS then recommended the creation of an independent organization within the Department of the Interior dedicated to topography of US territories. In 1879, President Hayes signed a bill appropriating money to establish a new federal agency, the US Geological Survey (USGS) within the Department of the Interior (Rabbitt, 1989), under the oversight of Clarence King (Nelson and Wright, 1997; Rabbitt, 1989). USGS quickly became the leading scientific bureau of the time and the most productive federal research agency of the 19th century (Nelson and Wright, 1989). USGS produced and circulated reports and maps, and quickly expanded its reports to drilling techniques and metallurgy education (Rabbitt, 1989). USGS's work was expanded in 1882, as Congress approved the creation of geological maps of the entire US, not just public lands (David and Wright, 1997; Rabbitt, 1989).

Much of the work of USGS also carried over to the development of the American petroleum industry. The networked institutional structure of relationships between federal agencies, academic institutions, and corporations was critical to the expansion of the US petroleum industry, as it diffused related knowledge (Nelson and Wright, 1997). Williamson et al. (1963) argue that USGS was the main actor in diffusing scientific information by changing the fledgling oil industries' opinion about the value of new techniques. USGS published reliable data openly and actively worked to educate American geologists, diffusing scientific information relevant to the industry (Rabbitt, 1989; Nelson and Wright, 1997).

Investment in Education, Basic Science, and R&D

The US and Germany, the two countries at the centre of the Second Industrial Revolution (Perez, 2010) also led the world in mining education during the mid-to-late 19th century (Williamson et al., 1963). In the US, this was partly supported by the states (e.g. the Colorado School of Mines). The USGS played an important role in circulating technical information regarding digging and drilling, the treatment and refinement of ores, as well as other useful information for geologists (Powell 1922). Yet, the federal government most consequentially influenced American education in related arts through the US Bureau of Mines.

USGS had established strong connections with the mining and mineral industries in publishing its reports and studies in key mining areas (Rabbitt, 1989). In 1899, the USGS director proposed creating a separate division explicitly focused on mines and mining. In 1904, Congress funded an analysis and testing of coal, creating a technological branch within USGS. In 1910, the Organic Act established this technological branch as its own entity, creating the US Bureau of Mines (USBM) (Powell, 1922). USBM was tasked to work as the main scientific agency in the field of technical processes of production and utilization in mineral technology and metallurgy (Powell, 1922).

However, at its inception, the agency was mainly oriented towards improving mining safety, yet its mission was extended in 1913 amid growing demand for mineral resources due to American industrialization and growing demand from Europe's military build-up. The amendment to the Organic Act empowered the USBM to conduct general inquiries and scientific and technologic investigations concerning mining and the preparation, treatment, and utilization of mineral substances (Powell, 1922). The declared goal of the agency was to improve efficiency and conservation in the economic development of the mineral industries (Powell, 1922). Also, the agency was to research the economics of these industries and to disseminate its insights (Powell, 1922).

Through the USBM then, the federal government provided extensive basic science and R&D assistance to the US mining and petroleum industries. The agency worked as a conductor of basic science and publicized its findings widely, as public education and diffusion of scientific and practical insight was a core mission of the agency (Powell, 1922). In this effort, the USBM created a network of experimental stations to conduct practically oriented R&D, comparable to the Agricultural Extension Service discussed above (Powell, 1922). In 1915, Congress authorized the creation of seven mine safety stations and ten mining experiment stations (Powell, 1922). In 1921, there were thirteen experiment stations and twelve field offices of the USBM (Powell, 1922). USBM thus expanded the network between USGS, universities, and mining companies, coordinating the exchange of information, and enabling R&D cooperation through its experiment stations. Moreover, the agency also cooperated with USGS and the National Institute of Standards and Technology to create common standards within the mining and petroleum industries (Powell, 1922).

The reach of USBM's educational activities is best demonstrated by pointing to the circulation of its publications. The USBM produced a variety of annual publications, from reports to technical papers, bulletins, and miners' circulars, reaching considerable circulation, standing at over 800,000 in total in 1920 (also see Figure 10 below). In the same year, the US Census listed roughly 1.1m Americans as employed in the extraction of minerals.

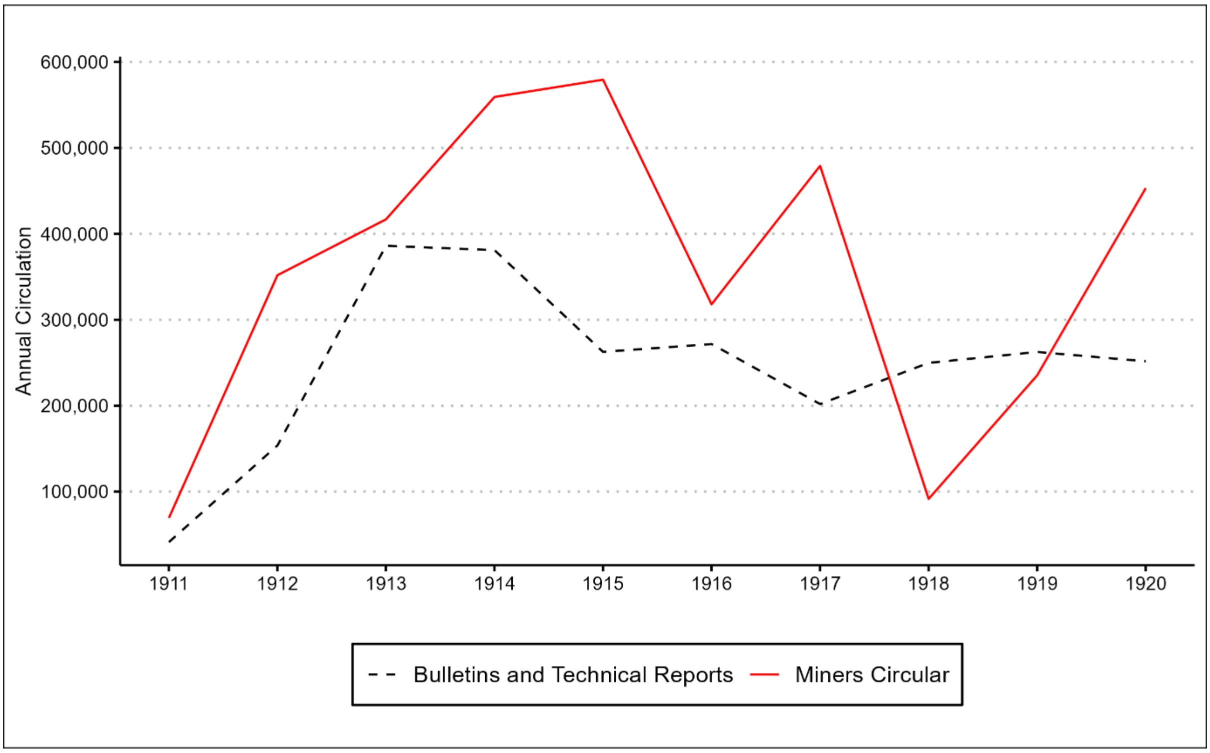

Figure 10: Annual Circulation of Select Bureau of Mines Publications, 1911 - 1920.
Notes: Bulletins and Technical Reports were separate publications dealing with similar subject matter in different formats.
Data Source: Powell, 1922.

Bulletins and technical reports detailed the results of technical and scientific investigations in different formats (Bulletins were more extensive). The miners' circulars dealt with accident prevention and other health and safety measures but also matters concerning the practical work in mines more generally (Powell, 1922). Powell (1922) reports that these circulars were written in widely accessible English and even translated into Italian, Polish, and Slovak. These publications were not free of charge, which given their circulation underscores the widespread interest in the information they contained. Technical reports published by the USBM in 1925 cost 30 cents (the New York Times at the time cost 2 cents). In 1919, the agency published a glossary of "all known terms used in the mining and mineral industry..." (Powell, 1922: 18). There was also an active effort to learn from others, as the Chief Mining Engineer toured European mining methods to report back multiple times (Powell, 1922).

Expansion of Federal Initiatives during WW1 and WW2

A critical turning point for both the American fossil fuel industry and the global use of oil in particular was WW1 (Johnston and McLeish, 2020; Yergin, 2011). In 1914, oil provided just 5% of world energy, while coal accounted for 74% (Clark, 1990). The US emerged as one of the most important explorers, developers, and exporters of oil throughout the European arms and navy race of the early 20th century (David and Wright, 1997). The British Navy switched to oil to propel its fleet in 1910, which allowed its ships to sail farther and faster, while Germany continued to use coal, primarily because Berlin was conscious of import dependencies and possessed no internal access to oil reserves, obsessively following a quest for complete autarky throughout the late 19th and early 20th century (Toprani, 2019). In the same year, President Taft argued in a message to Congress in favor of reserving fuel oil deposits for the Navy (Taft, 1910). In 1912, President Taft established the Naval Petroleum Reserve by executive order. In subsequent executive orders, four further reserves were created, which substantially increased demand for oil.

There were other ways in which WW1 created enormous demand for energy and minerals. German military strategy during WW1 strongly relied on railroads to quickly move troops; a strategy developed during the Franco-Prussian War of 1870 (Hughes, 1989, Yergin, 2011). On the flip side, the French economist Francis Delaisi argued that the Entente's control of oil and their extensive use of gasoline-fuelled trucks had given their armies a decisive logistical advantage. In 1918, Lord Curzon declared during the first post-war Inter-Allied Petroleum Conference "*The Allies floated to victory on a wave of oil.*" (Friedensburg, 1939: 121). This "wave of oil" was primarily supplied by the US as displayed in Figure 11.

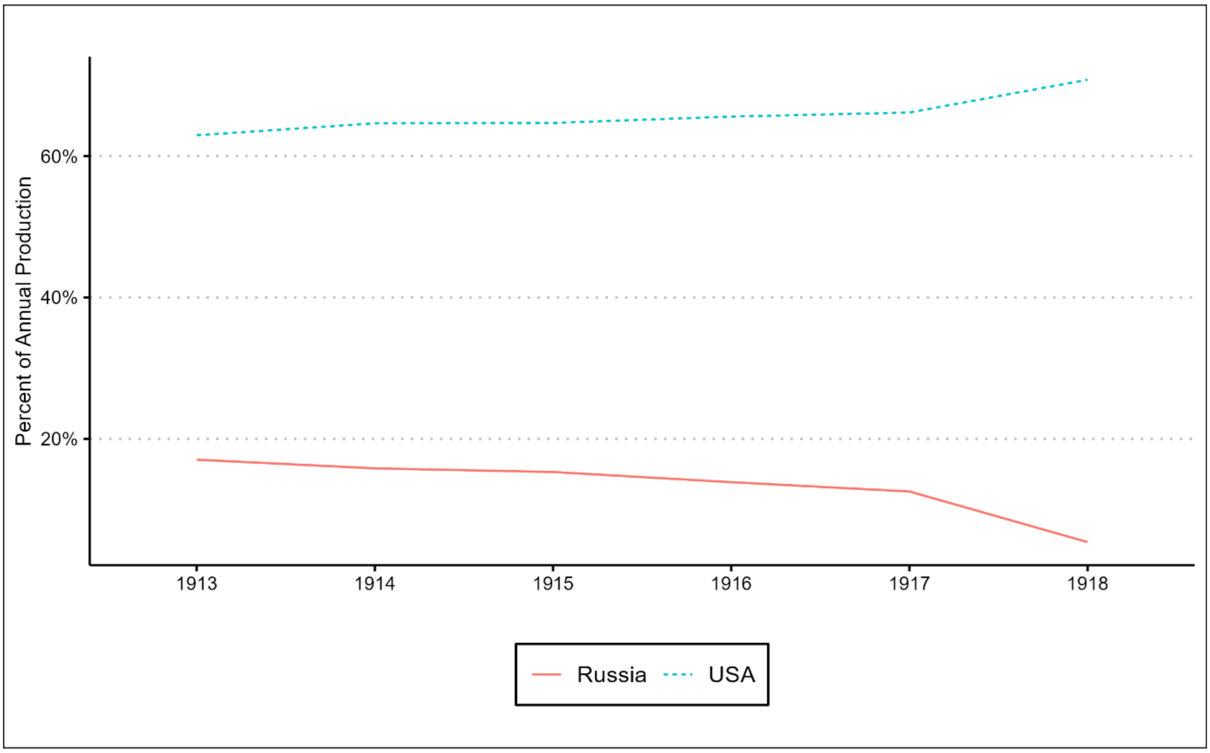

Figure 11: Percent of Annual Oil Production USA and Russia, 1913 – 1918.
Notes: The displayed data relies on annual production figures of British India, Austria-Hungary, Romania, Mexico, the US, and Russia, as well as a category for "other countries".
Data Source: Friedensburg, 1939.

The entire early 20th century saw a dramatic increase in US exports of raw materials as well as manufacturing goods to Europe (Johnston and McLeish, 2020). Europe's military build-up was a major boost to US weapons manufacturers, as well as manufacturers of motor vehicles. Ford exported 7,000 tractors to Britain, and within the US, tractor use also expanded under government loan schemes and public exposition events (see above, Rasmussen, 1991; Conkin, 2008). The number of tanks and armoured cars also saw an increase, which expanded the use of petroleum and did much to facilitate the energy transition from coal to oil[32] (Johnston and McLeish, 2020).

WW1 thus provided the US mineral and oil extraction industries with substantial increases in demand that allowed them to more quickly travel down learning curves that reduced the prices of associated technologies (Johnston and McLeish, 2020). Yet, there was also deliberate federal innovation policy in support of mineral extraction associated with the war. The economic mobilization, although less intense than in Europe, nonetheless significantly extended the influence, especially of the Department of War on the development of the American oil and minerals industry. The increasing demand for military use of oil contributed to the oil crisis of 1917 (Yergin, 2011). Yergin (2011) argues that disruptions in oil supply during 1917 forged closer cooperation between the US and European Allies in coordinating the continuous supply of oil. Moreover, the shortage generated durable efforts to maximize domestic oil production in the US and to improve productivity in the industry through innovation policy.

The activity of the US Geological Survey (USGS) and the US Bureau of Mines (USBM) was expanded during WW1 (Powell, 1922, Rabbitt, 1989). The appropriations for USBM expanded from roughly $1mn in 1917 to $4.7mn in 1918, and $11.8mn in 1919 (Powell, 1922). USGS on its part aided in the mapping of new oil fields (Rabbitt, 1989). There was more extensive R&D cooperation between USBM and USGS, universities, and private companies during and beyond WW1 (Kirk, 1996). Research and diffusion activities related to oil extraction techniques, synthetic fuel production, and fuel efficiency

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[32] The US entered the war late and did not develop a significant tank force compared to European allies. Yet in 1917, after the United States entered World War I, General Patton was sent to France, where he was tasked with learning about the French and British tank operations. Patton arranged for the US to acquire a license from French manufacturer Renault to domestically produce tanks. General Patton thus personally organized the technology transfer from Renault to American manufacturers (Hunnicutt, 1992). This led to the development of the M1917, an American-built version of the Renault FT, overseen by the Army but produced by a variety of private manufacturers (Hunnicutt, 1992).

were begun due to widespread concerns over the sufficiency of existing oil supplies. Due to widespread concerns over the shortage of various minerals as well as oil, USGS even extended its search and development activities beyond the territory of the US, successfully finding adequate supplies for all essential materials in Central and South America, as well as the West Indies (Rabbitt, 1989).

Relatedly, the USBM extended its system of laboratories and experimental stations to study coal, oil, and natural gas (Powell, 1922). These facilities researched improved extraction techniques, developing new uses for fossil fuels, and enhancing safety protocols. Federal investments were also made in infrastructure projects that supported the fossil fuel industry, such as pipelines, railroads, and ports (Kirk, 1996; Breslin, 2010). Federal programs were also initiated to train engineers and technicians in the latest fossil fuel technologies, which ensured a skilled workforce capable of advancing the industry (Breslin, 2010; David and Wright, 1997).

The end of World War 1 saw a dramatic reduction in federal expenditure (Rabbitt, 1989; Powell, 1922). Many skilled scientists that had been employed by various federal agencies during the war left government work and turned towards private industry. Many of those who left the USGS became leading geologists at American oil companies (Rabbitt, 1989). Later developments during the massive mobilization of World War 2 replicated and substantially expanded similar institutional arrangements.

Federal action and investments dramatically raised the knowledge and skills of workers in the American mining, extraction, and refining industries. Federal agencies were engaged in active efforts to aid in exploration and development of minerals and oil, and innovation in related techniques and tools. The massive demand by the US Navy as well as the demand from the Entente powers during WW1 profoundly drove the development of the American fossil fuel industry (Yergin, 2011; Johnston and McLeish, 2020).

Reasons for Federal Action

The initial creation of USGS was mainly driven by the need to obtain elementary information about the lands that the federal government legally held. Yet, it is noteworthy that these federal reports were almost always publicly circulated. There was a widespread view within the federal government that it was proper to provide detailed maps for private prospecting and to diffuse geological knowledge. While this raised the capacity of the federal government to sell public lands and offered new avenues for taxation, a strong emphasis on circulating information likely also made the work of USGS more politically palatable. Both actors within the Department of War and Congress deemed it proper that federal investments in geological mapping should benefit private industry by enabling the more large-scale exploitation of natural resources.

Industrialization and a growing domestic mining industry then created a business lobby for further federal innovation policy. There was growing demand for increasing federal support by metal-mining and coal-mining industries as early as 1896 (Powell, 1922; Rabbitt, 1989). During its annual convention that year, the American Mining Congress first proposed the creation of a federal Department of Mines (Powell, 1922). Subsequently, there were several bills introduced. But it took until 1907 when President Roosevelt proposed the creation of a US Bureau of Mines to be established in the Department of the Interior, after a series of high-profile mining accidents (Powell, 1922). Congress nevertheless took until 1910 to pass the Organic Act.

The 1913 expansion of USBM responsibilities must be seen in context with the growing European military build-up and the expanding need for resources (Hughes, 1989). Subsequent more extensive innovation policy aimed at R&D, and the diffusion of new technologies to raise US mining and petroleum extraction were directly tied to growing war demand.

Given the dramatic success of American mining and petroleum extracting industries and the widespread credit given to USGS and USBM for their work in raising and diffusing practical knowledge, American innovation policy related to fossil fuels must be seen as a success story.

Cases of Failure in US Innovation Policy

Above I presented two cases in which federal innovation policy enabled and manged the successful creation and diffusion of new technologies. Such policies can of course fail in a variety of ways. Political Economists typically think about policy or government failure in a particular way. Inspired by Neoclassical economics, they consider government failure as a situation in which "intervention" into private resource allocation decisions creates a situation that is inefficient compared to what a hypothetical free market would have provided absent transaction costs (Karna, Karlsson, and Engsberg, 2020).

Government action may lack pertinent information which can result in sub-optimal allocation of resources compared to a situation in which better informed private agents make these decisions. Government action might not pursue the goal of maximizing economic returns at all but rather follow political incentives of some kind. And, innovation policy can potentially devolve into rent-seeking, as inefficient industries demand subsidies for their R&D needs or other forms of federal action that are economically inefficient. While these issues are serious, they are competently treated elsewhere (see Karna, Karlsson, and Engsberg, 2020). I want to focus here on different dimensions of innovation policy failure that are more relevant to the issue of clean energy.

I will present below a case in which the American state actively and durably attempted to provide innovation policy with the goal of diffusing a new energy technology, but ultimately failed to successfully achieve this: The case of the civilian use of nuclear energy. This is a case in which federal R&D efforts were largely successful in creating a new technology, but failed to diffuse this technology due to lacking social acceptance and technical shortcomings, which were themselves related to military-motivated R&D.

This case contains elements of rent-seeking or political corruption of sorts. Nuclear physicists derived enormous salaries and career opportunities from the continuation of the Atomic Energy Commission after WW2, which arguably shrouded their judgment, and certainly contributed to their eagerness to pursue the technology[33]. Further, Army General Groves attempted to institutionalize a permanent hold of the Army on off-the-

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[33] See Cooke, 2009 for a more extensive treatment of this argument.

books appropriations for the Manhattan Project after the end of World War 2. He was prevented from doing so by Congress (Cooke, 2009). Nevertheless, I present this case primarily as an illustration of the limits of American innovation policy. The case is particularly instructive, as it shows that even sustained support by federal agencies, including those explicitly tasked with national security objectives, does not guarantee success.

Further, I will present a case of innovation policy that failed to be implemented because the barriers of the American political system could not be overcome despite widespread support and a plausible national security justification. I refer to the case of calls for comprehensive industrial policy aimed at improving the industrial base and innovation capacity of American manufacturing beginning in the late 1970s. While there were sustained, high-profile initiatives aimed at creating such policies in Congress and within the executive branch, this ultimately became a case of innovation policy that failed to be implemented. Together, these cases illustrate the limits and challenges of American innovation policy.

Failure Case 1: Civilian Use of Nuclear Energy

In many ways nuclear energy is one of the best examples of a technology that was only conceivable due to the enormous coordination capacity and financial investments of the American state. No private organization would have undergone the investments necessary to bring atomic science and technology to commercial viability, although its theoretical possibility came into view through advances in physics in the early 20th century. Yet, while the Manhattan Project successfully created an exceptionally destructive weapon[34], subsequent efforts by the Atomic Energy Commission to commercialize civilian uses of nuclear energy largely failed. Private investors remained hesitant, and existing projects relied on extensive public financing support and public insurance against ac-

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[34] Continuations of weapons-related nuclear research later successfully created thermonuclear devices (also known as hydrogen bombs) that release energy through the fusion of isotopes of hydrogen. Subsequent public research projects have attempted to use nuclear fusion instead of fission for the generation of energy. This has periodically led to flurries of private investment into fusion reactor technology, yet no system currently exists that is anywhere close to economically viable energy generation (Smil, 2023).

cident risk. After several high-profile accidents and mounting public and Congressional pressure, the Atomic Energy Agency was disbanded and large numbers of ordered reactors were cancelled.

The failure to commercialize nuclear power can mainly be attributed to technical lock-in resulting from the Navy-informed design decision of pressurized water reactors, persistently large capital requirements, a lack of social acceptance and associated soft costs. While the early 2000s experienced renewed interest in nuclear energy as a potential clean alternative to fossil fuels, only 2 additional atomic reactors have come online in the US since the late 1970s (in 2016 and 2023) and several have been decommissioned which has resulted in a net reduction in their total number (EIA 2024, Figure 12 below).

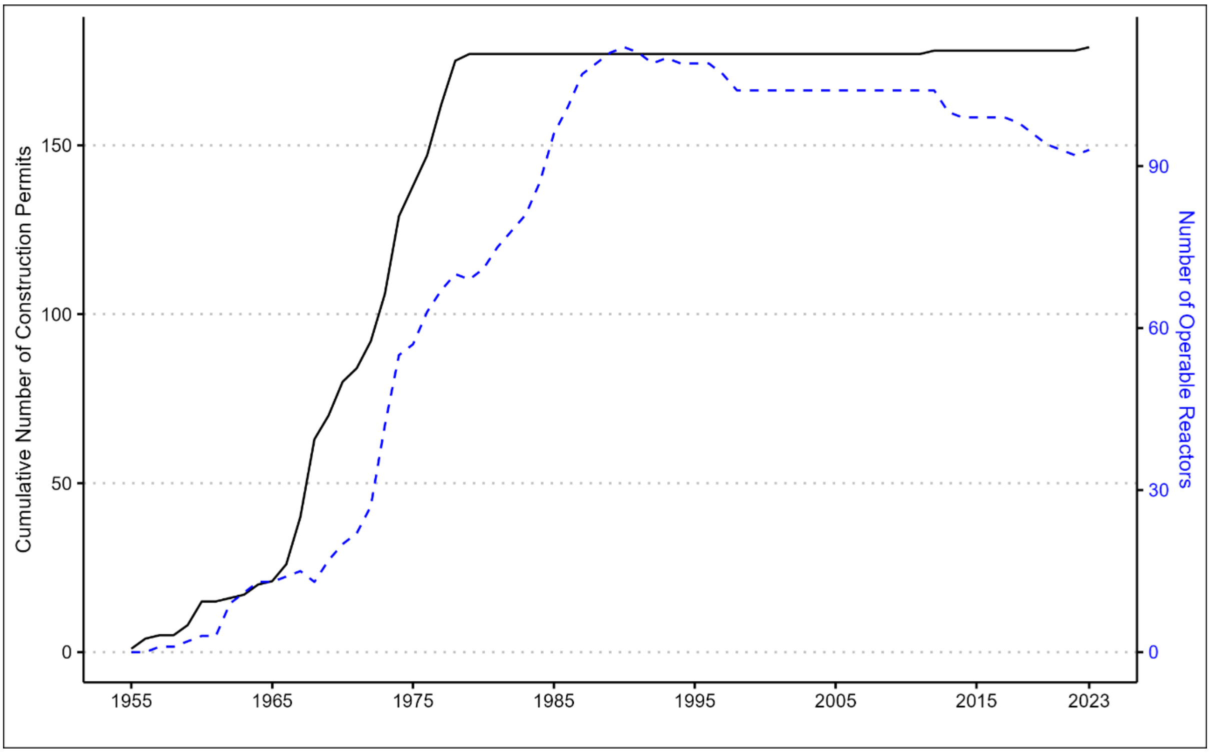

Figure 12: Cumulative Nuclear Construction Permits and Operable Reactors.
Data Source: IEA and Department of Energy.

Southern Company applied for a construction permit for two reactors based on the Westinghouse pressurized water design in 2008 and was granted the first construction permit for a nuclear reactor since 1979. In 2010, the Department of Energy conditionally approved a loan guarantee of $8.3bn to support Southern in this construction project (EIA, 2012). In 2023, the Nuclear Regulatory Commission, a successor institution of the Atomic Energy Commission, granted a construction permit to Kairos Power to build a molten-salt-based nuclear reactor (Zullo, 2023). This was the first non-water-cooled reactor design approved for construction in over 50 years. The Department of Energy contributed $303m in funding to the project, which has mainly been funded by private investors. That said, Oak Ridge National Laboratory and the Tennessee Valley Authority are partnering with Kairos Energy to provide engineering and scientific support (Zullo, 2023). Still, the total number of operating nuclear plants has declined from a peak in 1993 as displayed in the Figure 12.

While initial hopes for nuclear energy were high, and the American state spent inordinate amounts on R&D as well as financing of nuclear reactor projects, nuclear power has remained economically unviable (MacKerron, 1994, Smil, 2023). While some existing nuclear power generation facilities can be considered successful, the technical and social barriers to more widespread adoption of the technology have so far proven to be insurmountable. The recently renewed interest by DOE as well as some utilities and energy startups suggest that the story of atomic energy is not over, yet it remains questionable whether unproven new reactor designs will be able to avoid the fate of previous ones.

Historical Context

In 1938, German scientists Otto Hahn and Fritz Strassman discovered nuclear fission and physicists across the world immediately understood that this nuclear reaction, if directed, could be weaponized (Ruttan, 2006; Rhodes, 2012). Subsequently, most major combatants in WW2 began nuclear research programs (Smil, 2023). Émigré scientists Leo Szilard and Albert Einstein contacted President Roosevelt in 1939 and informed the President about the dangers of a potential German nuclear science program (Ruttan, 2006; Rhodes, 2012). A Presidential Advisory Committee soon after determined that it was theoretically possible to build such a bomb, which led President Roosevelt to direct the Army Corps of Engineers to commence planning a secret nuclear project (Ruttan, 2006; Hewlett and Anderson, 1962). In 1942, the Army Corps of Engineers began to create the Manhattan Project, which would forge an enormous system of scientific, technical, and engineering coordination (Ruttan, 2006; Hughes, 1989). Multiple people have argued that without the war impetus, the Hahn-Strassmann paper would have remained a scientific curiosity, as no private entity would have been willing to foot the bill for the basic science and R&D necessary to create nuclear technology (Ruttan, 2006; Pool, 1997). In retrospect, it has become clear that neither the German, French, nor British nuclear programs would have likely been able to produce a nuclear bomb (Smil, 2023; Cooke, 2009).

It is also inconceivable that anything as momentous as the Manhattan Project would have ever been tolerated by Congress or the Courts outside of wartime (Ruttan, 2006). The Manhattan Project was in fact classified and not under Congressional budgetary control, and in effect under the exclusive control of Army General Groves[35] (Cooke, 2009). At its peak, the Manhattan Project employed 130,000 people at around 20 sites across the entire country (Ruttan, 2006). According to Pool (1997), the manufacturing complex associated with the building of the first nuclear bomb was comparable to the size of the entire US automobile industry at the time. The total cost of the project in 1945 amounted to $2.2bn USD, equalling roughly $35bn USD in 2024 (Buck, 1983).

Civilian Conversion

Even after the immense exothermic capacity of nuclear fission had been demonstrated, first at the Trinity test and then with devastating effects in Hiroshima and Nagasaki, the civilian application of nuclear energy for electricity generation required considerable further government coordination and investment (Cooke, 2009; Buck, 1983; Ruttan, 2006). While General Groves attempted to retain military control of the Man-

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[35] Vice-President Truman was famously unaware of the Manhattan Project until President Roosevelt's death in office.

hattan Project after WW2, Congress, through a proposal from Senator McMahon pushed for civilian control and the establishment of a new federal agency (Cooke, 2009). In 1946, the Atomic Energy Commission (AEC) was created to regulate and develop nuclear technology[36] (Ruttan, 2006; Cooke, 2009). This new federal agency gained control of all laboratories and research facilities that had been built under the Manhattan Project (Ruttan, 2006). While the total appropriations for the Manhattan Project between 1942 – 1945 had amounted to $2.2bn, the Atomic Energy Commission received appropriations of a total of $34bn between 1946 and 1965, and roughly $2.3bn annually between 1966 and 1974 (Buck, 1983). The initial focus of the AEC on organizing the National Laboratories system out of the research facilities of the Manhattan Project, and to expand the exploration and production of uranium (Buck, 1983). It appears that roughly half of the appropriations were invested in ongoing nuclear R&D (Buck, 1983).

The successful Soviet nuclear test in 1949 resulted in the directive by President Truman to "*. . . continue work on all forms of weapons, including the so-called hydrogen or super-bomb.*" (cited in Buck, 1983: 13). Hence, until 1953, the enormous scientific and engineering complex of the American Energy Commission was almost entirely dedicated to the military. However, as early as 1951, a group of engineers from Argonne National Laboratory had successfully produced electricity from an experimental Fast Breeder Reactor (Buck, 1983). Further, the Navy conducted its own reactor program under Admiral Rickover, seeking to create a nuclear reactor engine that would allow submarines to remain submerged for longer periods of time[37](Buck, 1989; Ruttan, 2006).

Nevertheless, early projections by the Atomic Energy Commission suggested that the commercial generation of electricity through nuclear fission would be uneconomical, an assessment that was shared by utility companies (Smil, 2023). Cooke (2009) has

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[36] While this established civilian control over the American nuclear program, the Army and Navy remained heavily involved in nuclear management and research. A side effect of the creation of a civilian Atomic Energy Commission was that the American defense budget was ostensibly reduced substantially while the AEC continued to receive enormous appropriations for nuclear R&D (Cooke, 2009).

[37] The Navy's nuclear program aimed to outfit submarines with both nuclear weapons and nuclear engines, making them essentially invulnerable launchpads for nuclear weapons. These plans emerged early after the creation of the first nuclear weapons (Smil, 2023). The US Navy which had only fully transitioned from sailing ships to coal-fired engines by around 1890, was able to develop the Nautilus nuclear submarine in 1955.

argued that part of the motivation for a civilian nuclear power program came from the need of the American state to justify the ongoing funding for nuclear research in the early Cold War period (also see Friedman, 2000). In the context of American antipathy towards the concentration of federal power and the increasing criticism of federal action by Congress at the time, this assessment is particularly credible (Friedman, 2000). Further, it appears that the physicists that had been associated with the Manhattan project thought that civilian nuclear power could redeem the technology in the public eye and would also guarantee continued federal funding for their own research and careers (Smil, 2023; Cooke, 2009). Thus, to some degree, the continued attempts by the AEC to commercialize nuclear energy technology can be explained by bureaucratic self-justification.

A comprehensive commitment to the civilian use of nuclear energy was articulated in 1953 by President Eisenhower's "Atoms for Peace" speech in front of the United States General Assembly. Likely the most important reason for the interest in commercial use of nuclear fission technology for the American state was the progress by the British and Soviet nuclear programs (Cooke, 2009; Smil, 2023). Due to the close connection between the military and peaceful uses of nuclear technology, the American state felt it was necessary to remain at the cutting edge[38].

Hence, the 1954 Atomic Energy Act established guidelines for the use commercial use of nuclear materials and the creation of related facilities by private actors. The Act also encouraged the use of atomic energy for electricity generation by the private sector, allowing companies to participate in nuclear research and development, organized through a program of technology licensing. At the same time, the Act sought to provide a framework to straddle the commercial use of nuclear energy while implementing measures against military uses (Cooke, 2009).

The chairman of the AEC, Lewis Strauss, was at least publicly highly optimistic

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[38] Both Cooke (2009) and Smil (2023) indirectly suggest interpretations like the one provided here. It is not completely clear where the federal impetus for civilian use of nuclear power in the 1950s came from. Many relevant documents remain classified, and early US research into nuclear energy was shrouded in secrecy. In the 1950s, fossil fuels were cheap and abundant, and environmental concerns would not become politically relevant until the 1970s (Smil, 2023). It might be that American policymakers saw nuclear energy as an alternative to dependence on oil, but there are more likely a large and diverse array of reasons for the American push at civilian conversion.

about the prospects of civilian nuclear power, declaring in 1954 that it would soon become "too cheap to meter" (Poole, 1997). Yet internally there was significant scepticism on the part of AEC scientists (Smil, 2023). The AEC decided to develop a pressurized light-water reactor mainly due to the Navy's decision to develop water-cooled reactor designs to power its submarines and aircraft carriers. The Navy's R&D had made this design the most advanced and readily available and thus cheapest to pursue further[39] (Smil, 2023). In 1957, together with Westinghouse, the first nuclear reactor for commercial power generation was opened. The pressurized water reactor developed by Westinghouse became the industry standard (Cantelon, Hewlett, and Williams, 1991; Ruttan, 2006, Smil, 2023).

The choice of reactors was determined in large part by Navy design preferences rather than economic considerations or technical specifications for civilian use (Smil, 2023; Ruttan, 2006). In fact, no AEC scientists or utility company engineers thought that the Westinghouse design was ideal for commercial electricity generation (Smil, 2023). In a 1954 congressional report, the Westinghouse reactor was ranked as the least promising from a variety of proposed reactor designs for achieving economically competitive nuclear power. The report stated that "*It is clearly of conservative design and has a poor long-term prospect for producing low-cost atomic power*" (Subcommittee on Research and Development, 1954).

Nevertheless, the outwardly expressed opinion within Congress and the AEC at the time was that nuclear technology as such would be improved by the combination of private and public R&D, once initial reactor designs were commercialized (Smil, 2023). Still, utility companies remained hesitant to invest in building expensive nuclear reactors. Utility companies were not mainly concerned with the technical details of the water-cooled reactor design, but rather questioned the economics of nuclear energy in general due to safety concerns (Cooke, 2009). Both contractors and utilities insisted on virtually complete public liability insurance as they argued that the potential risks of accidents

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[39] At this point, it serves to remember Figure 5 on page 16. The water-cooled reactor design appeared closest to commercial viability at the time, given the extensive R&D that had already gone into it. Yet, many scientists at the time already articulated doubts whether this design could ever actually reach commercial viability.

of the new technology were unknown and could very easily surpass even the corporate assets of companies as large as General Electric (Cooke, 2009). Congress aimed to aid the diffusion of nuclear technology through the Price-Anderson Act of 1957, which capped legal liability for all private actors involved in reactor construction and operation (Ruttan, 2006; Cooke, 2009).

In 1963, some utilities came to the assessment that nuclear reactors would generate cheaper electricity than coal-fired power plants (Smil. 2023). Further, Congress passed the Clean Air Act of 1970, regulating the emission of certain environmental pollutants. Together with the oil shock of 1973, it seemed that the economics of nuclear electricity generation had changed sufficiently, and utilities applied for a record number of reactor construction facilities in the same year (Smil, 2023). Excitement also grew about new fast-breeder reactors that would use liquid sodium for cooling and suggested technological learning curves in creating more usable nuclear material promised cost savings (Smil, 2023; Ruttan, 2006). In the late 1960s, the AEC predicted that the US would use over 1,000 nuclear reactors by the year 2000, and General Electric projected that fossil fuels would be phased out by the 1990s (Smil, 2023).

Yet, the anticipated cost savings largely failed to materialize, and ongoing safety concerns led to an escalation of regulatory and other soft costs especially in the late 1970s. Nuclear projects retained large capital requirements and long construction periods, often associated with delays and substantial cost overruns (Smil, 2023; Cooke, 2009). While the number of applications for construction permits had increased in the early 1970s, it declined markedly by the end of the decade.

Energy Reorganization Act of 1974

The AEC was a contentious agency throughout its existence. In the public imagination, nuclear energy remained closely linked with nuclear weapons. In both technical and institutional terms, this was largely accurate (Cooke, 2009). While promoting and organizing the commercial use of nuclear energy, the AEC was also involved in ongoing nuclear tests and military-related research (Buck, 1983). Nuclear energy in general and the AEC in particular thus drew significant public ire during the 1960s and 1970s (Cooke, 2009).

By the early 1960s, reports by the Central Intelligence Agency as well as the AEC itself increasingly problematized the international diffusion of nuclear technology, which had been deliberately started under Eisenhower's Atoms for Peace initiative (Cooke, 2009). Reports stated that it was becoming increasingly easy for countries with access to commercial nuclear technology to enrich uranium sufficiently to build nuclear weapons (Cooke, 2009). Hence, by the 1960s it became clear that the AEC had been too optimistic about the distance between peaceful and military uses of nuclear technology (Cooke, 2009). It is likely that this realization influenced changes in the commercialization goals within both Congress and the AEC[40].

While Congress was generally supportive of the AEC's commercialization efforts, several Representatives and Senators were critical of high AEC budgets throughout the 1960s, and Congress adjusted budget proposals downward in multiple instances (Buck, 1983). Further, by the early 1970s, the AEC's capacity to regulate nuclear energy sufficiently while simultaneously promoting its commercial use was seen as no longer plausible (Cooke, 2009). Through the Energy Reorganization Act of 1974, Congress abolished the AEC, creating the Nuclear Regulatory Commission to oversee safety standards in the industry (Buck, 1983). The Act further provided for the creation of the separate Energy Research and Development Administration tasked with furthering the commercialization of nuclear energy.

The newly founded Nuclear Regulatory Commission (NRC) soon implemented a growing number of siting restrictions and safety standards (Smil, 2023). Some scholars have suggested that these regulations did little to increase the safety of nuclear energy while dramatically increasing its costs (Ruttan, 2006; Smil, 2023), others have suggested that the increased regulatory activity by the NRC betrayed an overly permissive attitude

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[40] It is difficult to assess to what extent the 1974 abolishment of the AEC was driven by national security consideration related to nuclear proliferation. Cooke (2009) suggests this factor might have been the most important one.

by the previous AEC (Cooke, 2009). In any event, few new applications to build nuclear reactors were filed, and many utilities cancelled projects. Emblematic for the fate of the industry, in 1982, the Washington Public Power Supply System walked away from two partially completed nuclear power reactors, after having borrowed and spent \$2.25bn (roughly \$8.5bn in 2023 USD), creating the largest municipal bond default in US history (Pope, 1991). The main reasons for the default were the escalating costs of the project combined with the realization that the Pacific Northwest's energy demand would not grow sufficiently to yield adequate returns in the future (Pope, 1991).

By 1985, nuclear energy was thoroughly discredited in the public eye (Cooke, 2009; Smil, 2023). Forbes magazine's cover story in 1985 read "*The failure of the US nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale. The utility industry has already invested \$125 billion in nuclear power... only the blind, or the biased, can now think that most of the money has been well spent.*" (Cook, 1985). While Cook (1985) framed nuclear as a failure of business, it was in many ways also a failure of the Atomic Energy Commission. In 2020, the Department of Energy estimated that a total of \$109.59bn had been invested in nuclear energy research between 1948 and 2018 in 2019 dollars. These figures do not include public support for loan guarantees, and the enormous public expenditures directed towards cleanup missions in the wake of multiple nuclear plant accidents (Cooke, 2009). Despite these multi-decade efforts by several federal agencies, and the strong connection between the peaceful nuclear power program and national security objectives of the American state, the widespread diffusion of nuclear power ultimately failed.

Reasons for Failure

Despite enormous R&D investments and continuous attempts at commercialization, the American state failed to coordinate a nuclear energy transition. In many ways it was public opinion that rejected nuclear power, or at least demanded safety measures that contributed to making it economically infeasible to scale nuclear power beyond what was achieved (Cooke, 2009; Smil, 2023).

The anti-nuclear movement drew its power from the general anti-authority and anti-military mood that swept the country during the 1960s and 1970s, connected to the Anti-Vietnam protests. Nuclear technology increasingly required surveillance and secrecy in research, and thus became associated with the authoritarian political tendencies that the student movements of the 1960s and 1970s opposed (Cooke, 2009; Kitschelt, 1986).[41] As Friedman (2000) has argued, the Jeffersonian political culture did not tolerate these developments. American activist Jerry Mander argued that "*if you accept nuclear power plants, you also accept a techno-scientific industrial-military elite. Without these people in charge, you could not have nuclear power.*" (quoted in Winner, 1986). Authors like Winner and Mander suggested that nuclear energy required a level of secrecy and technocratic political leadership that was ultimately unacceptable in a Liberal Democracy (Cooke, 2009; Friedman, 2000).

Apart from the political challenges of nuclear energy, there were also major technical and economic hurdles that were never completely overcome (Smil, 2023). Nuclear power has capital requirements, construction times, and ongoing safety requirements that are considerably higher than existing fossil fuel-based energy generation. Further, the AEC was attempting to commercialize nuclear power during a time in which overall demand for electricity was declining due to a combination of slowing population growth, more efficient energy usage, and de-industrialization (Smil, 2023; Pope, 1991). Ultimately, the combination of technical issues, economic barriers, and increasing soft costs related to public acceptance and costs of safety regulation have effectively stopped nuclear development in the US.

Civilian nuclear power is a case that demonstrates the limits of innovation policy in the American political economy. While geostrategic considerations were important factors in driving the civilian nuclear program, and the American state was heavily invested in continuing its pursuit, a combination of technical and economic hurdles, as well as public

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[41] The image of closed and secretive government research laboratories of the Cold War era has become a fixture of American pop culture of sorts, as can be seen in several episodes of the 1950s television series The Twilight Zone, the 1970 movie Colossus: The Forbin Project, as well as more recent productions like Netflix's Stranger Things and Wes Anderson's Asteroid City.

and Congressional opposition ultimately reined in the AEC.

Failure Case 2: The Reich-Magaziner Industrial Policy Push in the 1980/90s

It is difficult to identify dogs that do not bark. Similarly, it is hard to identify cases of innovation policy that were not considered or not implemented, despite a widely perceived need. Yet, failure of federal initiatives in innovation policy has been the norm, making it necessary to illustrate such cases.

In the 1980s and 1990s a group of scholars and political insiders forcefully articulated the need for federal action to ensure American technological competitiveness through a program of industrial policy. Emblematic for this intellectual movement was the 1982 publication of “Minding America’s Business” by Robert Reich and Ira Magaziner. I suggest that the Reich-Magaziner agenda is a case of failed innovation policy that was initially ignored by reluctant Presidents (Reagan and Bush Senior), while a later more enthusiastic President Clinton faced a much more adverse Congress, a large federal budget deficit, and a newly ascendant free-market ideology which resulted again in failure to implement innovation policy.

While the industrial policy agenda was supported by more than just Reich and Magaziner, I will refer to it in this way. I will use this case, as it demonstrates the difficulties inherent in the American polity to implement large federal policy schemes, even when there are considerable and durable efforts that often resonate widely. While the proponents of the Reich-Magaziner agenda pushed for industrial policy, their underlying concerns and much of their suggested program was strongly related to how I have defined innovation policy.

Historical Context

The 1970s were marked by a deteriorating US trade deficit, impressive industrial growth in Japan and Western Europe, and the collapse of the economic frameworks established by the New Deal domestically and the Bretton Woods system globally (Fraser and Gerstle, 1989; Gerstle, 2022; O'Mara, 2019). The 1970s featured the lowest economic growth since the Great Depression. Declines in productivity growth and deindustrialization were increasingly perceived to be the new norm in the American economy (Lichtenstein and Stein, 2023). Historians have described the 1970s as a period of crisis of US confidence which culminated in Jimmy Carter's Malaise speech in 1979 (Gerstle, 2023).[42] While this period in US history is impossible to see outside of the Reaganite "Neoliberal" policy response that succeeded it, the 1970s clearly indicated an exhaustion of the economic model of post-WW2 Keynesianism (Gerstle, 2023). American business and labor organizations were bloated, and close relationships with regulatory agencies resulted in protection from Schumpeterian forces and declining competitiveness. While this assessment was widely shared at the time, there was considerable disagreement about the adequate policy response. While much scholarship has covered the Neoliberal policy turn that was pursued, at the time, an influential group of scholars and political insiders promoted an alternative vision for economic renewal: active industrial policy with a focus on advanced technology (Lichtenstein and Stein, 2023)

This industrial policy debate of the 1980s and 1990s was in important part about challenges related to technological innovation. The continuous reduction of US manufacturing capacity was increasingly seen as a challenge to the innovation capacity of the economy. Cohen and Zysman (1987) argued that the reduction in manufacturing employment showed a failure of American competitiveness with newly innovative Japan and Western Europe. Proponents of industrial policy argued that there was underinvestment by private companies in the domestic industrial base and upgrading of technology, especially expansions in worker education and skill was considered necessary for continued innovation (Piore and Sable, 1981). Further, in the 1970s and 1980s, Japan, Taiwan, and Western Europe were seen as potent alternative models of economic policy in which governments were taking a much more active, or developmental role, allowing these economies to innovate and implement high-tech manufacturing techniques that leveraged well-educated industrial workers (Lichtenstein and Stein, 2023). The propo-

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[42] Carter did not mention the word "malaise" but his speech is nevertheless referred to in this way.

nents of the Reich-Magaziner agenda saw the United States economy at a crossroads and argued that federal policy was necessary to allow for a “high-road” economic growth strategy, based on investments in worker education and skill, to leverage cutting edge technology in industrial production (Lichtenstein and Stein, 2023).

While the Carter Administration passed the Bayh-Dole and Stephensen-Wydler acts in 1980, which I will later argue have been of extraordinary importance in shaping American innovation policy, these policies were not seen as remotely sufficient in meeting the industrial challenge by the promoters of industrial policy at the time.

As late as 1988, there were Congressional reports by the Office of Technology Assessment voicing concerns that the Soviet Union might be catching up technologically (Office of Technology Assessment, 1988). The Congressional report warned that American technological capacity to offset the Soviet convention advantage was increasingly challenged by some of the industrial shortcomings identified by the proponents of industrial policy. In 1989, Foreign Policy Magazine’s Charles Ferguson titled an article “America’s High-Tech Decline” arguing that the US was losing technological ground in semiconductors, computers, robotics, but also smart weapons and electronic warfare. As these reports and articles indicate, the concerns over US innovation were not purely economic in nature, but leading actors within the American state grew concerned about the sputtering American innovation engine. Commentators from within the military repeatedly warned about the slowdown in US innovativeness (see Weiss, 2024 for a summary of these calls). Interestingly, these arguments did not disappear entirely after the fall of the Soviet Union. The National Academy of Sciences has continuously warned about declining standards in US schooling, university education, and US R&D performance (see McNutt, 2024 for the most recent iteration).

The Industrial Policy promoters during this period saw the need to enable American businesses to economically compete. Robert Reich promoted that business should be induced to spend 1.5% of their sales on German-style vocational training for workers. Other proposals included large investments in R&D, education, and the creation of research parks according to the role model of the North Carolina Research Triangle

(Lichtenstein and Stein, 2023).

While the Reagan administration did create an R&D consortium dedicated to semiconductors (SEMATECH), its impact has been widely debated and did not strike contemporary industrial policy advocates as nearly sufficient (O'Mara, 2019). The Reagan administration went so far as to disagree with the very notion of industrial decline (Graham, 1994). Throughout the Reagan and Bush administrations, there were a series of bills introduced by Congress seeking to implement some of the ideas proposed by the Reich-Magaziner camp, including the Industrial Competitiveness Act of 1983, High-Technology Research and Development Act of 1983, the National Industrial Policy Act (1984), and the Industrial Revitalization Act of 1991.

Ultimately though, these initiatives did not result in tangible policies. Presidents Reagan and Bush were disinterested and blocked several initiatives, while President Clinton was much more eager early on in his Presidency, but a changed Congress and business mobilization made implementation of the Reich-Magaziner agenda impossible. By the end of the Clinton presidency, the momentum of the industrial policy agenda had subsided.

Reasons for Failure

The failure of the Reich-Magaziner agenda is in important ways emblematic of the difficulties in passing large federal policy programs in the American political economy (Hacker et al., 2022). While there was significant demand for increased federal initiative, unwilling Presidents were able to dampen Congressional initiatives, and after the 1994 midterm win of the "Gingrich Republicans", the Congressional openness to the Reich-Magaziner agenda was forestalled.

Moreover, the end of the Cold War also saw a dramatic drawdown of defense spending and growing need of existing federal agencies to defend their public worth (Ruttan, 2006). Funding for existing agencies has been under increasing partisan fire since (Negoita, 2015).

Further, the combination of Japanese industrial decline in the late 1980s and the return of robust economic growth in the US economy in the 1990s reduced both the appeal of radical economic reforms and returned confidence in the American economic model (Lichtenstein and Stein, 2023). Finally, the 1990s also saw increasing partisan polarization and a growing difficulty to agree to federal funding bills, in the face of persistently large federal deficits. In combination, these factors made the dramatic changes to federal innovation policy and increasing federal investment along the lines imagined by Reich and Magaziner unlikely.

Compared with some of the cases of success presented above, it might be premature to classify the Reich-Magaziner initiatives as failures. The time for this agenda appears to have come in the late 2010s, as the Trump and Biden administrations have pursued an aggressive industrial policy, in important part justified by rampant IP theft of Chinese companies, the growing geostrategic threat posed that Chinese diplomatic ambition poses to prevailing American national security considerations, but also electoral politics emanating from areas left behind in the de-industrializing American Knowledge Economy (Menaldo and Wittstock, 2024). Magaziner and Reich problematized many of these issues as early as 1982. The Biden administration has proposed a range of policies intended to create new high-technology hubs across the US, invest in science and education, upgrade the national laboratories, expand the role of the NSF and DOE, and to directly support R&D in a range of technologies.

In a 2024 American Affairs article, Weiss (2024) suggests that the 2020s might be a new Sputnik moment, since the Biden administration passed both the Inflation Reduction Act and the Chips and Science Act, suggesting a return of statecraft focused on cultivating American science to create defense industrial advantages. Director of the National Academies of Sciences Marcia McNutt [43] called for a "National Innovation Strategy" in 2024, echoing much of the Reich-Magaziner agenda and similar calls for federal investment in US technological competitiveness by calling for more strategic planning in US innovation policy.

The assessment that the 2020s will be the time for the Reich-Magaziner agenda

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[43] Prof. McNutt was the 15th director of the United States Geological Service (USGS) and is currently the 22nd President of the National Academy of Sciences

remains questionable with respect to investments in science and technology. The curious element of the industrial policy push of the Biden administration has been Congress's relative hesitancy to fund its innovation policy elements. The substantially more ambitious Endless Frontier Act was dramatically curtailed in 2021, and recent spending packages advanced by lawmakers have significantly reduced appropriations for the fundamental R&D provisions of the Chips and Science Act (Hammond, 2021; Mui, 2024). While the Biden administration has clearly prioritized innovation policy, Congress and concerns over the US fiscal position have put curbs on the extent of programs.

The cases of failure in American innovation policy presented here demonstrate the institutional barriers to policy implementation, the general character of American innovation policy, as well as the role played by the coordination of federal agencies, private actors, and universities. Below, I will step back from discussing specific technologies or social challenges and describe the workings of the American innovation system as it exists today more generally.

1.7 The Role of the American State in the Contemporary Innovation System

Especially since WW2, federal policy has played a central role in driving technological innovation in the United States. Most dramatically, the role of the federal government in spurring innovation during the Cold War is widely appreciated (O'Mara, 2019; Weiss, 2014; Mazzucato 2011). Ruttan (2006) emphasizes the catalytic role of military-related R&D for civilian uses of technology, arguing that many technologies currently in use could never have been commercialized without the active efforts of the federal government. Two recent studies of WW2 and Cold War US innovation policy find substantial and long-lasting effects of federal R&D on regional productivity and rates of innovation (Gross and Sampat, 2023; Kantor and Whalley, 2023).

Figure 13 graphs R&D spending as a percentage of GDP conducted by US businesses and the federal government between 1953 and 2021 and shows that R&D as a share of the economy almost doubled between 1953 and 1965.

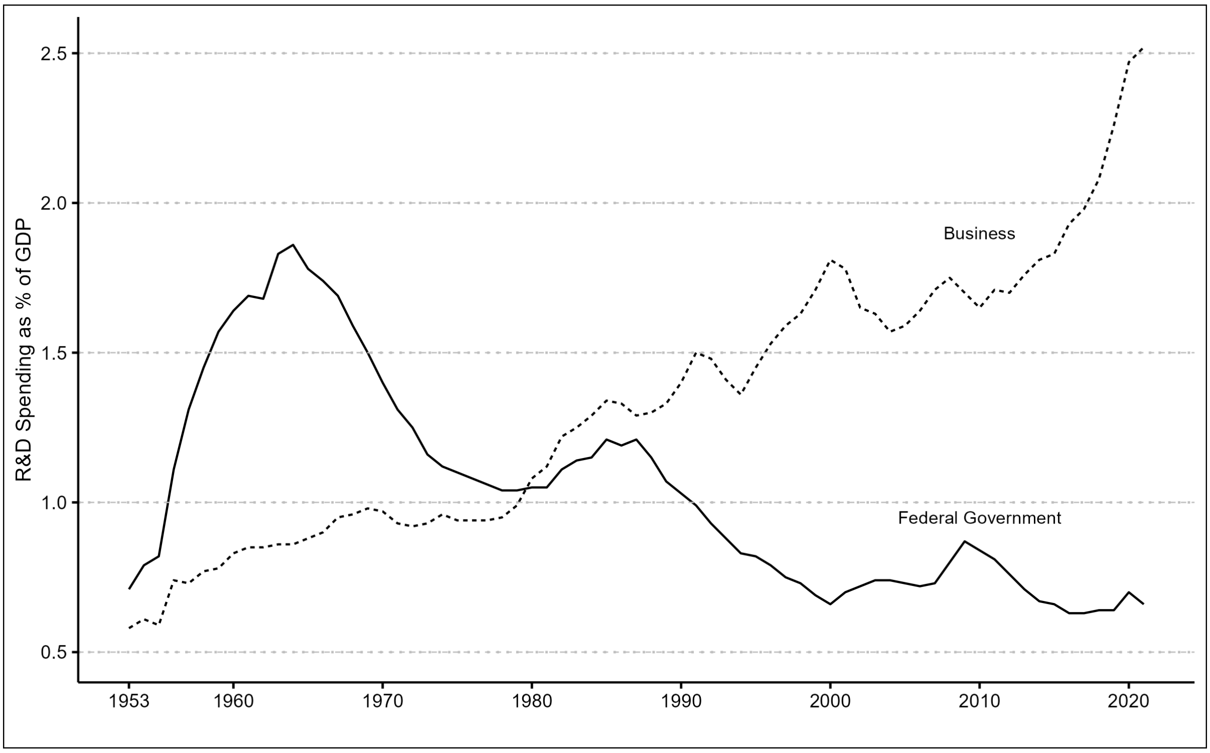

Figure 13: Public Versus Private R&D Spending (%GDP) from 1953 to 2021.
Data Sources: NSF; National Center for Science and Engineering Statistics, National Patterns of R&D Resources; Bureau of Economic Analysis statistics, 2022; Menaldo and Wittstock, 2024.

Private R&D funding surpassed public funding only in 1980. Moreover, World War II considerably reorganized how scientific research in the US was organized, as the federal government became much more directly involved in coordinating science and technology. The federal government became the most important funding source of basic and applied science but also mobilized substantial funds to build scientific installations for government-funded research. This practice was consolidated after the war when several governmental agencies began to coordinate public R&D across the country. The Atomic Energy Commission, which later became the Department of Energy, obtained control of nuclear weapons and conducted related R&D (see section 1.6). The Office of Naval Research, as well as other arms of the Department of Defense, assumed a major role in funding and supporting academic research in the physical sciences (National Academy of Sciences 1995). The National Institutes of Health established control over most health-related research, including biomedical research conducted in universities (Hurt 2015; National Academy of Sciences 1995).[44]

While several recent accounts foreground the role that federal agencies have played in funding R&D and coordinating the commercialization of technologies associated with microchips, biotechnology, and the internet, it is often assumed that the role of federal policy in directing innovation in the American political economy has waned since the end of the Cold War (Mowery, 2012; Dugan and Gabriel, 2013). In part, observers point to the dramatic decline in the relative importance of public R&D, especially after the end of the Cold War (see Figure 2.1). While I do not challenge this notion wholesale, I suggest here that there remain technological areas in which federal agencies have retained their catalytic role in technology development.

A growing literature has stressed the persistent role of US innovation policy in influencing technological, economic, and political outcomes. While government-funded R&D as a percentage of GDP has declined relative to private investment, the size of expenditures as such is not necessarily the best guide to the relative productivity of research efforts. Bloom et al. (2020) demonstrate that inventions and technologies vary dramatically in their importance, suggesting that the productivity of R&D expenditures is far more important than their gross size. Moreover, it remains the case that public actors fund large parts of basic research (Shaikh and Randhawa, 2022). While Figure 13 shows that private actors outspend the US government in recent periods, private actors tend to spend their R&D money systematically differently. Private companies often eschew risky, long-term investments with unclear payoffs (Shaikh and Randhawa, 2022; Wade, 2017; Weiss, 2014, Lazonick, 2007). Arora et al. (2018; 2019) show that private US firms have cut back substantially on investments in basic science and more speculative R&D in recent decades, instead mainly focusing on externally acquiring Intellectual Property (IP) and investing in its commercialization.

Industrial R&D in the US is increasingly organized through networks of firms, universities, industry groups, as well as governmental agencies (Shaikh and Randhawa, 2022; Schrank and Whitford 2009; Mowery, 2009; Chesbrough, 2010). While large, vertically

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[44] This paragraph draws on Menaldo and Wittstock (2024).

integrated companies of the Fordist era housed large corporate R&D labs directly within their corporate structure, contemporary US R&D is typically characterized by smaller, nimbler companies, inter-firm alliances, cross-licensing, joint ventures between public, private, and academic actors, and technology transfer through a robust market in IP (Arora and Gambardella, 2010; Schrank and Whitford, 2009; 2015). This R&D regime is sometimes referred to as "Open Innovation". However, while knowledge spillovers and network effects are common, a crucial feature of this system is the robust protection of IP, which allows knowledge and technology to be traded, enabling the division of innovative labor (Gans and Stern, 2010; Haber and Lamoreaux, 2020). Drawing on a survey of 5000 US manufacturing firms, Arora et al. (2016) find that almost 50% of US manufacturing firms' most important innovations between 2007 - 2009 came from collaborations with external actors like universities, smaller companies, crowdsourcing, or governmental agencies. The contemporary US innovation ecosystem thus takes the form of complex networks between universities, small and large firms, as well as governmental bodies. Within this system, some actors specialize in the production and sale of knowledge and technology, while others primarily focus on commercializing externally acquired IP.

Government-funded basic science plays a central role in this R&D regime. As federal agencies have continued to assume much of the risky investments in basic R&D, this has allowed many firms to buy or otherwise externally obtain promising technologies without ever having to hold risky, long-term investments into speculative R&D endeavors on their books (Arora et. al, 2018; 2019). Thus, while private R&D has indeed outpaced public R&D as a part of GDP since 1980, it is important to note that private R&D spending often follows public investments. In many cases, private actors invest considerable sums to commercialize technologies that have been created and prototyped with substantial aid from the federal government (Weiss, 2014).

Relatedly, while some may point to the American venture capital sector as the source of finance that allows inventors to experiment and quickly scale new technological applications, Janeway (2018) points out that 80% of venture capital returns have been concentrated in ICT and biotechnology, two industries incepted by federal government R&D, but also heavily and durably directed and nurtured by it (Mazzucato, 2013; O'Mara, 2021; Hurt, 2011). The American state continues to be the source of the most risk-tolerant capital (also see Wade, 2017; Weiss, 2014).

In contrast to business, federal agencies are not driven as much by concerns over the economic viability of novel technologies but are rather problem-oriented in their technology investments. As a result, federal agencies continue to be the funders or direct executors of large parts of the most innovative basic research. For example, research teams funded by the Department of Energy, or directly conducted by the National Laboratories overseen by DOE have consistently won between 20-49 of the annual R&D100 awards given out by R&D Magazine between 1999 and 2017.

Hence, US federal agencies continue to be important actors focusing on technology development within the networked US innovation ecosystem. Yet, the influence of federal agencies extends far beyond their intramural R&D investments, as they also exert substantial coordinating power over the activities of other actors. In the following section, I elaborate on the role that federal agencies have assumed in the wider US innovation ecosystem.

Institutions of the Contemporary US Innovation Ecosystem

Key reforms in the 1980s as well as the reduction in defense spending after the Cold War have to some extent reduced the role of the American state in innovation, but federal agencies still play important catalyzing roles.

As mentioned above, the late 1970s featured a re-emergence of debates over American industrial policy[45], not unlike those that are currently ongoing in the 2020s (Gerstle, 2020; Lichtenstein and Stein, 2023). At the time, all important political actors agreed that considerable institutional reform was necessary to reinvigorate the US economy, but there was little agreement on what form such reforms should take. Ultimately, Congress

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[45] For some reason, several authors refer to this as the "first" US industrial policy debate, which seems ahistorical, since national debates as early as the famous battle over the first national bank involving Alexander Hamilton featured major considerations of governmental support for industrialization (see Lind, 2012). Hence, I refer to the "re-emergence" of industrial policy debates.

implemented a series of legislation and programs that aimed at re-enforcing superiority in advanced technology for economic advantage (Block, 2008; Short, 2022). Demands for a comprehensive industrial policy that would have included more centralized planning akin to the Japanese Ministry of International Trade and Industry were forestalled (O'Mara, 2019; Lichtenstein and Stein, 2023; see above). Nonetheless, the reforms referred to here had important impacts on the role played by federal agencies in coordinating technological innovation in the US economy.

Some authors have described this set of reforms as the creation of the institutional structure of the American Knowledge Economy, in which the dominant business model became focused on creating advanced technologies to profit from associated IP (Schwartz, 2019; Short, 2022). In any case, these policy steps institutionalized the contours of the contemporary, networked R&D ecosystem within which the federal government plays a key role as a funding source of basic science and coordinator of other actors within the wider innovation ecosystem. Key reforms to intellectual property enabled federal agencies to effectively transfer technologies to private firms and allowed universities to become more directly involved in managing IP generated through intramural and government-orchestrated research. Further, federal agencies have taken a more active role in working as coordinators between scientists, entrepreneurs, finance, and established private companies, in the effort to commercialize cutting-edge technology and thereby secure the American technological lead in critical technologies and also to generate economic growth (Weiss, 2014; Ruttan. 2006; 2001).

In this effort, Block (2008) argues that DARPA became the paradigm for US technology policy. This model included small offices within federal agencies, staffed with experts who were lenient in supporting technological ideas in line with the mission-critical needs of the agency. Importantly, this support was not limited to financial assistance but also extended to connecting research teams with people working on related problems across other federal agencies, universities, and private companies (Wade, 2017; Block, 2008, Schrank and Whitford, 2009; 2015). Their efforts extended to connecting promising research ideas to outside funding, suppliers, or even potential customers. It is contemporary practice for federal agencies to target specific areas of technological interest with funding, and connect researchers from private, public, and academic sectors, in an active effort to coordinate connections between ideas, resources, and people. This current system was constructed in the late 1970s, as several policies deliberately created a market for knowledge and technology by strengthening IP laws and changing the relationship between federal agencies and their contractors.

In this same period, federal agencies realized that new technologies created in government labs often did not seamlessly move to commercial applications. DoD, DOE, and the National Institutes of Health (NIH) who together comprise most of federal R&D spending, observed that businesses only rarely took up federally created knowledge or technology to find commercial applications (Wade, 2017; Scott and Lodge, 1985). For DoD, private follow-on investment in and development of dual-use technology is a critical source of external R&D investment. In effect, DoD often actively "spins around" technologies, rather than private actors simply "spinning off" civilian uses of military technology (Weiss, 2014). As a result of private investment in dual-use technology, DoD attains cheaper access to technologies that are improved upon by private commercialization efforts (Weiss, 2014; Weiss and Thurbon, 2021). Hence, beyond considerations of innovation policy by the US executive branch, the DoD as a military actor has a vested interest in the private uptake of technology.

The leadership of DOE saw the debates over industrial policy that began in the late 1970s as an opportunity to protect its budget from looming budget cuts by establishing the commercial value of the network of National Laboratories (Block, 2008; Wade, 2017). DOE's budget includes the funding for the system of National Laboratories that grew out of weapons programs of the Cold War (see section 1.6). These installations remain expensive, but in the 1960s costs were spiraling out of control, raising budgetary concerns in Washington. The director of Oak Ridge National Laboratory commented on the spiralling costs asking: "Is Big Science ruining us financially?" (Seidel, 1986: 161). At the time still organized as the Atomic Energy Commission (AEC), the finances of the institution became part of the political debates surrounding declining US productivity growth, and the energy shock of the 1970s. In 1975, the AEC was first transferred into the Energy Research and Development Administration which ultimately became the Department of Energy.

In the 1980s, this new department was given four main missions, related to national security, science, energy, and environmental concerns. The national security mission mainly extended the AEC's role in managing the country's nuclear arsenal (Ruttan, 2006). Notably, the agency was also given a science mission, which saw DOE providing access to universities and industry alike to state-of-the-art scientific facilities. Most of these are organized through the 17 National Laboratories, funded, and overseen by DOE. Further, DOE was tasked with developing new energy technologies to reduce US dependence on Middle Eastern oil. Finally, DOE was tasked to ensure environmentally safe disposal of nuclear material (Ruttan, 2006).

Weiss (2014) argues that these policies were not part of industrial policy or innovation policy per se, but rather should be classified as "economic statecraft" since federal agencies were seeking to boost their access to technology for internal reasons. Yet the 1980s IP legislation and re-organization of federal agencies, especially DOE, must be understood in part as an industrial strategy. For what it's worth, the rationale of the Act focused heavily on economic arguments and was articulated as providing for "*Increased industrial and technological innovation...*" which "*...would reduce trade deficits, stabilize the dollar, increase productivity gains, increase employment, and stabilize prices.*" (15 USC Sec. 3701).

I would aver that the rationale of DOE's science mission especially must be seen in the larger context of initiatives enacted at the time that were at least partly aimed at reinvigorating the US economy through institutional reform aimed at accelerating the production and commercialization of cutting-edge technologies. The reorganization of DOE's extensive scientific budget and installations was to be used to effectively subsidize both university and industry R&D by providing access to facilities that would be uneconomic to build for even large industry conglomerates. Hence, DOE was turned into an enabling entity of the US growth regime built on cutting-edge technology often referred to as the Knowledge Economy (see Short, 2022, Iversen and Soskice, 2019; Schwartz, 2019). This becomes more evident from the additional institutional changes made to how federal agencies interact with universities and industry in conducting R&D projects. Effectively, all federal agencies were re-focused partly on leveraging their R&D investments to generate economic growth (Ruttan, 2006).

Government officials drew inspiration from two success stories of leveraging public R&D for the development of private industries focused on the application of resulting technologies. The Defense Advanced Research Projects Agency's (DARPA) investments in R&D conducted by the Lawrence Livermore National Laboratory and the universities Berkeley and Stanford had allowed the creation of private spin-off firms in the broad ICT sector across the entire Silicon Valley area (O'Mara, 2021; Wade, 2017; Harris, 2023). The US biotechnology industry was seen as a blueprint for how federal agencies could turn universities into business incubators (Hurt, 2011; Wade, 2017). The key reforms that were aimed at using federal R&D to spark industry creation were a set of intellectual property rights reforms related to knowledge and technology: the 1980 Bayh-Dole and Stevenson-Wydler Acts; the Federal Technology Transfer Act of 1986; and the National Competitiveness Technology Transfer Act of 1989.

The Bayh-Dole and Stevenson-Wydler Acts of 1980 changed the relationship between federal agencies and private contractors. Stevenson-Wydler encouraged the network of federal laboratories to increase collaboration with other public, private, and academic actors. Effectively, Stevenson-Wydler made technology transfer part of the mission of all federal agencies (Ruttan, 2006). Technology transfer across research institutions, but also to industry remains a central tenet of this mission to ensure the maturation and deployment of federal discoveries.

As a result, federal agencies today are actively engaged in licensing their technologies to other federal agencies, academia, state, and local governments – and importantly also to industry. To this end, most federal agencies and related National Laboratories have dedicated offices for technology transfer. Between 2003 and 2020, DoD has had on average more than 481 active invention and IP licenses per year, and DOE has had an average of 5303 active invention and IP licenses over the same time frame (National Institute for Standards and Technology, 2020). Further, National Laboratories administered by DoE were incentivized to actively promote their technologies; for instance, laboratories are allowed to take an equity share in the companies that commercialize the results of their research (Block, 2008; Ruttan, 2001).

Further, in fulfilling R&D projects, federal agencies often rely on public-private partnerships with universities or contracting companies. The Bayh-Dole Act secured patent rights for federal contractors to the knowledge and technology created during public-private R&D partnerships. In practice, this has meant that the individuals, firms, or universities conducting federally funded research retain property rights to resulting technology – even though the federal government funded the underlying research.

The explicit intent of these laws was to encourage growth in and sophistication of technology-based business models (Thurk, 2009) and to incentivize private follow-on spending on commercialization, which was often not forthcoming due to legal uncertainties over IP (Stevens, 2001). Before Bayh-Dole, the federal government retained patent and licensing rights in almost all technologies emanating from federally funded research. While federal agencies often attempted to license these inventions, they lacked a legal framework to offer exclusive licenses. As a result, before Bayh-Dole, only 5% of the approximately 28,000 patents held by the federal government had been successfully licensed (GAO, 1998). Companies were unwilling to invest in the commercialization of intellectual property that might be licensed to multiple firms (Stevens, 2001; Payne, 2023). Bayh-Dole changed incentives markedly, by creating the legal framework that allowed federal agencies to grant exclusive licenses to individual firms. The legislation has been widely credited with creating a system in which private investors have legal certainty when investing in the commercialization of technologies based on federally funded IP. In 2002, The Economist magazine argued that Bayh-Dole was "*Possibly the most inspired piece of legislation to be enacted in America over the past half-century ...* ", arguing that "*this single policy measure helped to reverse America's precipitous slide into industrial irrelevance.*"

Bayh-Dole opened a pipeline from federal R&D, through active technology transfer efforts of universities, to private investments in startup formation and commercialization. While private investments are often considerably larger than the initial federal R&D investment underlying any single patent, the federal government is nonetheless the main facilitator of initial technology development by providing highly speculative R&D grants, while private follow-on investment focuses on technology development and commercialization once workable technologies have been identified. Of course, this process often sparks follow-on innovation by private actors as well.

Both the Federal Technology Transfer Act of 1986 and the National Competitiveness Technology Transfer Act of 1989 encouraged federal agencies and national laboratories to enter more public-private R&D partnerships – legally organizing them as Collaborative Research and Development Agreements (CRADAs). The result has been that public-private collaboration on R&D today typically results in the assignment of the developed IP to the contracting entities rather than the funding of a federal agency or National Laboratory. Thus, basic R&D initiated, coordinated, and funded by federal agencies intentionally spins out IP to private entities which are further encouraged to invest in their commercialization. According to data from the National Institute of Standards and Technology, DOE has, on average, been involved in 773 active CRADAs per calendar year between 2003 and 2020. DoD has on average been involved in over 3310 active CRADAs per year over the same time frame.

Encouraged to commercialize their patent portfolios, federal agencies also collaborate on major demonstration projects and are in active conversation with other agencies, universities, and private financiers to lower private investment risk in commercializing their inventions. To this end, federal agencies like DOE, NIH, and DoD offer funds to commercialize technology, and DOE operates a large loan guarantee program. Further, in 1982, the Small Business Administration (SBA) program was created to provide funding for start-ups seeking to commercialize technology emanating from federal research. This program is funded from the R&D budgets of participating federal agencies and regularly connects university researchers with entrepreneurs to commercialize federal research outputs. SBIR aimed to stimulate technological innovation, meet federal research and development needs and increase the commercialization of innovations derived from federal research. As a result, the SBIR program helps bridge the gap between basic science and commercialization and often complements venture capital by de-risking early-stage technology.

In combination, these reforms substantially reshaped both the mission of federal agencies and their means of engagement with industry and universities. Universities themselves transformed. At least since the late 1970s, the American University has developed into an incubator of new firms and efforts to commercialize technologies emanating from university research (Etzkowitz, 2003). The rise of the US biotech industry since the late 1970s is the most extreme example of this dynamic. Academic departments across the country developed close ties with biotech firms in their regions, and academics were often encouraged to become entrepreneurs or part owners themselves (Vallas, Kleinman, and Biscotti, 2011; Powell, Koput, and Smith-Doerr, 1996). Major research universities today commonly feature technology transfer offices, staffed with lawyers and administrators who aid academic inventors in securing patents, negotiating contracts with firms for technology transfer, or aiding in creating joint ventures (Owen-Smith, 2003). Importantly, universities also remain key executors of federal research. For example, between 2000 – 2022, almost 50% of all patents related to solar energy technologies granted to universities were based on R&D funded by federal agencies. A sample of 550 of some of the largest US research universities shows that on average more than 60% of the R&D dollars spent between 2000 – 2022 were based on federal funding (Association of University Technology Managers, 2022).

Thus, the 1980s featured a set of policy changes that altered the interaction between federal agencies, universities, and private companies in R&D. As a result of the combined effect of these reforms, federal agencies today are in a central position in the American innovation ecosystem. Federal agencies provide crucial basic research but also provide the expertise and scientific installations necessary for universities and industry to carry out similar work. Further, through CRADAs, federal R&D initiatives typically assign IP over resulting knowledge to private actors, thereby enabling firms to commercialize new technologies. Further, federal agencies are actively engaged in coordinating networks of public, private, and academic researchers on specific issues, and incentivizing the private commercialization of technology through a variety of instruments. Contemporary technological innovation in the US continues to be importantly guided and coordinated by a network of federal agencies, associated federal laboratories, technology transfer offices, universities, and private companies carrying out publicly funded R&D (see Block and Keller, 2015; Weiss, 2014; Brenitz, 2021).

1.8 Discussion and Conclusion

Technological innovation faces a variety of practical challenges. Clean energy innovation in the context of cheap fossil fuel energy is especially unlikely to be adequately provided by profit-oriented private companies. Scholars within the environmental policy literature have proposed several public policy approaches to meeting the challenges of technological innovation in clean energy. In the United States, there have been relatively few successful federal initiatives to raise the price of using fossil fuels. Yet, American inventors have produced considerable numbers of inventions in clean energy technology.

In the American political economy, there are multiple political veto points for federal policy action, which represent considerable institutional barriers to the federal implementation of innovation policy. I have argued that these barriers have historically been overcome most often in the context of enduring socio-economic challenges or wars. Yet, I have also argued that even when crises provide political openings to implement federal innovation policy, the institutional configuration of the American polity strongly influences and disciplines American innovation policy. I have explained how this has given rise to a distinctly American form of innovation policy, in which federal agencies mainly work to coordinate the actions of firms and universities in a heavily decentralized manner.

The historical case studies of American innovation policy I have provided should also impress upon the reader that it is rarely possible to point to single policy initiatives implemented at a district juncture to describe how the American state has historically solved market failures related to technological innovation. These tend to be long efforts, proceeding in fits and starts, and blurred responsibilities between federal agencies. In the following Chapter, I return to the question of federal innovation policy in the case of clean energy.

Chapter 2: Clean Energy Innovation as a National Security Mission

2.1 Introduction

In August of 2022, President Biden signed the Inflation Reduction Act, which, despite its misleading name, represented the "*single largest investment in climate and energy in American history*" (White House, 2022). One intended goal was to ensure the American position as a world leader in clean energy through active industrial policy favoring the domestic production of electric vehicles, advanced batteries, and other clean energy technologies.

One month later, national security advisor Jake Sullivan declared clean energy technology to be an industry of central national security interest and that leadership in clean energy technology was a national security imperative. According to Sullivan, clean energy had the potential to ensure US energy independence and security and would act as a crucial "*force multiplier*". The year 2022 thus appears to mark a decisive break in US foreign economic policy on multiple fronts. The Biden administration has implemented explicit industrial policy of a scale unthinkable just a few years ago. The IRA is also seen as a breakthrough in federal climate policy. Yet, the strategic focus of the American state on clean energy technology, which was made explicit in 2022, has a much longer history.

The main claim advanced in this Chapter is that federal innovation policy implemented in the late 2000s is a major, albeit underappreciated reason for the continuing innovative performance of US actors in clean energy technologies. I show that federal agencies are central actors within the US clean energy innovation network. Federal agencies fund highly influential R&D and amplify the innovative performance of private companies and universities through public-private partnerships.

Clean energy innovation policies implemented in the early and mid-2000s have been strongly in line with the historical character of American innovation policy outlined in Chapter 1. Recurring energy crises and military demand for energy technology drove innovation policy during the Bush administration. At the same time, federal policy generally eschewed policies that would have directly regulated the use of harmful technologies, instead focusing heavily on investing in providing technological alternatives through federal R&D. In doing so, federal agencies leveraged a decentralized research network including firms and universities. An economic crisis, the Great Recession of 2008, enabled the Obama administration to pass considerable expansions of federal R&D and technology diffusion efforts.

Importantly, I argue that rather than concern over the adverse environmental effects of fossil fuels, US clean energy innovation policy has in large part been motivated by concerns over energy security and energy-related military-strategic concerns of the Department of Defense. I show that the Department of Defense was a crucial actor pushing for federal investment in clean energy technology, and committed to supporting technological development internally, as well as in coordination with the Department of Energy. In turn, the Department of Energy has been a key actor in driving and coordinating US innovation in clean energy.

Below, I turn to the historical record to outline how clean energy technology became a part of federal efforts to ensure the energy security and operational capacity of the Department of Defense (DoD) in the early 2000s. I discuss the main programs and mechanisms through which federal agencies have influenced R&D and technology commercialization in clean energy.

I additionally make several empirical contributions in this Chapter. I create and use network data gleaned from patents granted by the USPTO to show that US innovation has strongly relied on funding in basic science and R&D conducted by DOE and DoD in the 2000s. While those agencies' inventions in the 1960s - 1980s were path-defining, even recent inventive steps have strongly relied on R&D conducted, financed, and/or organized by federal agencies.

Further, I use company-level patenting information to estimate the effect of R&D cooperation between private firms and federal agencies on the level of private follow-on innovation. I find that R&D collaboration significantly and substantially raises private follow-on innovation.

Through tracing the considerable impact that deliberate federal innovation policy has had on US innovation in clean energy technology, this study qualifies the notion of the United States as a climate policy laggard. Federal innovation policy has actively pursued the creation of alternative energy technologies. Crucial pieces of this strategy were put in place in the 1970s and 1980s, but the Bush administration in the 2000s clearly thought to leverage and expand federal capacity in science and technology to accelerate clean energy innovation. These initiatives were significantly expanded under the Obama administration. Yet, innovation policy in this area has strongly relied on investments in basic science and R&D, as well as some subsidization of new technologies. There have been comparably few attempts to actively phase out fossil fuels, policies which environmental policy scholars have traditionally focused on.

This study also interrogates the actions and preferences of federal agencies and the role they play in generating and channeling technological innovation. In doing so, this Chapter also relates to contemporary accounts of the American Knowledge Economy, which generally argue that successive legislation beginning in the 1980s created an environment that foregrounded investment in intellectual property (IP) as a corporate business strategy (Schwartz, 2020; Short, 2023; Pistor, 2019). Short (2022) argues that political efforts at increasing the federal government's ability to steer this process have been underdeveloped. I argue here that federal agencies, and especially DoD, are themselves key interest groups who demand investment in technological innovation, and themselves act as crucial drivers of technological development. I demonstrate here that the demand of federal agencies to meet their own mission needs continues to play an important role in influencing federal support for technological innovation and has important downstream effects on the direction of innovation in the American political economy (see Weiss, 2014). US military goals and national security considerations continue to have a substantial impact on the intensity and direction of innovation. The US executive branch and the federal agencies that comprise it retain considerable coordinating capacity over a network of private actors and universities and have actively influenced basic science and R&D related to clean energy technology in ways reminiscent of historical technology policy initiatives implemented by the American state and discussed in Chapter 1.

This Chapter proceeds as follows: Section 2 will trace the early institutional history of US clean energy innovation. Section 3 will present the argument that federal policies were key in generating technological advancements that are currently enabling the global clean energy transition. Section 4 will empirically demonstrate the central position of federal agencies in US clean energy innovation by leveraging network data gleaned from patent citations. Further, Section 5 presents firm-level evidence of the innovation-boosting effect of public R&D investments. Section 6 concludes.

2.2 Federal R&D and Clean Energy

Many of the mature clean energy technologies currently employed across the globe were invented or considerably advanced by the R&D efforts of the US federal government (Nemet, 2019; Nahm, 2021). At several points throughout the second half of the 20th century, energy security considerations animated federal investment in R&D related to energy alternatives.

The 1970s oil shocks animated US policymakers and Presidents to build and expand on a set of key federal institutions to improve American energy security. Some of the institutional infrastructure of US innovation policy, like the modern configuration of the Department of Energy, were created during that time. Nonetheless, as I shall argue below, more recent developments, specifically in the 2000s, have been critical in fully utilizing this infrastructure to generate recent innovation in clean energy. Fears over long-term US energy security flared up during the Bush administration in the early 2000s, importantly because the DoD became a major source of demand for alternative energy technology. This resulted in several key initiatives – notably ARPA-E, the Energy Frontier Research Centers, the SunShot initiative, as well as closer energy-research cooperation between DoD and DOE. Below, I trace important pieces of historical developments that sparked the creation of US institutions that implemented major R&D initiatives to generate innovation in clean energy in the 2000s.

1970s Energy Crisis

During the first oil shock in 1973, the US pioneered deliberate innovation policy aimed at advancing technological alternatives to fossil fuels (Hansen et al., 2019). The oil embargo caused dramatic energy price increases – sparking multiple policy initiatives seeking to reduce US dependence on fossil fuel imports. President Nixon launched *Project Independence* aiming to achieve energy self-sufficiency in late 1973. Invoking the Manhattan Project, Nixon declared that American capacities in science and technology would be the ideal vehicle to end dependence on foreign oil (Hansen et al., 2019). Faced with the signal that existing energy carriers may not remain reliable, the US government thus acted as an investor without concern for immediate or even medium-term economic returns on investment in R&D (Janeway, 2018). The decision to invest substantial amounts in uncertain technologies was driven by geostrategic as well as political concerns, rather than expectations of being able to realize economic returns on these technology investments any time soon.

One of the first initiatives was the enactment of the Solar Photovoltaic Energy Research, Development, and Demonstration Act of 1974, which created the first sizable research program for solar energy with expenditures of $1 billion (plus another $1.5 billion in the 1978 act) with a focus on basic research and broader R&D (West, 2014). The silicon photocell used in solar PV was invented by Bell Labs in the 1950s and commercialized towards the aerospace market, NASA was an important customer of First Resort (West, 2014). Modern solar energy's first applications thus were already tied to the US innovation ecosystem institutionalized throughout the Cold War. In 1955, the US Army funded the R&D underlying US patent 2711379, which described a "Method of Controlling the Impurities in Semiconducting Materials", which signified an important step in improving the performance and efficiency of solar cells.[46] In 1977, The Energy Research and Development Administration established the Solar Energy Research Institute (SERI)

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[46] Other important foundational patents funded by the federal government include the 1958 Air-Force funded patent US2844640, describing a Cadmium Sulfide Barrier Layer Cell, and the 1960 patent US2944165, describing a "Semiconductive Device Powered by Light", funded and assigned to the US Air Force (see SERI, 1986). Also, in 1960, patent US2962539, describing a "Solar Cell Array" was assigned to the US Army.

in Golden, Colorado. This would later become the National Renewable Energy Laboratory (NREL) in 1991 – becoming part of the network of federal laboratories overseen by the Department of Energy. Beginning in 1991, NREL led an R&D grants program that funded promising research in energy alternatives.

NASA additionally led the Low-Cost Silicon Solar Array project in which the US government spent $235 million from 1975 to 1986. NASA itself was granted several important patents in solar energy technology which contributed decisively to the technology.[47]This first public-private partnership in clean energy technology R&D coordinated efforts by universities and industry but was administered by the NASA Jet Propulsion Laboratory (another National Laboratory) which had experience with space applications and ties to the aerospace industry (West, 2014, Knight, 2011).

In 1977, President Ford folded the Energy Research and Development Administration (created in 1974) into the newly established Department of Energy which would also control all federal nuclear sites (Ruttan, 2006). The Energy Research and Development Administration led a major R&D push into alternative energy technologies after its creation, also venturing into electric vehicles, which had been advanced by NASA (Buck, 1982). Within DOE, the Office of Energy Efficiency and Renewable Energy (EERE) was formed in 1981 to pursue the explicit mission to fund ground-breaking research and development in alternative energy technologies, demonstrate their capacity, and aid in wider deployment.

In addition to creating an infrastructure of federal research installations that were at least partly focused on RD in energy alternatives, the bipartisan agreement also funded considerable RD delivered through large government contractors from the aerospace, energy, and defense sectors (Righter, 1996).

Despite being willing to invest in alternatives during this period, US policymakers remained most optimistic about nuclear energy becoming the main substitute for fossil fuels (see section 1.6 in Chapter 1). Further, most efforts related to energy alternatives

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[47] One example is the patent US4040867A granted in 1976 for a Solar Cell Shingle, which describes a shingle that arranges solar cells in an overlapping manner which maximizes the surface area exposed to sunlight while maintaining the integrity of the roof. In 1977, the Energy Research and Development Administration was granted US4002499 for a "Radiant Energy Collector"

focused on the research and development of new technologies, leveraging and expanding the expertise of the federal laboratory system.

These early efforts largely neglected to create demand-pull policies that may foster R&D by private actors. That said, the National Energy Conservation Act of 1978 included Congressional mandates on all federal agencies to promote conservation, efficiency, and the development of renewable energy sources, seeking to create demand for energy alternatives. In 1970, Congress passed the Clean Air Act, regulating the emission of air pollution.

However, despite relatively short periods of high oil prices, renewable energy technologies at the time were generally not price competitive. It appeared that US policymakers concluded that expensive investments in basic research and development of clean energy technologies were necessary before enacting policies that would force utilities to buy clean energy or to enact policies penalizing the use of fossil fuels.[48] Given that US industry and consumers were already experiencing substantial energy price increases, such policy avenues would have been both politically unappealing and likely would have prolonged energy price increases.

As oil prices increased again in 1979, then President Carter signed the Energy Security Act of 1980, which consisted of six separate acts incentivizing the production and uptake of synthetic fuels, biofuels, solar energy, geothermal energy, marine energy, and other renewable technologies. After the Three Mile Island nuclear meltdown in 1979, confidence in nuclear energy had waned (see section 1.6 in Chapter 1). The consequent reduction in the federal interest in nuclear energy was also driven by the stubbornly high soft costs associated with this energy source (Ruttan, 2006, see section 1.6).

Yet, after the election of Ronald Reagan, oil prices decreased substantially for the first time since 1973. In the effort to remove many of the price controls implemented under previous administrations, Reagan also removed several federal support projects for

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[48] Forcing utilities to buy electricity from more expensive energy sources raises the price of electricity, possibly considerably so. At the time, the conversion efficiency of solar energy for example was dramatically lower than it is today, and the technology did not benefit from economies of scale in panel manufacturing that have been achieved by Chinese manufacturers (Nahm, 2021). As recently as 2010, the price per Mwh of solar energy stood at $359 compared to coal with $111 (Nemet, 2019).

renewable energy implemented by the Carter administration. Reagan's relative neglect of federal efforts in sparking a new industry led to a decline in the fledging US renewable sector, seeing many ventures go out of business, as the technology proved economically unsustainable in a cheap oil market (West, 2014; Nahm, 2021). A key challenge in coordinating both governmental and private actors in developing and commercializing alternative energy technologies was that fossil fuel prices were not consistently high, but rather quite low, punctuated with short-lived spikes. (Congressional Research Service, 2004). Periods of stable oil prices created uncertainty for private investment in renewable energy, while public and Congressional opposition to the costs of new public programs was most pronounced during long phases of low fossil fuel energy prices (Congressional Research Service, 2004).

Hence, throughout the period after the 1973 oil shocks until the early 1990s, R&D funding by the federal government enabled dramatic increases in the efficiency of solar PV cells and reductions in the price of wind turbine installations (Loferski, 1993). US inventors were considerably more innovative than their Japanese or German counterparts throughout this period (see Figure 1, page 8) and the US federal government spent more on clean energy R&D than Japan or Germany (Clark, 2018). However, federal support was limited and there was little sustained effort throughout the 1980s and 1990s at funding and coordinating R&D in renewable energy or to commercialize technologies after the initial forays. The Reagan administration reduced funding for The Solar Energy Research Institute (SERI), but R&D conducted by the national laboratories nonetheless laid the foundation for many of the currently relatively mature technologies (Nahm, 2021). Federal support for renewable energy did not increase substantially throughout the 1990s, but federal laboratories still made breakthrough inventions in this period, especially in solar energy (Knight, 2011).[49]

In 1991, SERI's mandate was considerably broadened and transformed into the

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[49] Some examples of highly cited patents US5460660 for an apparatus encapsulating a photovoltaic module, filed by Photon Energy IC (R&D funded by DOE). The 1982 patent US4409424 describing a "Compensated amorphous silicon solar cell", was granted to DOE; the 1982 US4409423 was assigned to the US Air Force for a "Hole Matrix vertical junction solar cell", providing a vertical junction solar cell that improved the utilization of light.

National Renewable Energy Laboratory (NREL). In 1993, NREL established the National Wind Technology Center in Boulder, CO, providing technology testbeds, demonstration sites, as well as training programs (Nahm, 2021).

After the relative decline of federal support through the 1990s, the 2000s featured a dramatic increase in federal support for innovation in US clean energy technology, which was in important part motivated by heightened concerns over energy security. Figure 14 shows the initial increase in federal R&D investment in clean energy (including nuclear and energy efficiency spending) during the late 1970s, as well as their stark decline throughout the 1980s. Federal investment in alternative energy R&D as a percentage of GDP would only increase again in the mid-2000s.

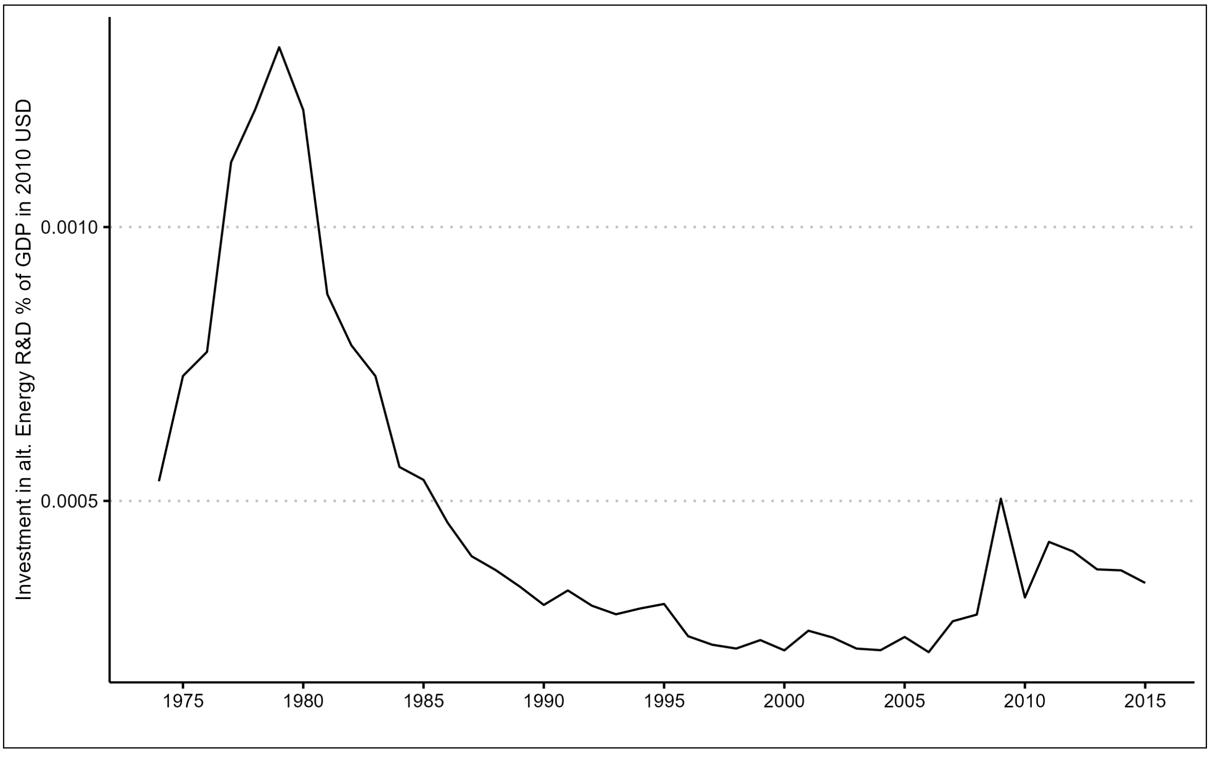

Figure 14: Federal R&D Investment in Alternative Energy Technologies (% GDP), 1974 - 2015

Notes: This estimate includes R&D spending on Nuclear Energy and Energy Efficiency. Dollar values are expressed in 2021 USD.
Data Source: International Energy Agency

In the late 1990s, oil and energy prices in the US increased significantly for the fourth time since 1973 (Congressional Research Service, 2004). This re-ignited earlier debates about the adequacy of accessible energy supplies and raised calls for federal action by President Bush to provide price relief to citizens, but also to deliver a long-term plan to secure energy needs (Congressional Research Service, 2004). The political urgency and salience of US energy security were further amplified by the 2001 and 2003 invasions of Afghanistan and Iraq. The Department of Defense (DoD) is the single largest institutional consumer of fossil fuels and has consistently accounted for over 80% of US government energy consumption and approximately 1% of total American energy consumption (Department of Energy 2020, Crawford, 2019; 2022). As a result, access to affordable energy is critical for US military capacity and of acute concern to DoD leadership (DoD, 2010; 2014).

High energy prices during the early 2000s drove the Bush administration to pursue its strategy of “Energy Security for the 21st Century” (White House, Bush Website). Technological innovation in energy alternatives, energy efficiency, and alternative fuels, was a cornerstone of this energy strategy – and aimed at reducing dependence on energy imports (White House, 2007). President Bush’s energy strategy explicitly fused the goals of confronting climate change and improving energy security through energy supply diversification. Thus, the Bush administration began to considerably increase the utilization of the federal innovation infrastructure built after 1973 to the end of developing and delivering technological improvements in clean energy.

2.3 The Department of Defense and Clean Energy

Throughout the 2000s, key decision-makers within DoD assessed that energy alternatives would improve the military capacity and resiliency of its branches (DoD, 2010). Continued reliance on fossil fuels was increasingly seen as a cost burden as well as a strategic handicap. DoD also came to understand that independent, renewable sources of power and microgrids for military installations would improve facilities’ resilience against natural disasters and foreign sabotage (DoD, 2010). As a result, DoD became an important source of demand for energy alternatives and specific applications using solar, wind, and energy storage technologies.

In 2003, then-Lieutenant General Jim Mattis, who later served as Secretary of Defense from 2017 to 2019 under the Trump administration, proclaimed that US military forces must "be unleashed from the tether of fuel" (Lynn, 2017), realizing the operational liability imposed on US military forces by being solely reliant on fossil fuels. Between fiscal years 2003-2007, more than 3,000 Army personnel contractors were wounded or killed in action because of attacks on fuel and water resupply convoys (Weiss, 2014). In 2006, Marine Corps General Zilmer sent a resource request to the Pentagon for a "*renewable and self-sustainable energy solution ... to augment our use of fossil fuels with renewable energy, such as photovoltaic solar panels and wind turbines*" (Weiss, 2014).

Partly in reaction to this plea, the Undersecretary of Defense for Acquisition and Sustainment directed the Defense Science Board to create a task force to examine DoD's Energy Strategy. Citing significant risks to national security and DoD's operational capacity, the Undersecretary was seeking to reduce DoD's energy demand, identify related obstacles, and assess potential commercial and security benefits associated with different solutions (Weiss, 2014). In February 2008, the Defense Science Board Task Force on DoD Energy Strategy published its report finding that "*It is unlikely that energy efficiency has a higher value to any other organization in the country, possibly the world.*" (DoD Energy Strategy, 2008: 36). The report's key finding was that DoD could dramatically improve the security and resilience of its installations by investing in alternative energy technologies, which would reduce DoD energy consumption and allow powering of installations through a blend of new technologies on-site. The Defense Science Board was also cognizant of the potential wider economic impact their actions would have, stating that "*If DoD were to invest in technologies that improved efficiency. . . , it would probably become a technology incubator and provide mature technologies to the marketplace for industry to adopt for commercial purposes*" (DoD Energy Strategy, 2008: 36).

The Center for Naval Analyses (CNA) military advisory board issued a report in 2009 concluding that integrating energy security and climate change goals into national security and military planning processes was of the highest priority. The report also made detailed recommendations for DoD to reduce its energy use, to "*aggressively pursue energy* *efficiency, smart grid technologies, and electrification of its vehicle fleet.*" (CNA, 2009). Further, the CNA advised DoD to expand the adoption of distributed and renewable energy generation at its installations (CNA, 2009). In the same year, the Defense Logistics Agency's mission which manages the US global defense supply chain was expanded to incorporate the areas of renewable and alternative energy sources. DLA Energy's business units have since pursued solar power, hydrogen power, synthetic fuels, and other alternative fuels and renewable energy sources through new procurement, research, and development initiatives (DLA, 2010).

The 2010 Quadrennial Defense Review articulated energy security as a national security priority for the first time (DoD, 2010). The Defense Review also stated explicitly how the DoD expected climate change would affect the international strategic environment (also see Crawford, 2022). The report stressed that the current energy demands of the agency were too high, and that business-as-usual could imperil strategic capacity in the future (DoD, 2010). Subsequently, all major branches of DoD set ambitious climate targets (Crawford, 2022). In 2010, the Department of the Army published its Net Zero Initiative, committing to using 100% carbon-pollution-free electricity at its installations by 2030. Further, the Army declared that it would install a microgrid on every installation by 2035, including renewable energy generation and large-scale battery storage (DOA, 2010). Further, the Army aimed to reduce GHG emissions from all its buildings by 50% compared to a 2005 baseline by 2032. Finally, all non-tactical vehicles would be electric by 2035 (DOA, 2010). In the same year, the Navy published its own "Energy Strategic Roadmap", which articulated the goal of receiving 50% of its energy consumption from alternative sources by 2020. Further, the Navy planned to create a "Green Fleet" using mixes of biofuels and electric motors and demonstrate these capabilities by 2016. 50% of the Navy's installations would be net-zero by 2020 (DON, 2010). The Air Force also issued an Energy Plan in 2010, with the vision to "*make energy a consideration in all that we do*" (Air Force, 2010). The branch planned to increase energy efficiency in its installations, increase the use of renewable energy, and increase the use of biofuels in domestic aviation to 50% by 2016.

Crucially, the clean energy initiative of DoD also spurred cooperation with DOE. In 2010, the Department of Defense signed a Memorandum of Understanding with the Department of Energy (DOE), seeking to better leverage the scientific expertise of DOE in aiding DoD in its quest to reduce its use of fossil fuels. DoD explicitly declared its intention to speed up innovation and commercialization of new energy and conservation technologies. In this effort, DoD was seeking to create markets for clean energy technologies coming out of DOE laboratories (DoD, 2010; Army Corps of Engineers, 2010). DoD explicitly declared that its installations would serve as testbeds for DOE technologies and that it would also serve as an end-user for those technologies (see DoD 2010). In the DoD-DOE Memorandum of Understanding, the signatories made it explicit that increased efficiency in energy use will increase the operational capacity of DoD branches and reduce long-term energy costs.

Within DOE, the Office for Energy Efficiency and Renewable Energy (EERE) coordinates research, development, demonstration, and deployment efforts in three broad areas: Energy Efficiency, Renewable Energy, and Vehicle Technologies. EERE includes offices for several renewable energy technologies that are actively engaged in building and maintaining R&D networks around these technologies. These technology development offices aim to reduce costs and increase US capacity in those technologies they focus on. The DOE utilizes its national laboratories and attendant technology offices to achieve these missions in important ways by including universities and private companies in its R&D efforts. DOE's focus between 2000-2022 has been on Energy Efficiency and Renewable Energy technologies, as evident in Table 2. Table 2 shows that, since 2000, DOE has primarily invested in R&D related to fossil fuel alternatives and energy efficiency.

Area	**Budget FY 2000 – FY2022 (in $bn)**	**Percent of Budget**
Energy Efficiency and Renewable Energy	33.5	9.9%
Nuclear Energy	16.8	5%
Fossil Energy	14.6	4.3%
ARPA – E	4.2	1.2%
Electricity Delivery and Energy Reliability	2.9	0.8%
Total	**72**	**21.3%**

Table 2: DOE Energy Technology R&D Funding (in constant 2022 billion USD)

Notes: The total R&D budget for the period of FY 2000 – 2022 was 337.5 bn USD. 140.4 bn USD was spent on Atomic Energy Defense R&D, which is a core responsibility of DOE, and institutionalizes its relation to the National Security considerations of the White House, as well as DoD. Roughly 128.5 bn USD were spent on basic R&D conducted by the Office of Science, which conducts research in basic energy sciences, biological and environmental research, Fusion Energy Sciences, High Energy Physics, Nuclear Physics, and Advanced Scientific Computing.

Data Source: National Science Foundation.

In 2012, DoD announced cooperation with DOE's EERE to deploy 3 gigawatts of renewable energy on military installations.[50] Beyond its cooperation with DOE, DoD has directly contracted with the private sector in its installation energy test-bed initiative. According to a 2014 Pew Research report, the number of energy-saving and efficiency projects at military installations doubled between 2010 and 2012, jumping from 630 to 1339. The number of renewable energy projects increased from 454 to 700 (Pew, 2014). DoD has increased its use of renewable energy from 1.2m Mwh in 2010 to 1.9m Mwh in 2021 across 2,127 renewable energy projects. In 2021, DoD was the largest user of Solar PV across the US federal government (roughly 65% of federal use in 2021). DoD thus acted as an important buyer of first resort, creating crucial early-stage cash flow for businesses that seek to find commercial applications for cutting-edge technologies. In August 2013 alone, the Pentagon awarded $8.3 billion in 2023 USD of contracts to 22 companies for the right to sell solar energy to the US Army (Parnell, 2013). In the

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[50] Information about Federal Energy use can be found on the website of the Department of Energy here: https://www.energy.gov/femp/federal-agency-use-renewable-electric-energy

following month, DoD issued 10 additional contracts for wind energy worth a combined $8.84 billion in 2023 USD (Smith, 2013).

In the 2000s, DoD thus planned to significantly reorganize its energy use and realized that renewable energy applications, energy storage, micro-grids, and electric vehicles would have significant upsides for its installations' security and resilience to attack and would additionally improve its operational capacity. By the mid-2000s, individual branches of DoD were implementing concrete strategies on how to achieve these goals, setting ambitious targets.

Key Federal Actions in the 2000s

The Bush administration initiated several policy initiatives that aimed to leverage federal science and technology prowess to improve US energy security. In 2005, President Bush signed the Energy Policy Act, announcing that the Federal government would reduce its energy consumption by 2% in 2006, aiming for total reductions of 20% by 2015. In this effort, the federal government would also commit to agency-wide green power purchase goals of 3% for 2007-2009, 5% for 2010-2012, and at least 7.5% beginning in 2013. Here, federal agencies would widen their role as purchasers to create a market for clean power producers. While the Act included substantial tax breaks for fossil fuel producers ($2.8 bn), it also included $2.7bn for renewable electricity production, $1.3bn for energy efficiency, and $4.3bn for nuclear power.

In the same year, Congress tasked the National Academies to "*identify the most urgent challenges the US faces in maintaining leadership in key areas of science and technology*" (National Acamy of Sciences, 2007). The National Academy subsequently released the report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, calling for decisive action by the federal government to ensure US economic competitiveness via coordinated innovation policy. Crucially, the report identified energy security as a key long-term challenge and recommended the creation of an Advanced Research Projects Agency within the US Department of Energy

(DOE) modelled after the Defense Advanced Research Projects Agency (DARPA).

In 2007, Congress passed the Energy Independence and Security Act (Pub. L. 110 - 69). Energy security was declared as a strategic goal of US foreign policy and national security strategy to be fulfilled in large part by DOE through research projects aimed at improving alternative energy technologies. The Energy Independence and Security Act of 2007 also changed the focus of the Small Business Administration (SBA) program, which was originally created in 1982 to provide funding for start-ups seeking to commercialize technology and is funded through R&D budgets of participating agencies. This amendment reoriented SBA's efforts towards funding small ventures conducting clean energy related R&D commercializing attendant technologies. The act also expanded federal research programs on carbon capture (Pub. L. 110 – 69). In the same year, the America Competes Act officially authorized the creation of an Advanced Research Program Agency specifically devoted to innovation in energy (ARPA-E).

Further, in 2007, President Bush signed the Energy policy of the Department of Defense (10 USC. § 2991), stressing the national security benefits of renewable energy, the law called on DoD to produce or procure 25% of its electricity use from renewable sources by 2025 (ACORE, 2018).

The mid-2000s saw a significant re-orientation in federal innovation policy as the White House and DoD sought to ensure US energy security through innovation in energy technology. These efforts were in important part motivated by the energy needs of DoD, the Pentagon's assessment of the impact of Climate Change on National Security, and the realization that alternative energy sources would improve DoD's operational capacity.

President Bush's Energy strategy explicitly fused the goals of confronting climate change and improving energy security through energy supply diversification. To provide systematic evidence of the focus on national security concerns related to clean energy, I present below two figures based on the text in press releases published by the White House. Figure 15 below displays the conditional probability that a White House press release between 2001 - 2023 mentions keywords related to national security or energy security when discussing clean energy.

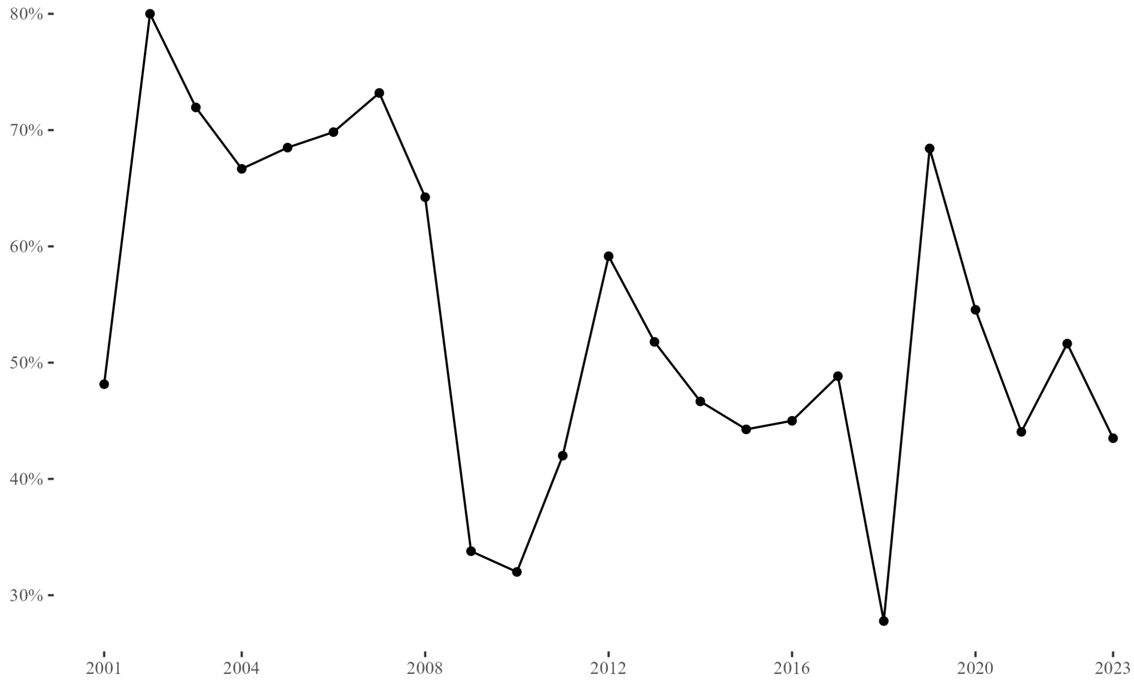

Figure 15: Conditional Probability of Discussing National Security or Energy Security when Discussing Clean Energy.
Notes: Based on Statements and other Releases from the archived websites of the Bush, Obama, Trump, and Biden presidencies, aggregated by year. I use a set of keywords related to clean energy and another set related to national security to calculate the depicted conditional probability. The lists of keywords can be found in the Appendix.
Data Source: Archives of Presidents' Press Releases; Authors' calculations.

Figure 15 indicates that clean energy is strongly connected to discussions of national security throughout the entire period between 2001 – 2023 for the US executive branch. On average, 53.7 percent of the time, when a White House press release mentions clean energy, it discusses the topic in some relation to national security or energy security. This connection between clean energy and national security was especially pronounced during the Bush administration between 2001 – 2008. On average, 67.8 percent of Bush White House Press Releases during this period mention keywords related to national security or energy security when discussing clean energy.

Figure 16 shows the most frequent terms (bigrams[51]) associated with a set of clean energy keywords across all four Presidential administrations since 2000.[52] Together, these

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[51] Bigrams are two adjacent tokens of text.

[52] The sets of keywords used to produce both Figures 15 and 16 are listed in the Appendix.

two figures demonstrate that for all administrations keywords associated with the topic of clean energy are closely associated with terms like "national security" and "energy security" in the way that I have argued in this Chapter.

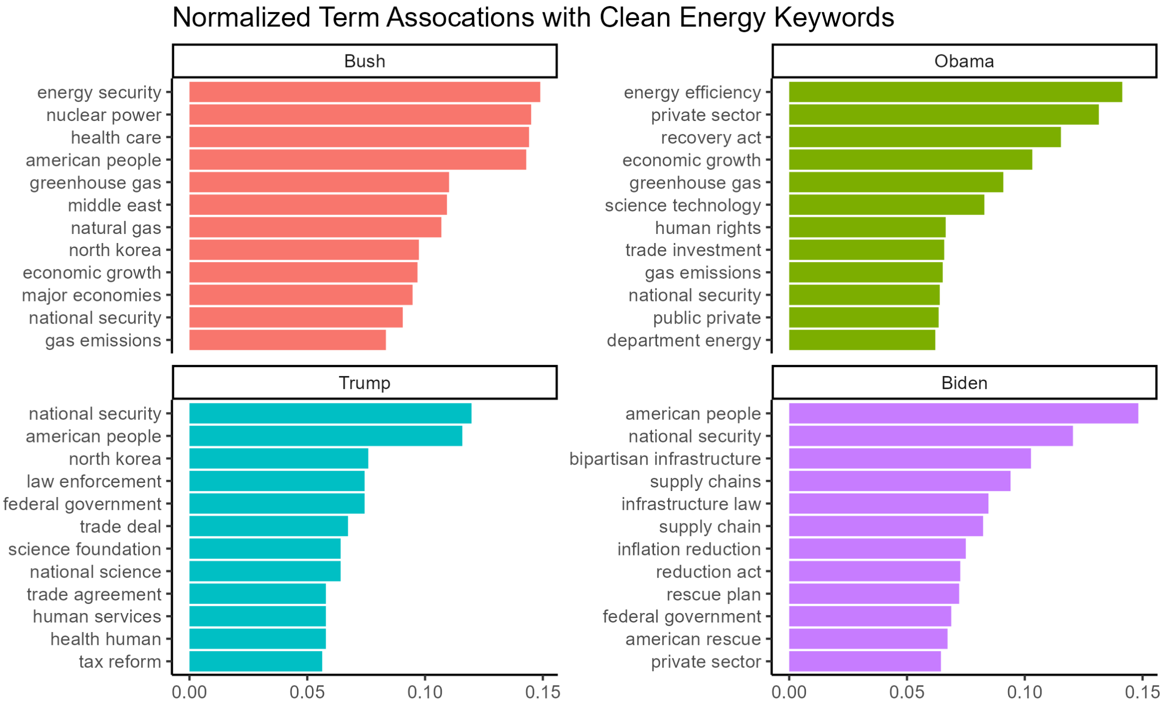

Figure 16: Normalized Term Associations with Clean Energy Keywords
Notes: Based on Presidential Press releases. Displayed are the most frequent bigrams associated with a set of clean energy keywords. I have normalized these frequencies by the number of total bigrams within the corpus of each presidency.
Data Source: Archives of Presidents' Press Releases; Authors' calculations.

Obama Administration and Beyond

The federal government further raised its commitment to clean energy technology R&D during the Obama administration. In 2009, President Obama visited the Massachusetts Institute of Technology to deliver a speech on "American Leadership in clean energy." Here, President Obama stressed two points: Clean energy would be critical to ensure US economic and diplomatic leadership, and the US edge in technological innovation would allow an energy transition away from fossil fuels (Nahm, 2021).

The Obama administration implemented a set of key initiatives to boost clean energy R&D through the American Recovery and Reinvestment Act. The Great Recession of 2008 and the 2009 stimulus provided a political opening to combine federal stimulus spending with substantial investment in clean energy under the banner of improving national energy security. The stimulus included investment and tax credits to boost the clean energy economy to the tune of $114bn in 2023 USD. Of this, DOE invested over $38bn in more than 15,000 clean energy projects through loan guarantees (Congressional Research Service, 2009). These projects were not considered R&D, but rather commercialization projects, as DOE sought to aggressively promote the diffusion of alternative energy technologies.

The 2009 stimulus also funded ARPA-E for the first time, allocating $400m ($506.63 million in 2023 USD).[53] The purpose of ARPA-E was to support "transformational" or "breakthrough" energy research, with the broad goal of enhancing the nation's economic and energy security (CRS, 2009). ARPA-E effectively expanded the purview of DOE in the realm of energy innovation, by creating an agency dedicated to "moonshots" in energy research.

The 2009 ARRA further raised the executive branch's focus on clean energy R&D, by establishing the Energy Frontier Research Center (ERFC) program under the DOE's Office of Science. The program is intended to accelerate the transformative discovery of new energy technologies by furthering a network of academia, industry, and National Laboratories. The Energy Frontiers program recruited several National Laboratories, universities, and private businesses as primary research centers, with smaller partners across the country. Between 2009 and 2016, the DOE Office of Science invested $895m in 2023 USD. As of 2016, the EFRCs had produced more than 7,500 peer-reviewed publications, 490 invention disclosures, 380 US Patent applications, and 100 technology licenses(DOE, 2017).[54]

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[53] In addition, ARRA provided $300m for Defense-wide funding for research, development, test, and evaluation projects under the Near-Term Energy Efficiency Technology Demonstrations and Research program (CRS, 2009). $4.7 bn of these funds were directed to be used "*to invest in energy efficiency projects and to repair and modernize*" DoD facilities (CRS, 2009).

[54] Since 2016, several programs were extended or new ones added, yielding renewals of $380m in total in 2018, and further funding of $100m in 2020. Finally, in 2022, the program added 16 new centers and renewed and extended 27 other projects for a total of $420m.

In addition, the Obama administration launched the SunShot initiative in 2011, setting the ambitious goal of providing the technological basis for cost-competitive solar energy by 2020 without subsidies. The SunShot was coordinated through DOE's Solar Energy Technology Office, which is a part of the Office of Energy Efficiency and Renewable Energy (EERE) within DOE, executed in cooperation between the national laboratories, private industry, universities, as well as state and local governments (DOE, 2017).

The combined effect of the increased R&D efforts of the American state under both the Bush and Obama administrations can be gleaned from the number of patents granted by the US Patent and Trademark Office (USPTO) that disclosed the receipt of federal R&D funding. Figure 17 below shows the substantial increase in the percentage of federally funded patents granted at the USPTO in clean energy-related technology areas. This is an output measure of the increased federal investment in clean energy R&D beginning in the mid-2000s, resulting from the change in the strategic focus of DoD, and more active efforts, especially by DOE).

The USPTO granted 153,354 patents between 2000-2022 to US organizations in the CPC technology category Y02[55], which denotes clean energy and related technologies. 14,515 of these patents feature government interest statements which clarify that the patent is based on R&D directly funded by federal agencies. So, 9.4% of all clean-energy related patents since 2000 have been the result of publicly funded R&D. This is a significantly higher share than among other technology classes over the same time frame, where publicly funded R&D has accounted for 5.2% of all patents granted to US inventors and assigned to US organizations. DoD and DOE alone have funded research behind 5% of all clean-energy related patents granted by the USPTO between 2000 – 2022.

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[55] The Cooperative Patent Classification Category Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reductions technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

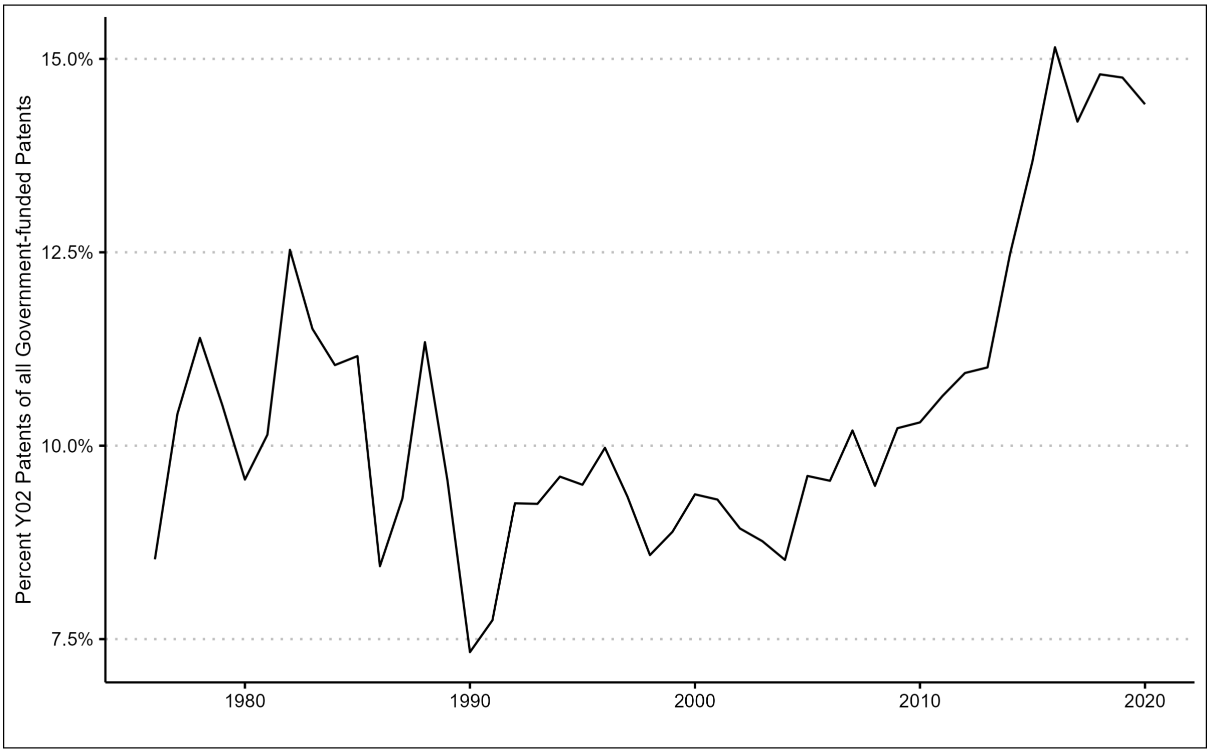

Figure 17: Annual Share of Patents granted in Clean Energy-related technologies of all Patents funded by US Federal Agencies, 1976 - 2020.
Notes: Based on patents granted in technology class Y02 (Technologies or Applications for Mitigation or Adaptation against Climate Change). This category includes technologies related to carbon capture, emissions reduction, alternative energy technologies like solar, wind, geothermal, etc., fuel cells, batteries, electric vehicles, and associated technologies. Patents are categorized as federally funded if the patent discloses the receipt of federal agency research grants, which also includes a government technology interest statement.
Data Source: USPTO

Further, Table 3 shows an overview of select innovation policies related to clean energy implemented under the Bush and Obama administrations.

Policy Approach	**Administration**	**Policy**	**Outcome**
Market Push	Bush	Kyoto Protocol	Not implemented
Market Pull	Bush	DOE Loan Guarantee Program and energy tax credits	Implemented
Market Push	Bush	Clear Skies Act of 2003	Did not pass Congress
R&D	Bush	2007 Energy Independence and Security Act	Implemented
Market Pull	Bush	Federal Green Power Purchasing Program	Implemented
R&D	Bush / Obama	ARPA-E	Implemented
Market Pull	Obama	ARRA additions to DOE Loan Guarantee Program	Implemented
R&D	Obama	SunShot Initiative	Implemented
Market Push	Obama	Waxman-Markey Bill (American Clean Energy and Security Act of 2009)	Did not pass Senate
Tech Diffusion	Obama	Energy Efficiency and Conservation Block Grant Program, Tax credit, Smart Grid and Energy Storage Investment and Demonstration Projects, Workforce Development Grants	Implemented
R&D	Obama	Advanced Vehicles and Fuels provisions in ARRA	Implemented
Tech Diffusion	Obama	Advanced Vehicle Tax Incentives	Implemented
R&D	Obama	Energy Frontiers Program	Implemented
Tech Diffusion	Obama	Battery Technology and Transportation Electrification programs	Implemented
R&D	Obama	Carbon Capture and Storage	Implemented
Tech Diffusion	Obama	Clean Energy Equipment Manufacturing Tax Credit	Implemented
Market Push	Obama	Clean Power Plan	EPA issued pollution standards

Table 3: Select Innovation Policies Related to Clean Energy

Table 3 as well as the above discussion also demonstrates that clean energy innovation policies implemented in the early and mid-2000s have been strongly in line with the historical character of American innovation policy outlined in Chapter 1. Recurring energy crises and military demand for energy technology drove innovation policy during the Bush administration. At the same time, federal policy generally eschewed policies that would have directly regulated the use of environmentally harmful technologies, instead focusing heavily on investing in providing technological alternatives through federal R&D. In doing so, federal agencies leveraged a decentralized research network including firms and universities. An economic crisis, the Great Recession of 2008, enabled the Obama administration to pass considerable expansions of federal R&D and technology diffusion efforts.

The confluence of widely shared concerns over energy security, the political salience of the issue given increased energy prices at the time, as well as the assessment by DoD that business-as-usual was unsustainable from a geostrategic perspective, gave way to a significant increase in focus on the goal of improving US energy security through innovation in alternative energy technologies. However, this re-orientation was not a wholesale embrace of renewable energy. Rather, innovation in clean energy was seen as one avenue to diversifying energy use without increasing energy costs for consumers or DoD in the short term. While the Bush administration took important steps to spur innovation in clean energy, it simultaneously resisted carbon taxation, also on the grounds of national security and related provisions were ultimately struck from the 2007 Energy Independence and Security Act (Sissine, 2007). Diversifying energy sources through creating renewable alternatives was firmly in line with the goal of improving US energy security but implementing policies that would have raised the costs of fossil fuels was anathema. The resulting all-of-the-above energy policy approach primarily aimed to improve access to cheaper and more diversified sources of energy.

After these substantial steps taken by the Bush and Obama administrations, federal commitment to innovation in clean energy remained largely in place under the Trump administration. Despite President Trump's skepticism towards climate change and US withdrawal from the Paris Agreement, federal agency involvement in clean energy innovation was not meaningfully curtailed. President Trump expressed hostility towards specific federal R&D programs – including ARPA-E. However, both DoD and DOE carried on their R&D efforts. In a 2017 interview, Chief of the US Army Operational Energy Office Paul Roege stated that the "*Military is not going to change its stance on renewable energy because it has already made the justification for and the connection between, green energy and resilience.*" (quoted in Berdikeeva, 2017). Similarly, Lt. Col. Wayne Kinsel, head of the infrastructure unit of the Air Force Asset Management Division for Logistics made it clear that DoD's commitment to clean power was "*not political*" and would continue under the Trump administration (Gardner, 2017). Further, DoD's 2016 Operational energy strategy reiterated the importance of energy security, and DoD's commitment to diversifying its energy base (DoD, 2016). The 2018 National Defense Authorization Act (NDAA), an annual authorization bill that sets defense funding levels and policies, included provisions for the military to act on clean energy. The provisions, which President Trump signed into law, explicitly named climate change as "*a direct threat to the national security of the United States*" and directed the Defense Department to prepare for its impacts.

The Biden administration has further accelerated the role that the US federal government plays in renewable energy innovation. Openly calling climate change the "*greatest national security threat*" (White House, 2021), Biden's IRA initiative can be seen as an effort to close the loop in the innovation lifecycle, seeking to provide demand-pull policies by providing extensive tax breaks and subsidies for clean energy technologies manufactured and deployed in the US. Less commonly discussed are other recent efforts at technology commercialization and diffusion. The Office of Clean Energy Demonstrations (OCED) was established in December 2021 as part of the Bipartisan Infrastructure Law. This demonstration program aims to accelerate the speed at which technologies move from federal labs to markets[56]. The efforts at commercialization of the substantial amounts of scientific and technological advance that national laboratories, universities,

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[56] The program explicitly seeks to "*fill a critical innovation gap*" (OCED, 2021).

and private actors (often in coordination) have produced throughout the 2000s/10s are immense: The OCED program seeks to spend roughly \$25bn on demonstration projects ranging from large-scale carbon capture programs, regional clean hydrogen hubs, regional direct air capture, industry applications, to clean energy demonstration projects. Thus, while earlier efforts focused more strongly on investing in the creation of a technological base for energy alternatives, recent initiatives appear to stress the move to market and deployment, however mainly focusing on inducements and demonstration instead of direct regulation.

In addition, the Biden administration has doubled down on further investment in R&D, beginning with the Energy Earth Shot initiative in 2021. Modeled in part after the SunShot Initiative implemented under Obama, these initiatives are overseen by DOE and are explicitly designed to drive down the costs of key technologies like hydrogen, long-duration energy storage, carbon-negative technologies, geothermal energy, offshore wind, and industrial heat decarbonization technologies (DOE, 2023).

Thus, the 2000s marked a significant turning point in federal energy policy, as energy security was formulated as a key national security objective – and the military-strategic importance of clean energy increased. DoD realized the geopolitical significance of clean energy technologies early, and subsequently engaged in several initiatives to ensure increased R&D investment in these areas, but also signaling its role as a buyer of first resort and actor in the effort to commercialize new technologies through grants, contracts, and demonstration projects. The Department of Energy enlarged its organizational purview, increasingly coordinating all major clean energy R&D initiatives.

In the following section, I turn to adduce empirical evidence for the central position of federal agencies in coordinating American innovation in clean energy technology in the 2000s. To do so, I employ a network analysis of patent citations to trace the relative importance of different inventors. Further, I provide empirical evidence of the positive impact of public-private R&D cooperations on the research productivity of cooperating private actors.

2.4 A Network Analysis of Clean Energy Patents

The previous sections showcased several key federal policy initiatives to generate technological innovation in clean energy. However, it remains unclear how important these federal efforts have been compared to private R&D in explaining that the US is so highly innovative in clean energy technology. This section is dedicated to empirically evaluating the importance of federal R&D, within the wider US clean energy innovation ecosystem. Below, I provide evidence of the importance of federal R&D for overall US clean energy innovation by taking advantage of and connecting several pieces of information recorded in patent filings at the USPTO.

Any patent granted by the USPTO notes the organization the patent was assigned to.[57] I use this information to aggregate patents to organizations, yielding information on the number of relevant patents held by different organizations. Further, patents granted at the USPTO are required to disclose prior inventive steps upon which the invention relies. There is a legal duty to disclose knowledge of prior patents on the part of the applicant, and the patent examiner holds the applicant accountable for doing so (Hall, Jaffe, and Trajtenberg, 2001). Because of this, several researchers have argued that forward citations in patents showcase the transfer of ideas and technology (Jaffe, Trajtenberg, and Henderson,1993, Caballero and Jaffe, 1993; Jaffe, Trajtenberg, and Fogarty 2000). In essence, if patent A cites patent B, then patent A relies on the knowledge embedded in patent B for the inventive step protected by patent A. Hence, the network of patent citations within a technology class traces the flow of knowledge across inventions and inventors.

By implication, patent citations also give insight into the relative importance and technological impact of patents. Patents that are cited more often and by a larger variety of other inventors can be considered more influential (Henderson, Jaffe, and Trajtenberg 1998; Brantle and Fallah 2007). This logic extends to the company or organization that funds the R&D underlying the patented technology and subsequently gets assigned the

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[57] In some cases, patents are unassigned, in other cases, they are assigned to an individual inventor rather than a company, university, or governmental agency. In the analysis below, I exclusively consider patents that have been assigned to either a company, university, or government agency.

patent.[58]

Organizations that hold patents that are cited often and widely have invested in the creation of and now own highly important technological information, and the organization whose patents cite the patents of another organization is in effect relying on the other firm's knowledge in advancing the protected technology.

I thus interpret every instance of a patent citation as a link between the cited patent's organization to the organization whose patent is citing it. This connection can be interpreted as the cited patent sending information to the citing patent (Or organization A sending information to organization B). When considering all patents granted within a technology class, the citations between these patents form a network of patent citations. This network depicts how inventions disclosed in patents, inventors, and assignee organizations have relied on each other. Hence, in recording which patents rely on other patents' prior inventive steps, patents and their citations record the general structure of the research network and the relative importance of different institutions that gave rise to these inventions.

If it is indeed the case that governmental R&D in clean energy has played a significant role in amplifying overall US innovation in this technology class, one would expect the patents funded by federal R&D to be especially influential. If many other innovative actors cite these patents, then they appear to be important for follow-on innovation by private actors. Large numbers of citations to patents generated by federal R&D efforts would imply that knowledge was generated and then transmitted from government efforts to other actors in the network. If federal R&D has been important, federal agencies should have a prominent position in the clean energy innovation network. This means that we would also expect many different organizations to be citing governmental patents, suggesting usefulness to many different actors. Further, we would expect that federal agencies are closely connected to other highly innovative actors. This would mean that other organizations that are themselves highly innovative are citing governmental

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[58] Patents typically note the identity of the individual or group of researchers that are considered the inventors but also note the university, firm, or governmental agency that the patent is assigned to. Some patents are not assigned to an institution and are thus presumably exclusively the result of the research of the individual inventor. In the following analysis, I ignore such patents.

patents.

To study the importance of governmental efforts in the creation of innovation in clean energy, I analyze the patent-citation network created by all US-based inventors for technologies related to solar energy between 2000 – 2022 (CPC subgroup H02S[59]). This allows me to investigate the relative importance of different patents and the organizations holding them in informing recent inventive steps in solar energy technology.[60] Additionally, I analyze the patent-citation network of the wider universe of all patents tagged as Y02[61] granted to US inventors by the USPTO between 2000-2022.

The Patent Citation Network of Solar Energy

Within the 2000-2022 timeframe, the USPTO granted 2760 distinct patents to American inventors within the solar energy technology category (CPC H02S). 255 of these 2760 patents were directly funded by federal agencies (roughly 9.5% of all solar patents granted within this timeframe). From the following analysis, I exclude all patents that have not been assigned to any organization, or those that have been exclusively cited by non-American organizations.[62]

Focusing on assigned US solar energy patents leaves 2720 patents granted between 2000 and 2022 that have been assigned to 776 unique organizations. I use this data to create a patent-citation network dataset by using the information about cited patents by each of the 2720 original solar energy patents. This dataset displays the relative importance of prior art in informing recent technological improvements in solar energy technology.[63] I aggregate all patents to the organization they have been assigned to,

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[59] CPC Subclass H02S is defined by the USTPO as: Generation of electric power by conversion of infra-red radiation, visible light, or ultraviolet light, e.g. using photovoltaic modules (obtaining electrical energy from radioactive sources).

[60] Exclusively focusing on patents in one category of clean energy technology significantly reduces the complexity of the analysis and makes it more illustrative. In later analyses below, I extend the technologies under consideration to all technologies in the CPC category Y02

[61] The Cooperative Patent Classification Category Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reduction technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

[62] Some patents are assigned to individual inventors rather than firms, universities, or government bodies.

[63] Of course, many patents granted between 2000 -2022 cite patents that themselves have been granted

based on the record of the patent.[64]

I restrict attention to citations to patents that have themselves been granted after January 1999. In doing so, I exclude reference to technologies that federal agencies may have created in earlier periods. As recounted above, DoD, DOE, and NASA were instrumental in creating some of the basic technological advancements in solar energy, however, this happened between 1970 and 1990 (also see Nemet, 2019). Here, I seek to investigate the extent to which recent clean energy innovation in the US has been driven by federal technology investments beginning in the mid-2000s. Hence, it makes sense to exclude all citations to patents granted earlier. This means that only patents granted after 1999 will count towards the level of influence of an organization. I thus deliberately bias against identifying the true magnitude of the influence of the federal government on technological progress in solar energy, since DoD, DOE, and NASA were influential in early innovation steps which might be foundational and thus still widely cited by follow-on innovators. I thus exclusively focus on the period that matters for the argument that increased federal R&D effort on energy alternatives after 2000 has played a key role in producing foundational knowledge in the most recent period.

A network consists of nodes (or vertices), which in this case are the organizations that a given patent has been assigned to. I assume that the assignee organization has funded the R&D underlying the patent. Nodes are connected through edges (or links or ties). In this network dataset, every edge of Patent A to Patent B represents that Patent B has cited Patent A. This is thus a directed network: When patent A cites patent B, patent B in effect sends a tie to patent A, as illustrated in Figure 18 (patent B sent information to patent A, which necessitated the citation of A to B).

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within the same timeframe. Thus, citations do not exclusively tie back to patents granted before the 2000-2022 period.

[64] I combine the different branches of the Department of Defense (Army, Navy, and Air Force). I label patents assigned to national laboratories to those federal agencies which they contract with.

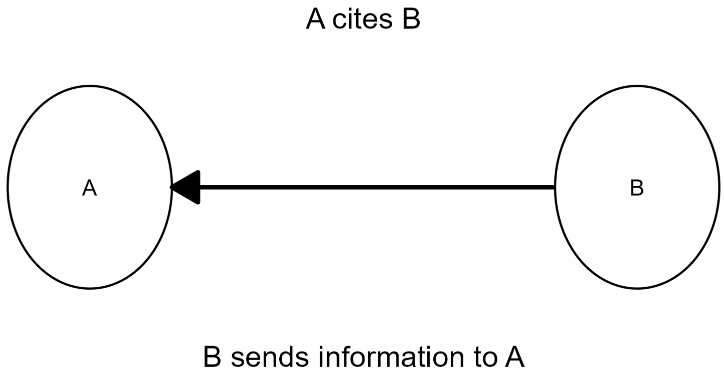

Figure 18: Illustration of Directed Citation Network Tie
Notes: Author's illustration

Further, I exclude all self-citations or instances where an organization's patent granted between 2000 – 2022 cites other patents assigned to the same organization (also called loops in networks). Since companies might strongly rely on prior art developed by themselves, excluding self-citations reduces the danger that companies with many patents between 2000-2022 could appear to be especially important in informing recent innovation.

The resulting solar technology network dataset consists of 2918 total nodes. There are a total of 7063 connections or edges between these nodes, representing citations between patents. Figure 19 below shows this version of the US Solar Energy Patent Citation network between 2000-2022, while Table 4 provides summary statistics. The relative node size in Figure 19 displays the number of different citation connections to other organizations (the out-degree), which means that larger nodes are connected to a larger number of companies who are citing their patents, and/or are cited more often.

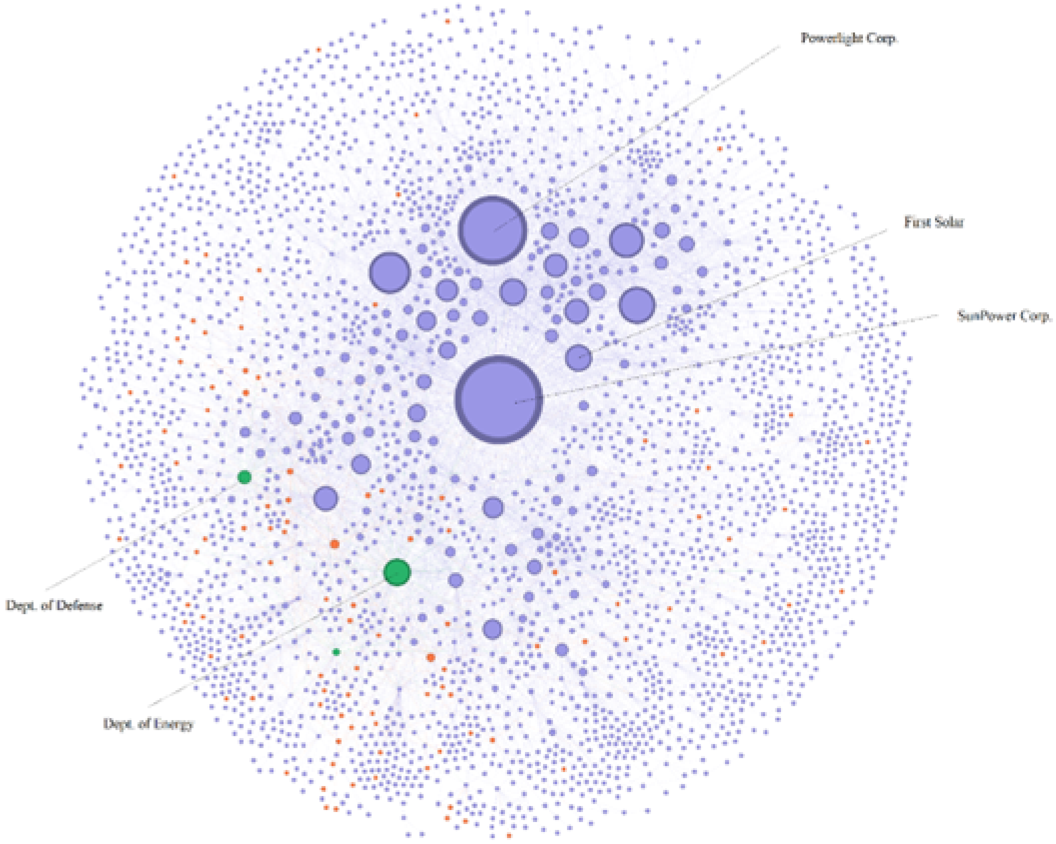

Figure 19: US Solar Energy Patent Citation Network –Patents Aggregated at Assignee Organization.
Notes: This network includes all patents filed in solar energy (CPC H02S) by US inventors that have been assigned to US organizations. All patents are aggregated to the organization they have been assigned to, as noted on the granted patent. Companies are pictured in purple, universities in orange, and governmental agencies in green. The size of each node is determined by its weighted out-degree (the number of outgoing citation connections to other organizations, weighted by the total number of citations) and scaled from 5 – 100.
Data Source: USPTO; Author's calculations.

Organization	**Number of Citations**	**Out-Degree**	**Kleinberg Hub Score**
SunPower Corp.	1335 (1st)	124 (1st)	1 (1st)
DOE	363 (7th)	63 (6th)	0.38 (16th)
First Solar	361 (8th)	68 (4th)	0.67 (2nd)
DoD	147 (28th)	85 (17th)	0.19 (60th)
99th Percentile	145.7	27	0.29

Table 4: Summary Statistics – Solar Energy Network
Notes: Number of Citations, Number of Companies citing organizations (Out degree), and Kleinberg Network Hub Scores for select Organizations in the Solar Technology Patents Citation Network. Data Source: USPTO. Author's calculations.

The distribution of patent citations in this network is highly skewed, over 85% of organizations are cited fewer than 10 times. The average number of citations is 9.4. Out of 2918 distinct nodes of the network, only 45 have 100 or more citations. The network overall is thus characterized by a small number of organizations that produce the most original patents, but who also monopolize the majority of citations to their patents, thus forming the core of organizations that produce the most important technological advances within solar energy.

DOE and DoD emerge as holders of some of the most highly cited patents in this technology class. SunPower Corporation is the most cited American company in solar energy technology patents, with 1335 total citations. PowerLight Corporation is the second most cited organization with 1034 citations to its patents.[65] Patents held by DOE have been cited 363 times, which makes DOE the 7th most cited organization in solar technology between 2000 - 2022. DoD has 324 citations to its patents (18th most patent citations). This places DOE and DoD firmly within the 99% percentile of patent citations in solar energy technology.

Further, In the context of a network, the Kleinberg hub score refers to a measure of the importance or centrality of a node (Kleinberg, 1998). This metric quantifies the extent to which a node connects to other highly connected nodes within the network. Nodes with high hub scores are influential or central within the network structure.[66] SunPower Corporation is the most important node in the US solar energy network (Hub score of 1). DOE has a Hub-Score within the 99th percentile of the entire network. DoD is within the 98th percentile.

DoD and DOE appear to be important within the Solar technology network, their patents being cited often and widely. Their Hub scores indicate that they are connected to other highly influential players in the network. Yet, the above analysis systematically underestimates the importance of federal agencies in US clean energy innovation. Most of the time, patents that arise from federally funded R&D are not assigned to the federal

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[65] Incidentally, Powerlight Corporation was acquired by SunPower in 2007.

[66] The hub score is scaled from 0-1, and thus indicates the relative importance of different nodes within a specific network.

agencies funding all or part of the R&D. Rather, patents that arise from federally funded R&D are typically assigned to private companies or universities. Intellectual Property rights legislation of the 1980s both encouraged federal agencies to conduct public-private R&D partnerships and created the legal means to grant exclusive licenses to resulting patents to universities or firms (Bayh-Dole and Stevenson-Wydler acts, see Chapter 1). For example, of the 255 solar energy patents resulting from government-funded R&D granted between 2000 – 2022, only 21% were assigned to a government agency or the contractor of a National Laboratory. In aggregating patents at the organization level, the above analysis used the assignee organization disclosed on the patent and ignored if the underlying patents had received federal research funding. Hence, the analysis significantly underestimates the importance of technologies embodied in patents that have been created based on R&D efforts of federal agencies. Notably, SunPower Corp. has been one of the most frequent private recipients of federally funded patents in the period under investigation. SunPower was assigned 39 publicly funded solar energy patents, while several other highly cited actors we re also the private recipients of such patents.[67]

Assigning Patents to the Governmental Agencies Funding R&D

The prior network dataset and analysis showed that US innovation in solar energy technology since 2000 has significantly relied on patents held by federal agencies. However, I made the analytical choice not to aggregate patents that featured government interest statements to the funding agency. In aggregating patents to the assignee organization, I assume that it is this organization that funded the underlying R&D. In the case of patents that feature government interest statements, this assumption does not hold. These patents note explicitly that the patented technology has been created based on publicly funded R&D. In the analysis following below, I instead aggregate these patents to the federal agency that funded the R&D, as noted in the records of the USPTO.

Figure 20 shows how dramatically the network graph changes when publicly funded

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[67] PowerLight Corp. received 8 publicly funded patents, Boeing received 7, General Electric received 3.

patents are assigned to the funding public agency rather than the firm or university holding the patent. Table 5 provides summary statistics for this version of the Solar Energy patent citation network. The Department of Energy has been the single most cited organization in the entire network. DoD is now the fourth most cited organization. According to citations made by companies and their patents within this technological space, the main source of technological advancements in solar energy technology have been patents resulting from R&D partnerships between DOE and a variety of firms which have mainly resulted in the assignment of patents to private companies.

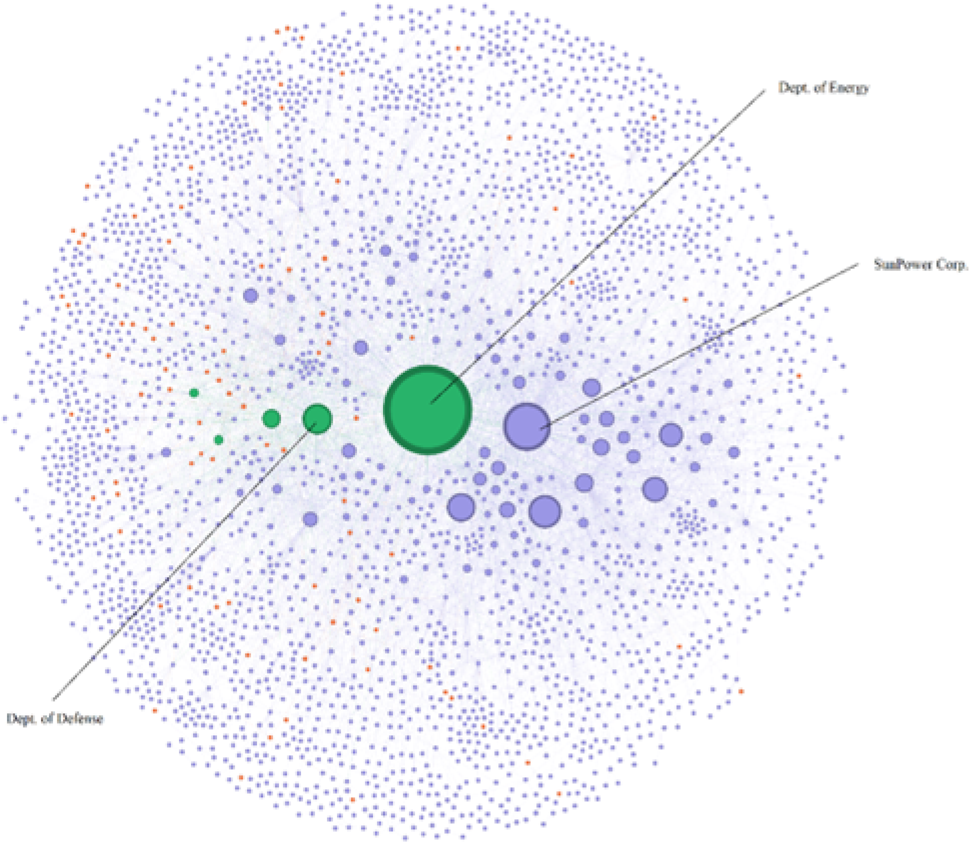

Figure 20: Solar Energy Technology Patent Citation Network – Publicly-funded Patents Allocated to Funding Agency.
Notes: This network includes all patents filed in solar energy (CPC H02S) by US inventors that have been assigned to US organizations. Publicly funded patents are allocated to the funding agency as noted on the patent record. All patents without disclosures of public funding are allocated to the organization they have been assigned to, as noted on the granted patent. Companies are pictured in purple, universities in orange, and governmental agencies in green. The size of each node is determined by its weighted out-degree (the number different of outgoing citation connections to other organizations, weighted by the total number of citations) and scaled from 5 – 100.
Data Source: USPTO, Author's calculations.

Organization	Citations	Out Degree	Kleinberg Hub Score
DOE	2099 (1st)	215 (1st)	1 (1st)
SunPower	1069 (2nd)	109 (3rd)	0.68 (2nd)
DoD	625 (4th)	112 (2nd)	0.41 (5th)
First Solar	349 (9th)	66 (6th)	0.46 (3rd)
99th Percentile	141.3	27	0.21

Table 5: Summary Statistics for Updated Solar Patent Citation Network
Notes: This network includes all patents filed in solar energy (CPC H02S) between 2000 – 2022, by US inventors that have been assigned to US organizations. I aggregate publicly-funded patents to the federal agencies that funded the underlying research. I display the number of citations, the number of companies citing organizations (Out degree), and Kleinberg Hub Scores for select organizations.
Data Source: USPTO. Author's calculations.

Table 5 additionally shows that DOE and DoD have high Out-Degree values in this updated version of the network, meaning that these federal agencies are connected to the largest number of other patenting organizations. The Kleinberg hub scores of these federal agencies also demonstrate their centrality in the network.

The network of patent citations emerging from US solar energy patents granted between 2000-2022 shows that federal agencies have been of formidable importance in informing follow-on innovation. Patents resulting from R&D funded by DOE especially have been by far the most widely cited across the entire network of actors innovating in solar energy technology. Thus, the solar technology patent data shows the tremendous importance of patents held by federal agencies for innovation in solar technology between 2000 – 2022. Innovation in solar energy has been heavily reliant on prior art disclosed in patents assigned to DOE and DoD. Further, DOE and DoD have provided R&D funding for projects that have resulted in patents that have greatly informed recent inventive steps in solar energy.

The Wider Network of Clean Energy Patents

While the focus on solar energy patents above allowed for a more parsimonious analysis, it might be the case that solar technology is not representative of the wider US clean energy sector. Thus, I now turn towards a network analysis of all patents granted to US inventors and assigned to US organizations within the technology class Y02[68] granted between 2000-2022, and their citations to patents themselves were granted later than January 1999. I exclude citations to patents granted earlier to limit focus to those technologies of more recent vintage.

The USPTO granted 153,354 Y02 patents to US inventors between 2000-2022. I follow the same methodology as explained above. I assign all patents arising from federally funded R&D to the agency funding the research. I restrict attention to citations made to patents themselves granted only after January 1999 to restrict attention to recent inventions. I also exclude all patents not assigned to US organizations, or citations made by non-American organizations. This yields 153,247 patents with complete citation information, which I turn into network data. This yields a network with 50,011 nodes, and 602,845 edges or citation connections between them. Table 6 below provides summary statistics of select nodes within this wider network of American clean energy patents.

Organization	**Citations**	**Out-Degree**	**Hub Score**
DOE	70,038 (1st)	9129 (1st)	0.97 (2nd)
DoD	51,277 (2nd)	7912 (2nd)	1 (1st)
IBM	44,980 (3rd)	5623 (3rd)	0.86 (3rd)
GE	37,244 (5th)	5421 (4th)	0.69 (6th)
99th Percentile	531.8	147.2	0.0365

Table 6: Summary Statistics – Y02 Patent Citation Network
Notes: This network consists of all patents granted to US inventors by the USPTO between 2000-2022, tagged as CPC Y02. The network consists of 50,011 nodes and 602,845 edges. Data Source: USPTO. Author's calculations.

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[68] The Cooperative Patent Classification Category Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reductions technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

Figure 21 displays the wider clean energy patent citation network. The Departments of Energy and Defense are the most widely cited organizations within this network. This means that patents funded by DOE and DoD have been the most important source of innovation between 2000 – 2022. NSF, NASA, and patents disclosing funding from the US Government without further information on the specific agency, also emerge as important sources of patent citations.[69] Further, General Electric (GE) and International Business Machines (IBM) are two private firms that stand out as central nodes within this network. Table 6 shows that DOE and DoD also feature the highest Out-Degree and Hub Scores, underscoring their importance within the network.

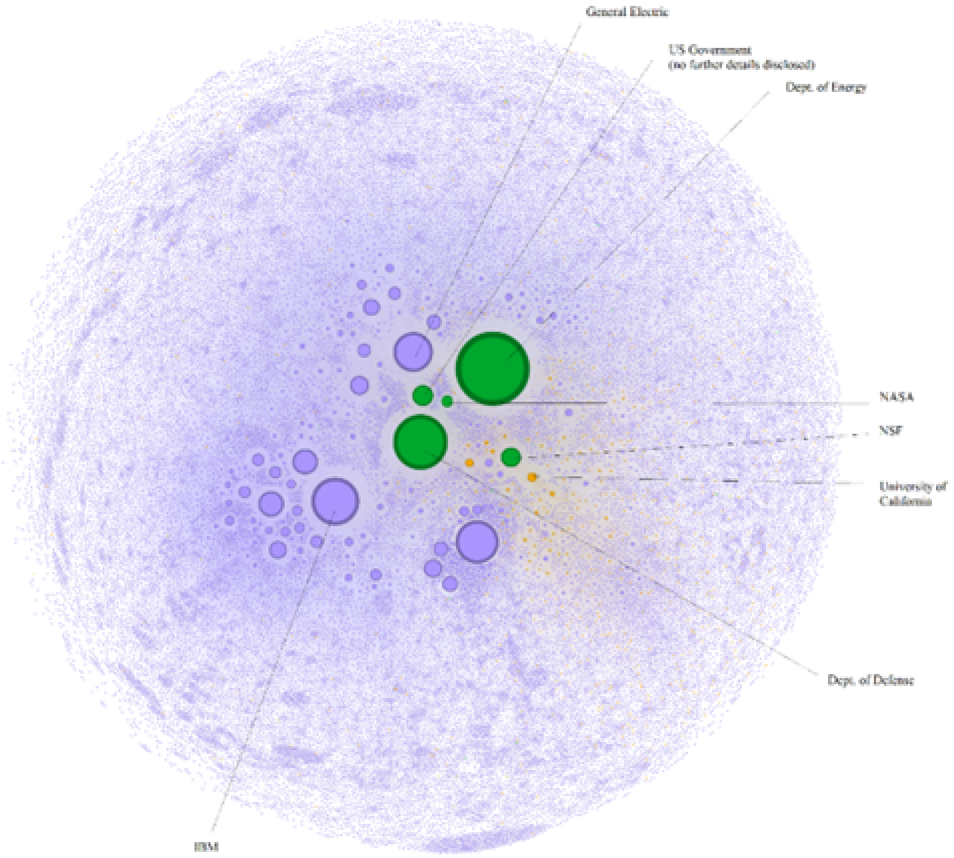

Figure 21: The US Patent Citation Network of Clean Energy Technology.
Notes: Node size is determined by the weighted out-degree of each node and scaled from 10-500. Federal agencies are in green, universities are in orange, and private companies are in purple. Government-funded patents are allocated to the federal agency that disclosed federal funding on the patent. All privately funded patents are allocated to the assignee organization noted on the patent. Data Source: USPTO. Author's calculations.

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[69] Not all patents that disclose federal funding specify the agency providing the funding. I aggregate these cases into a separate category labeled "US Government".

Finally, Figure 22 below displays the rising importance of DoD and DOE in clean energy technology throughout the 2000s/10s. Here, I calculate annual network statistics by creating sub-networks bounded by any given year. Figure 22 shows that both DoD and DOE have steadily increased their number of annual patent citations, the number of different companies that cite their patents, their Hub scores, and their Eigenvector centralities.[70] Eigenvectors are a measure of the network centrality of a node.

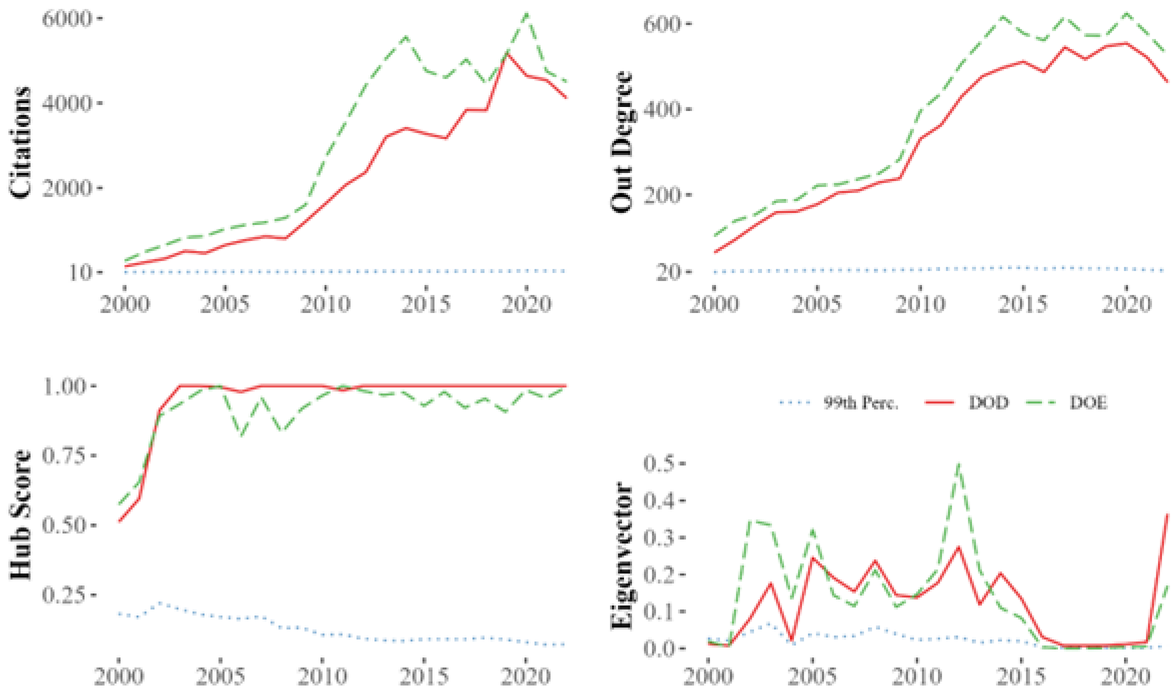

Figure 22: Network Statistics for DOE, DoD, and 99th Percentile, 2000 - 2022.

Notes: Referencing all Clean Energy patents granted between 2000-2022 (CPC Y02), I display the number of outgoing citations, the out-degree, Kleinberg Hub scores, and Eigenvectors for DOE, DoD, and the 99th percentile of all organizations' patents. Government-funded patents are allocated to the funding agency, and privately funded patents are allocated to the assignee organization noted on the patent.
Data Source: USPTO. Author's calculations.

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[70] Eigenvector scores in network data measure the "influence" of a node by considering not just the number of its direct connections (degree centrality) but also the centrality of its neighbors. Nodes receive high eigenvector scores if they are connected to many other nodes that are also highly connected. In the context of network data, the network is represented by an adjacency matrix A. Each element A_{ij} of this matrix is set to 1 if there is a connection from node i to node j and set to 0 if there is no connection. Eigenvector centrality is determined by identifying the principal eigenvector of this adjacency matrix. An eigenvector x and its corresponding eigenvalue γ satisfy the equation $Ax = \gamma x$.

The Importance of Federal Agencies Within the US Clean Energy Innovation Network

Figures 21 and 22 demonstrate that federal agencies are by far the most cited organizations within the US clean energy patent citation network. Hence, federal agencies have been the most important sources of information for clean energy innovation between 2000 - 2020. Figure 22 additionally shows the annual network statistics for the 99th percentile of nodes within the network to demonstrate that there is a dramatic difference between the most important nodes within the network and the rest.

To emphasize this point, I show the distribution of out-degree values of organizations within the Y02 patent citation network below. The outdegree represents the number of different nodes that a node has outgoing ties with. In the context of the patent citation network, an organization's outdegree captures the number of other organizations that cite its patents. I prune the network, focusing only on organizations that are themselves cited at least 50 times.[71] I do so to emphasize the network structure of those organizations that are most important within the wider network.

Even this pruned network remains highly skewed, in that a small number of organizations' patents are highly influential, whereas many organizations are cited only a few times – or only peripherally important. In this pruned network that is focused on more widely cited patents, 11.4% of all organizations cite government patents. Further, organizations that cite federal agencies have higher outdegree values themselves on average (10.74436 versus 3.5 on average). Further, DOE and DoD remain the most important nodes within this network, featuring the highest number of other actors citing their patents. The most important private entity is IBM, which holds a variety of patents with relevance to energy technology, including energy-saving tools.

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[71] This is an arbitrary threshold, but I try to eliminate nodes from the network that have small numbers of citations and might thus not properly contribute to characterizing the main actors within the network itself.

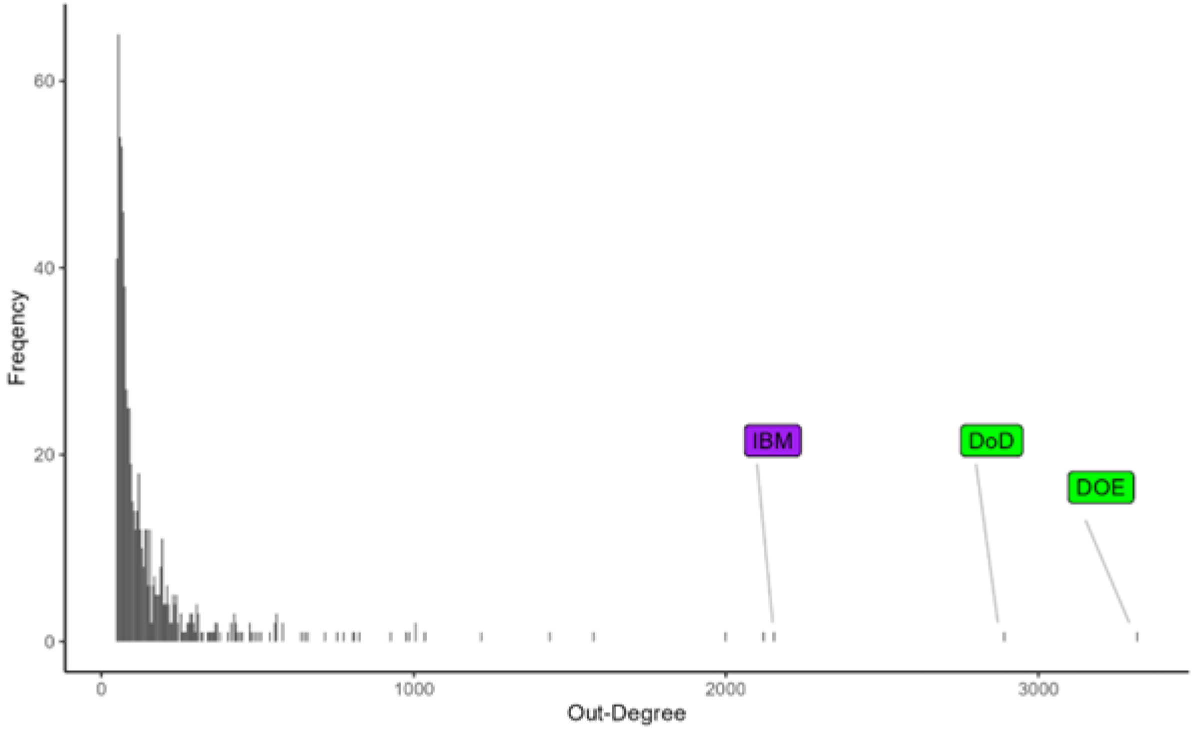

Figure 23: Out-Degree Distribution of Reduced-Form Clean Energy Patent Citation Network.
Notes: I filter the patent citation network introduced in section 3 for nodes with out-degrees larger than 50. I thus only display organizations that are themselves cited by at least 50 different organizations.
Data Source: USPTO, Author's calculations.

Network Resilience

Federal agencies are highly important for information flow within this network. To demonstrate this, I test the resilience of the network by comparing several network statistics of the full network to a version of it that removes all government organizations.[72] Table 7 shows the result. Table 7 presents five network statistics that capture the overall connectedness of a network in different ways. All these metrics change in a direction suggesting the importance of federal agencies when removing federal agencies from the network.

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[72] Removing the federal agencies from the network does not create a proper counterfactual to the real network. This means that removing federal agencies does not give an accurate representation of what the network would look like in the absence of federal R&D activities. Rather it is a useful exercise to further probe how important federal agencies are in the existing patent citation network.

Statistic	**Full Network**	**Network without Federal Agencies**	**Difference**
Avg. In-Degree	3.32793	1.544691	-1.78324
Avg. Path Length	48.01333	898.1712	+850.1579
Clustering Coeff.	0.085457	0.086821	+0.001364
Modularity	0.381997	0.65286	+0.270863

Table 7: Network Resilience Statistics – Comparing CE Patent Citation Network with and without Federal Agencies

Notes: I calculate the reported network statistics for the full network presented in section 3, as well as the analogous network removing all federal agencies. Data Source: USPTO, Author's calculations.

The in-degree statistic measures the number of incoming connections for the average node in the network. This measures the number of other organizations that a node is connected to or cites patents from. When removing the five government nodes, this dramatically decreases, suggesting that the average organization would have access to far less important information.

The average path length is the average of the shortest paths for all possible pairs of network nodes. It gives an idea of how efficiently information or resources can be transferred across the network. A smaller average path length indicates a more interconnected network. The average path length increases substantially when removing government nodes – suggesting that the network becomes less well connected.

This is supported by the increase of the clustering coefficient of the network when removing federal agencies. The clustering coefficient measures the degree to which nodes in a network tend to cluster together. It is a measure of the likelihood that two connected nodes are also connected to a common third node. High clustering coefficients indicate a tendency towards cliquishness or local tight-knit groups within the network. The pruned network shows an increase in the clustering coefficient, which suggests that governmental nodes connect otherwise disconnected nodes.

Similarly, Modularity measures the strength of division of a network into modules (also called groups, clusters, or communities). Networks with high modularity have dense connections between the nodes within modules but sparse connections between nodes in different modules. This measure is particularly useful for identifying community structure in complex networks. Table 7 shows that the pruned network has significantly higher modularity, suggesting that federal agencies connect the full network.

This section has thus demonstrated the central position of federal agencies within the US clean energy ecosystem by relying on the network of patent citations. The patent citation network presented above demonstrates that US patenting strongly relies on technological innovation produced by federal agencies. By focusing exclusively on patents granted since 2000, I show the importance of recent federally funded technologies, excluding foundational research by federal agencies between the 1970s and 2000 (see Nemet, 2019; Nahm 2021). Patents funded by federal agencies within the last 20 years have been the most heavily relied-upon pieces of information for technological innovation in clean energy technologies in the US.

2.5 The Effect of Network Inclusion on Firms and Universities

Section 5 has shown the extraordinary importance of federally funded R&D for US innovation in clean energy over the last two decades. But what is the connection between cooperation between private and public entities and the technological innovativeness of private actors?

I suggest that federal agencies improve the technological capability of universities and firms by financing basic R&D and cooperating with them on R&D projects. In this way, federal agencies act as motors of technological innovation, by providing crucial financial and technical inputs to innovation. In fulfilling R&D projects, federal agencies often rely on public-private partnerships with universities or contracting companies. These partnerships are legally organized as Collaborative Research and Development Agreements (CRADAs). The Bayh-Dole and Stevenson-Wydler Acts of 1980 both encouraged the network of federal laboratories to increase collaboration with other public, private, and academic actors but also allowed universities, non-profit organizations, and small businesses to secure patent rights to inventions developed from federally funded research (see Chapter 1). As a result, universities, and firms involved in public-private partnerships can attain exclusive patent licenses to knowledge or technology created by federally funded research. Most patents resulting from federally funded R&D in clean energy end up being held by universities or private firms. Hence, private companies are incentivized to cooperate on R&D and to invest in the commercialization of technology or other follow-on innovations.

Moreover, I suggest that companies that cooperate with federal agencies gain capabilities through this process - subsequently raising private innovation output. Further, companies might also shift their focus and thus innovate more in this specific technology category because of cooperation with federal agencies.

The Effect of Patent transfer on private innovation

I use annual Y02 patent data from the USPTO to measure the innovative output of US organizations (firms and universities) annually. I aggregate all patents granted in the CPC Class Y02 between 2000 and 2020 to the organization they were assigned to. I use the number of Y02 patents granted per year as the main dependent variable, measuring innovation in clean energy-related technology at the organization level. In subsequent analyses, I refer to the dependent variable as *Private Y02 Patents*.

Additionally, I use the record of government interest statements on patents that received federal funding as an indicator of whether an organization cooperated with federal agencies on the R&D underlying a patent. Patents granted at the USPTO disclose the receipt of public funding for the underlying R&D through these government interest statements. This allows me to create an annual count of the number of clean energy-related patents assigned to a given organization that was based on federal R&D.[73] I refer to this main independent variable as *Public Y02*. *Public Y02* is an indirect measure of the number of public-private R&D collaborations that an organization has been part of.

An organization enters my panel dataset once it is granted the first patent in technology class Y02 by the USPTO. To focus attention on companies that are active in clean energy related innovation, I restrict the analysis to companies that have been granted at

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[73] This is almost certainly an underestimate, as there are likely firms that cooperate with federal agencies in various forms but have never been directly assigned a federally funded patent.

least 10 patents between 2000 – 2020. While this considerably reduces the number of organizations, it allows me to focus on companies that are more active in this technology category, and thus be more accurately described as clean energy adjacent.[74] The full sample comprises 8532 different organizations; when filtering for those with more than 10 patents, the dataset is reduced to 1529 different organizations.[75]

To ascertain the organization-level effect of cooperation with federal agencies, I begin by fitting a series of organization-level regression models estimated via OLS. I include organization and year-fixed effects to account for both time-invariant and time-varying factors associated with organizations. The models take the following form:

$$PrivateY02_{i,t} = \beta_{0i,t} + \beta_1 PublicY02_{i,t} + \alpha_i + \gamma_t + \epsilon_{it} \tag{1}$$

where,

- $PrivateY02$ is Private Patents granted to Organization i in year t,
- β_0 is the intercept,
- β_1 is the coefficients of Public Patents assigned to Organization i in year t,
- α captures all unobserved, time-invariant characteristics of organization i ,
- γ captures any unobserved effects that vary across time but are constant across organizations,
- ϵ is the error term.

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[74] There is a considerable number of organizations that were only granted a small number of patents in the CPC subgroup Y02 during the relevant timeframe. These organizations cannot properly be described as active within the Clean Energy technology space.

[75] The main dependent variable of interest, the number of annual patents per company has a minimum of zero, a maximum of 705, a median of 1, and an average of 5.025.

I estimate all models with Driscoll-Kraay standard errors to account for cross-sectional dependence and serial correlation in panel data (Driscoll and Kraay, 1998).[76] Column 1 in Table 8 shows a baseline specification using the full sample of 1529 organizations over the 2000-2020 timeframe. The estimated coefficient for *Public Y02* indicates that increasing the number of public patents assigned to a company by one is associated with an increase in *Private Y02 Patents* by more than 3.

In model 2, displayed in column 2 of Table 8, I lag *Public Y02* by two years. Granted patents are a lagging indicator of innovative activity since there is often a considerable time gap between the initial R&D period and the actual granting of a patent at the USPTO. Since I want to measure whether an organization cooperated with federal agencies, a two-year lag of *Public Y02* is a reasonable proxy. Being granted a patent based on publicly funded R&D in year X indicates that the organization in question was part of a public-private R&D partnership in X – 2 years. Further, sequencing treatment and outcome in time allows me to reduce the danger of capturing reverse causality, as more innovative companies might be more likely to be chosen as partners for R&D projects. Column 2 in Table 8 shows that the 2-year lag of Public Y02 remains strongly and significantly associated with Private Y02 Patents. I additionally provide models with 3- and 4-year lags of the independent variable.

In the third set of models, displayed in columns 5-7 of Table 8, I exclude universities but still use the lagged versions of *Public Y02*.

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[76] Driscoll-Kraay standard errors are robust to heteroskedasticity (variability in a measure that is unequal over time), serial correlation (errors in the regression model are correlated over time), and cross-sectional dependence (errors across different entities, like firms of geographical areas, are correlated at a given point in time). Driscoll-Kraay standard errors allow to correct for the presence of any of these issues, allowing more reliable estimation of quantities of interest.

Table 8: OLS Models Estimated with Driscoll-Kraay Standard Errors

	DV: Private Y02 Patents						
	Full Sample (1)	Lagged Sample (2-4)			Only Firms (5-7)		
Public Y02	3.05***						
	[0.9]						
2-Year Lag		2.2***			3.8***		
		[0.6]			[1.14]		
3-Year Lag			1.8**			3.1**	
			[0.61]			[1.1]	
4-Year Lag				1.5*			2.5*
				[0.7]			[1.3]
Organization FE	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y
Observations	21,873	18,821	17,317	15,838	16,552	15,187	13,847
Adj. R2	0.67	0.69	0.70	0.71	0.70	0.71	0.73

*** Significance at 1% level. ** Significance at 5% level. * Significance at 10% level. Note: Standard errors are in brackets. The full sample contains 1529 separate entities. The sample restricted to private firms consists of 1365 separate firms.

Columns 1 through 7 of Table 8 display statistically significant and substantively meaningful effect sizes of *Public Y02* on *Private Y02 Patents*. These models all suggest that companies that are being assigned publicly funded patents subsequently significantly and meaningfully increase the number of private patents that they produce. Interestingly, this effect appears to be stronger for firms as displayed in columns 5-7. Hence, it appears to be the case that both universities and firms increase their private innovation output after being assigned publicly funded patents. I interpret this as the result of increased technological capability and focus on clean energy-related technologies resulting from cooperation with federal agencies on R&D projects.

Alternative specifications

All models displayed in Table 8 are estimated via OLS, which might fail to appropriately estimate the effect of *Public Y02* on *Private Y02 Patents* given that the dependent variable is a count. Below, I show the result of an alternative model specification. Despite changing my estimating method, the underlying regression equation does not change. The alternative specification includes both year and organization fixed effects, using the sample restricted to firms (excluding universities), and using the two-year lag of *Public Y02*.

For the average firm, both being assigned a public patent and being granted a patent at all are rare events. In many years, a firm might not be granted any patents at all, which creates zero inflation in the dependent variable. As a result, not accounting for zero inflation might lead to not adequately estimating the effect of *Public Y02* on *Private Y02 Patents*. To address this, I additionally present the results of a Zero-Inflated Negative Binomial model.

I show a summary of the estimated effects in Figure 24 below. The output of this model is best interpreted after converting estimated point estimates to percentage changes in the dependent variable associated with a one-unit increase in lagged *Public Y02*. On average, these models suggest a roughly 8% increase in the expected count of *Private Y02 Patents* for a one-unit increase in the 2-year lag of *Public Y02*. These alternative specifications suggest that firms that were granted publicly funded Y02 patents in the past become more likely to privately innovate in subsequent periods.

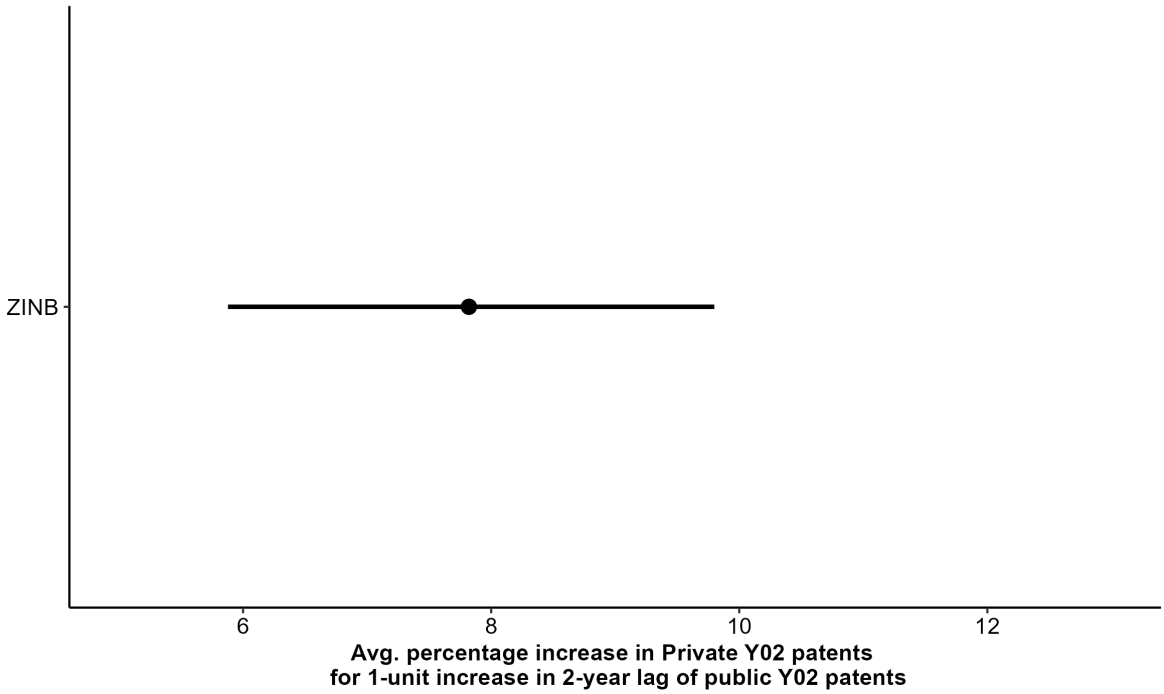

Figure 24: Count Model Results with 95% Confidence Intervals, DV is Private Y02 Patents.
Notes: The number of observations is 16552, for 1366 companies that enter the panel once they first patent. The displayed quantity is the exponentiated coefficient, which corresponds to the average expected percentage increase in the dependent variable as a result of a one-unit increase in the 2-year lag of Public Y02. ZINB is the zero-inflated negative binomial model. The model is estimated with organization and year-fixed effects, as well as robust standard errors., clustered at the organization level.

Firms that cooperate with federal agencies appear to become more innovative as a result. OLS models estimated with firm and year fixed effects, as well as alternative specifications estimated via a Zero-Inflated Negative Binomial model all suggest that there is a significant and substantially meaningfully positive effect of direct cooperation with federal agencies on firm innovativeness in clean energy-related technology.

2.6 Conclusion

In this Chapter, I have made the case that initiatives at the federal level in the United States have been crucial and underappreciated drivers of the innovation performance of American inventors in Clean Energy technologies. While the United States has not passed comprehensive climate policy measures comparable with Japan or Europe, several important policies facilitated considerable R&D investments implemented by federal agencies.

I have suggested that the mission-driven goals of federal agencies, and especially the Department of Defense, have played a key role in motivating these steps. Both DoD and DOE have coordinated R&D investments that raised the innovative capabilities of American universities and firms throughout the 2000s. Drawing on patent citation data, I show evidence indicating the central role played by DoD and DOE in the innovation ecosystem related to clean energy. Federal agencies emerge as the most important sources of information on US innovation in clean energy technologies between 2000-2020. Beyond producing crucial basic research that private innovators have made heavy use of, federal agencies also directly raise the innovative activity of private actors through R&D cooperation. I show that private actors that cooperated with federal agencies on R&D projects raised their subsequent privately funded innovation output, suggesting that federal agencies raise the technological capability of US organizations by financing basic R&D and cooperating with firms on R&D projects. Federal agencies have thus acted as critical motors of technological innovation in clean energy over the last two decades. Federal science and technology policy has thus played a major role in improving the technologies that are currently used in the global clean energy transition.

Chapter 3: The Geography of US Clean Energy Innovation

3.1 Introduction

While the US is a leading innovator in clean energy technologies, only a few geographic areas within the country account for most of this activity. Areas across the US differ dramatically in their orientation towards generating advancements in this technology class. Santa Clara County in California alone accounted for more than 8% of patents granted in clean energy technologies between 2010-2020 while accounting for just .6% of the total US population. Similarly, the spatial distribution of the formation of new companies related to clean energy has been highly uneven. According to data from Crunchbase, since 2010, 35% of new companies have been created in just 10 counties, and 50% of new companies have been created in just 20 counties.

There is considerable overlap between areas that feature large amounts of technological innovation and the locations where most new businesses are formed. Moreover, many of the most innovative and economically dynamic areas are also close to sites of major federal R&D investments related to clean energy. Examples include the wider Denver, Colorado area, close to the National Renewable Energy Laboratory in Golden, Colorado. Another example is King County, Washington, which features the University of Washington and Boeing. Other examples are Travis and Harris counties in Texas, which are the main sites of the University of Texas system, a major recipient of federal R&D. California's Bay Area is home to four different National Laboratories, as well as Stanford and Berkeley University, all of which are major executors of R&D conducted by the Department of Energy.

In this Chapter, I argue that the geography of US clean energy innovation is systematically linked to the geographical distribution of federal R&D investments. I thus extend the argument presented in Chapter 2, arguing that the US federal government plays a critical role in the contemporary US clean energy innovation network, to the extent that federal R&D spending influences the geography of the US clean energy industry.

Clean energy technology is a window into the way the federal government and its agencies influence technological innovation. A set of institutional changes enacted in the 1980s created the institutional framework for federal agencies to drive technological innovation. As a result, federal agencies play key roles in solving a variety of strategic problems in the creation and commercialization of new technologies: Federal agencies fund basic research often eschewed by private actors; they focus projects on specific technologies and connect researchers who work on similar problems, they provide access to scientific equipment and resources, further, they coordinate with universities and firms to commercialize technology created by public-private partnerships and they provide venture capital funding themselves but also coordinate access to outside finance.

Importantly, the R&D efforts of federal agencies are geographically uneven, which reinforces the creation of research clusters that focus on the creation and commercialization of specific technologies. There is a growing amount of evidence suggesting that federal innovation policy that started in WW2 and continued throughout the Cold War amplified the growth of innovation clusters (Gross and Sampat, 2023; Kantor and Whaley, 2023). Federal investments in war-related research programs boosted the development of local science and technology-related infrastructure.

Historically, several industries within the country have geographically clustered around the sites of federal military-related investments. Examples are the wider Puget Sound area in Washington state as well as Los Angeles, CA in the case of the aerospace industry. Another example is the wider IT industry in the California Bay area, which was the recipient of federal spending related to information technology research. North Carolina's Research Triangle, as well as Middlesex County in Massachusetts, have been clusters of biotechnology-related research (see Hurt, 2015; Vallas, Kleinman, and Biscotti, 2011).

These research clusters have attracted highly skilled workers and capital, further amplifying their relative advantage over other regions in generating technological innovation and spawning new firms with technology-oriented business models. Relatedly, these clusters also feature much higher rates of business formation and employment in high-tech industries (Moretti, 2012). Some scholars have even suggested the existence of a

"Matthew" effect[77], as areas with initial advantages further improved over time, but also depleted other areas of highly skilled workers and capital (Glaeser and Hausman, 2020).

In this Chapter, I make a similar case for technologies related to clean energy. I show that the geographic pattern of US clean energy innovation is systematically related to the distribution of federal R&D initiatives, showcasing the important role of federally funded R&D, but also indicating that the geographic pattern of US innovation is amplified by the uneven distribution of federal R&D spending.

To empirically support my case, I take advantage of several pieces of information recorded in patent filings at the USPTO to create an output measure of the geographic variation in federal clean energy R&D efforts at the county-year level. I also create an annual county-level measure of privately funded innovation in clean energy technology, to link public R&D investments to private innovation. Empirically, I show that past public R&D investments are systematically associated with increased private patenting at the county level. I show that areas that featured higher federal R&D activity in the past feature higher levels of privately funded innovation in later periods. Federal funding has thus contributed to the creation of regional clean energy innovation clusters that feature higher rates of company formation and higher rates of venture capital investment in clean energy companies.

This Chapter thus relates to the influence of federal innovation policy on the polarization of areas in their orientation towards technology which has important political implications (see Menaldo and Wittstock, 2024; Short, 2022).

This is the first study of the geography of US clean energy innovation that I am aware of. I additionally provide both theoretical rationale and empirical evidence of the spatial connection between private innovation efforts in clean energy technology and public R&D. I provide novel evidence of the positive impact of public-private R&D cooperation on the volume of private follow-on innovation, by focusing on the geographic impact of public R&D. Also, I make a methodological contribution by connecting and

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[77] The "Matthew Effect" is a biblical reference to the book of Matthew and describes a tendency of accumulating advantage, as areas or individuals with some initial advantage continue to accumulate further favors and by depriving others of the capacity to do the same.

leveraging several pieces of information from patent grants at the USPTO, including the use of federal interest statements on patents as a proxy for the primary locations of technology-specific R&D spending by public agencies.

The following section will situate this Chapter in the wider debate on the changing nature of US innovation policy. Section 3 discusses the unequal geographic distribution of federal R&D investments. Section 4 provides empirical evidence of the effects of federal R&D investments on subsequent private follow-on innovation. Section 5 concludes.

3.2 The Geography of US Clean Energy Innovation

Areas across the United States vary dramatically in their orientation towards generating and commercializing novel technologies. Innovative activity is especially concentrated (see Menaldo and Wittstock, 2024). This dynamic is even more pronounced in sub-categories of technologies, whose development is often clustered in specific regions that concentrate the actors engaged in related research.

Figure 25 below displays the geography of US patenting in clean energy-related technologies, measured in the average number of clean energy-related patents per 10k People at the county level between 2010 and 2020.[78] Figure 25 shows that there are several hubs of innovative activity in this technology class. Some small counties have very high per capita patenting rates primarily due to their low populations such as Cottonwood, MN, Bartholomew IN; Los Alamos, NM. But there are a couple of counties that produce the lion's share of all clean energy patents. Notable here are Santa Clara, CA; San Diego, CA; Oakland, MI; King, WA; Middlesex, MA; Alameda, CA; and Hartford, CT. Between 2010 and 2020 Santa Clara, CA was granted 8.28% of all clean energy patents granted to US inventors by the USPTO – while accounting for .6% of the US population in 2020. If we aggregate the California bay area into one commuting zone – the eleven counties comprising this area were granted almost 15% percent of all clean energy patents.

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[78] I use the Cooperative Patent Classification (CPC) subgroup Y02 to identify patents related to clean energy. CPC Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reductions technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

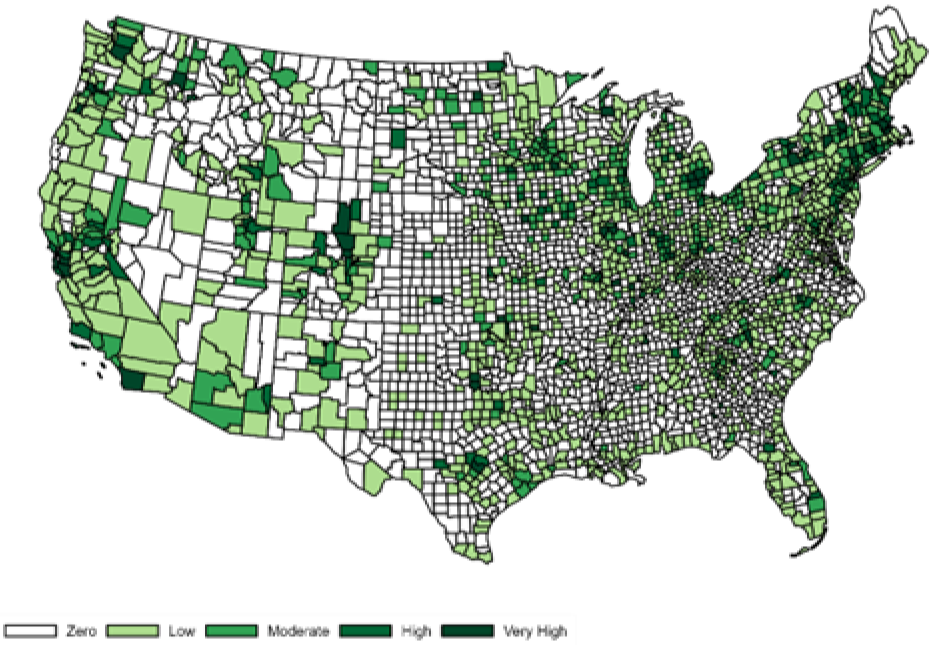

Figure 25: Average number of Clean Energy Patents per 10k Inhabitants Between 2010 – 2020.
Notes: Clean energy patents are patents granted in CPC subgroup Y02. I aggregate patent data at the county of the first-named inventor's address. I calculate the average number of patents between 2010 and 2020 at the county level, then divide by the population in 2020, multiplying by 10000. The resulting measure ranges from 0 to 7.04 Clean Energy patents per 10k inhabitants.
Data Sources: USPTO, US Census, Author's calculations.

While the areas that are especially innovative in clean energy are often also more innovative in general, there are significant differences in relative degree. Santa Clara, CA, Los Angeles, CA, San Diego, CA, Middlesex, MA, King, WA, and Benton, WA for example have higher percentages of all patents in Y02 compared to other technology classes. Counties that are located around the National Renewable Energy Laboratory in Colorado (Jefferson, Denver, Adams, Boulder, and Arapahoe counties) also have relatively higher patenting rates in Clean Energy compared to other technologies.

What's more, the most innovative geographic areas in the United States have recently increased their total share of all patents with then Clean Energy technology class. Figure 26 demonstrates this by graphing the share of all Y02 patents that have been granted to the top 5% of patenting counties from 1970 to 2020.

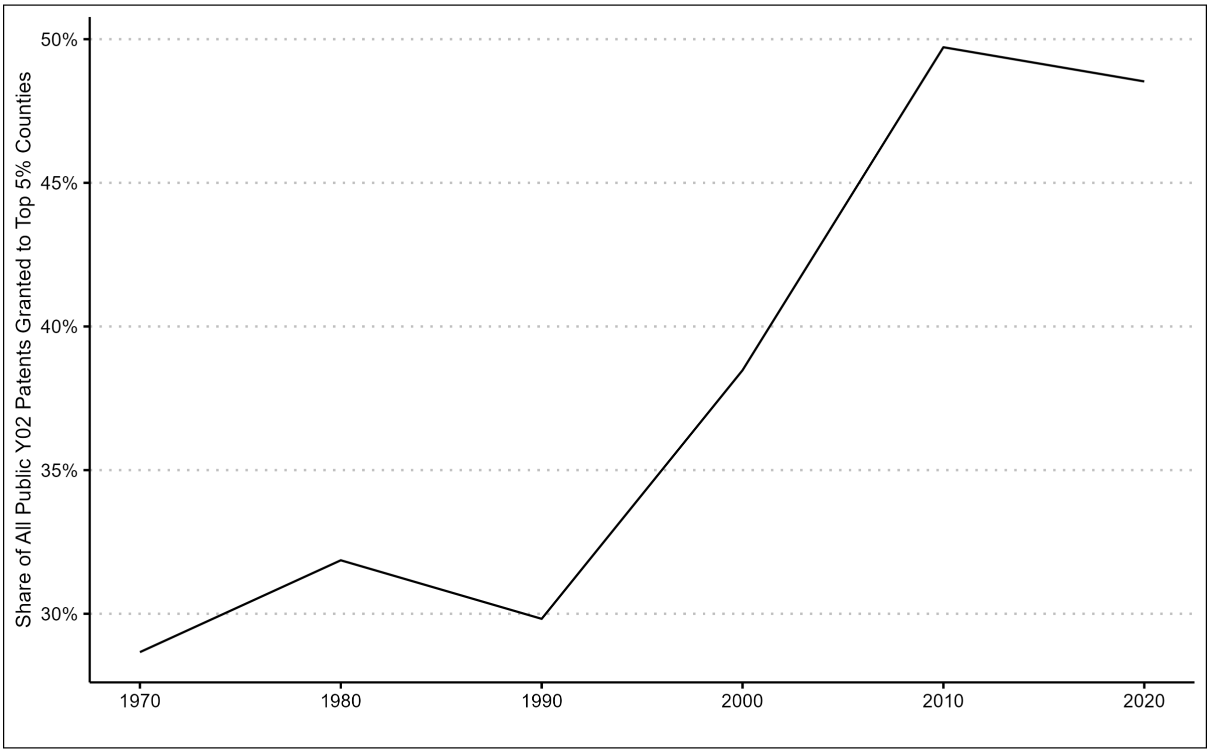

Figure 26: Matthew Effect in Clean Energy Patents: Share of all Patents Granted to Top 5% of Counties.
Notes: I show the average decadal number of Y02 patents granted per county, and the decadal population estimates of the US Census.
Data Source: USPTO, US Census, Author's Calculations.

Figure 26 demonstrates that the most innovative 5% of counties have increasingly accounted for substantially larger parts of total patenting in this technology class since the 1990s, accounting for almost 50% in 2010. This is development is unexpected, as the maturing of a technology would typically suggest diffusion, as a growing number of actors learn to use and contribute to the technology. While there was a small number of actors engaged in clean energy related R&D in the 1970s, the number of actors has increased substantially since. Yet, the geographical concentration of where patenting in this technology class takes place has increased.

Many of the areas that are especially innovative in clean energy technologies are also the sites of large amounts of federal investment in clean energy R&D and are close to National Laboratories. I suggest below that the geography of US innovation in clean energy is systematically linked to the geography of federal R&D investments, revealing the significant impact that the US state retains on driving innovation in this specific technology class.

3.3 The Link Between Federal R&D and Private Innovation

Federal R&D spending reinforces the advantage of “treated’ regions in producing technological innovation compared to others. Places of federal investment concentrate resources and trained people, generating agglomeration effects (see Gross and Sampat, 2023). Federal R&D initiatives and public-private partnerships provide the impetus and resources to generate knowledge competencies and innovation capacities in the networks of researchers who work on federal R&D projects. These people and their knowledge competencies are locally embedded in the sense that the value of their skills is amplified by being close to each other, and close to the research facilities specialized in related research.

Hence, federal investments in specific areas create research clusters that are at least partly devoted to specific technologies. These clusters concentrate and train people with expertise in related technologies. In this way, these sites of intensive R&D activity become sites of prototyping and initial steps of technology commercialization. This explains the frequent geographic link between innovation and company formation. Places like the Puget Sound area in King County, WA feature agglomerations of highly skilled scientists and workers associated with a variety of clean-energy adjacent technologies. Often, these skills have been honed through public-private partnerships between federal agencies, National Laboratories, Boeing, and/or the University of Washington. The agglomeration of trained workers often leads to the creation of technology-based business models incorporated in the region.

Figure 27 below shows the connection between past federal R&D investments and current business creation in clean energy. Counties that feature evidence of higher public R&D investments between 2000-2010 feature larger numbers of business creation in clean energy in the 2011-2022 period.

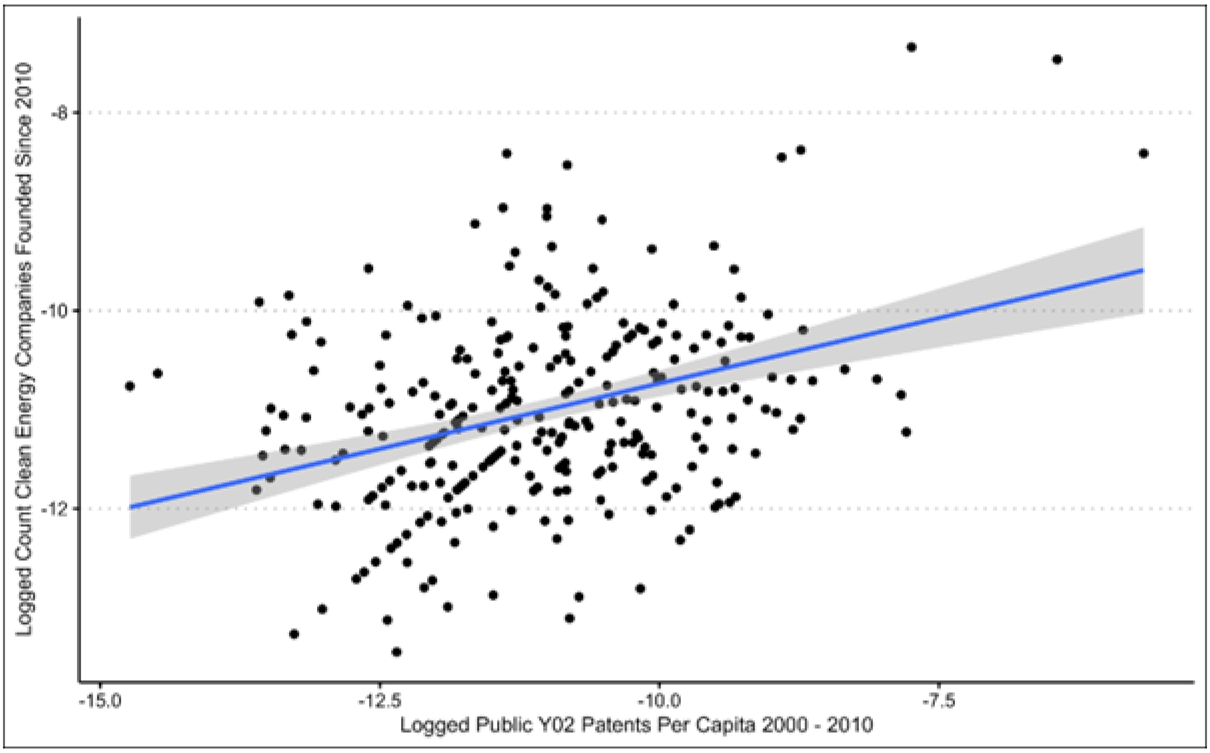

Figure 27: Connection Between Federal R&D and Company Formation.
Notes: I use data from Crunchbase to obtain information about the geography of the US clean energy industry. Crunchbase provides a broad industry classification, which I filter for US-headquartered companies within clean energy industries. I only show counties with patents and who have received funding. Both scales are logged.
Data Sources: USPTO, Crunchbase.

Further, within these research clusters themselves, state and local economic development agencies often attempt to facilitate commercialization. In many cases, it is state or local governments who seek to leverage the knowledge competencies embedded in these areas to generate local economic growth. These local initiatives are often supported by federal agencies.

One example is the Clean Energy Institute (CEI) at the University of Washington, started in 2013 by the state of Washington but cooperating extensively with the Pacific Northwest National Laboratory, the National Renewable Energy Laboratory, and DOE more generally. CEI focuses on the scientific advancement of next-generation solar energy and battery materials and devices. Yet, CEI also actively encourages and facilitates the commercialization of technologies created by its fellows and students, through legal, financial, and business support. In 2017, CEI opened access to state-of-the-art scientific installations for prototyping, testing, and demonstrating novel, zero-emission technologies on a pay-as-you-go basis (CEI Website). CEI is thus part scientific and educational institution, but also acts as a business incubator focused specifically on Clean Energy technology.

There are similar programs across many areas in the US in which research on clean energy technologies is clustered. The State of Massachusetts created the Clean Energy Center (MassCEC), a state economic development agency, which seeks to leverage the state's R&D prowess into start-up and job creation in related industries. In Colorado state, the National Renewable Energy Laboratory organizes the CleanTech Institute as well as the Industry Growth Forum and Innovation and Entrepreneurship center. All these initiatives aim at providing resources to prospective entrepreneurs in the wider clean energy space.

The viability of such initiatives depends on the agglomeration of scientists and other knowledge workers familiar with related technology. Here, I argue that federal R&D investments drive the geographic clustering of clean energy innovation. Federal investments in R&D and public-private partnerships raise the technological capacity of the areas that receive these funds. By extension, I suggest that the influence of the federal government within the contemporary US innovation ecosystem can be inferred from the effect that these federal investments have on the relative increase in innovation in those areas that are treated by federal investments compared to those that are not.

Figure 28 graphs the share of publicly funded clean energy patents that have been assigned to the top 5% of counties. Figure 28 shows that while the share of publicly funded patents granted to the most innovative counties was high in the late 1970s it decreased considerably until 2000. In the 1970s, clean energy technologies were at early stages of technological development, and only few companies, universities, and governmental research installations had the scientific expertise to make technological contributions. As a result, the share of all patents granted to the most innovative areas was correspondingly high. As information and expertise diffused, innovation in this technology class became more geographically widespread.

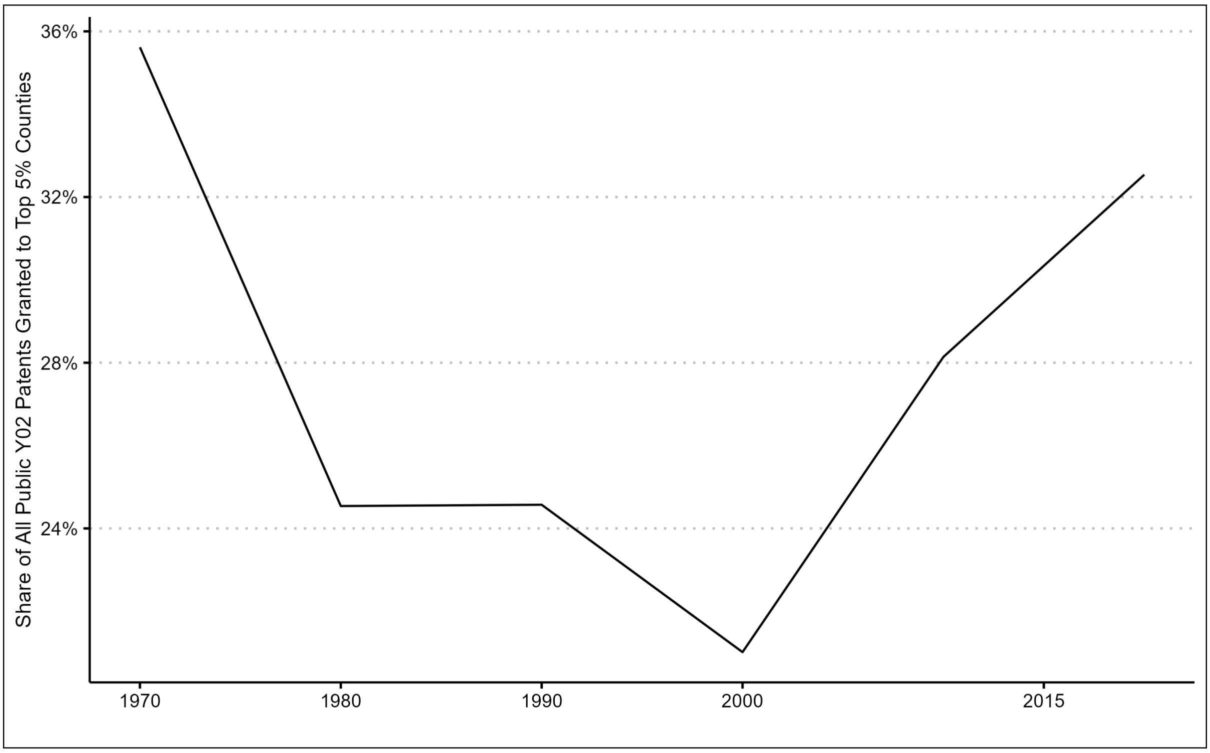

Figure 28: Share of Publicly Funded Clean Energy Patents Assigned to Top 5% of Counties.
Notes: I show the average decadal number of publicly funded Y02 patents granted per county, and the decadal population estimates of the US Census.
Data Source: USPTO, US Census, Author's Calculations.

Importantly, the share of all Y02 patents granted to the top 5% of patenting counties has considerably increased again since 2000. While the overall number of Y02 patents granted to American inventors has increased over this timeframe as well, from 3,862 in 2000 to 14,245 in 2020[79], Figure 28 suggests that the most innovative areas in the United States received an outsized share of public R&D investments. Hence, it appears that the clean energy R&D push of the 2000s has been strongly focused on a set of clean energy clusters, which might have contributed to the Matthew effect dynamic evident in Figure 26 on page 155.

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[79] Publicly funded Y02 patents increased from 304 in 2000 to 1170 in 2020.

3.4 Empirical Analysis

Have public R&D investments in the 2000s spurred more private follow-on investment in the areas that feature the universities, firms, and governmental research institutions carrying out federal R&D?

Federal R&D investments are difficult to geographically track comprehensively. One indicator is data on federal funding for R&D conducted by US universities. The Association of University Technology Managers, a non-profit organization of technology transfer professionals publishes annual data of the largest US universities, research centers, and research hospitals that are engaged in technology transfer. This data shows that the geographic distribution of federal R&D investments is quite uneven. In 2022, the top 5 universities received roughly 15% of federal R&D funding given to organizations within the sample. The top five US universities are also highly productive in terms of patenting, accounting for 11% of all patents filed by US universities. Further, 14% of new startups are formed at the top 5 universities.

Yet, there are no comparable figures that aggregate the total amount of R&D spent by all federal agencies on specific technology classes. Hence, I propose a different way to measure the geography of federal R&D investments and the conduct of public-private partnerships. To ascertain if federal efforts at clean energy R&D have spurred private follow-on investment, I take advantage of and connect several pieces of information recorded in patent filings at the USPTO.

As explained in Chapters 2 and 3 above, federal agencies primarily execute federal R&D through public-private partnerships, either with firms or universities, which are legally organized as CRADAs. Under the Bayh-Dole and Stevenson-Wydler Acts, the resulting IP is often assigned to the private firm or university that cooperates with the funding agency. Thus, the recipients of publicly funded patents provide insight into the distribution of federal R&D efforts. Patents granted by the USPTO record government interest statements in patents based on publicly funded R&D efforts. This allows me to identify patents that have resulted from R&D funded by different federal agencies. I label these patents as “public”. I use data on granted patents from the USPTO in the CPC subgroup Y02 between 2000 and 2020. The CPC classification Y02 is used to label inventions related to clean energy.[80] Identifying publicly funded patents within the Y02 subgroup thus gives me an output measure of federal R&D efforts in clean energy.

Patents granted by the USPTO include the address of the first-named inventor as it appears on the granted patent document. This allows me to identify where R&D was conducted.[81] I aggregate the number of publicly funded Y02 patents that feature a government interest statement at the county level for any given year, creating an output measure of the annual geographic variation in federal R&D efforts across the US I label this measure *Public Y02 Patents*. To measure innovation in clean energy technologies that is not immediately related to federal R&D efforts, I use data on granted patents from the USPTO between 2000 and 2020 in the CPC subgroup Y02 that do not feature public interest statements. I label these patents as “private”, inferring that they have been privately funded. I label this *Private Y02*. Distinguishing between publicly and privately funded patents based on the records of governmental interest statements thus allows me to create two county level measures, denoting the private and public outcomes of R&D investment in clean energy between 2000-2020. This results in a measure for the geographic distribution of innovation across the US, as well as intertemporal variation between and within counties.

To assess the impact of federal initiatives on private innovation in clean energy technology I leverage this geographic variation. Figure 29 displays the strong clustering of patenting in clean-energy-related technologies across the US geography in 2020.

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[80] The Cooperative Patent Classification category Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reductions technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

[81] This is a commonly used approach to measuring the geography of innovation (see Menaldo and Wittstock 2023; Acemoglu, Moscana, and Robinson 2016; Corradini 2020; Xu, Watts, and Reed 2019; Gross and Sampat 2020; Hean and Partridge 2021).

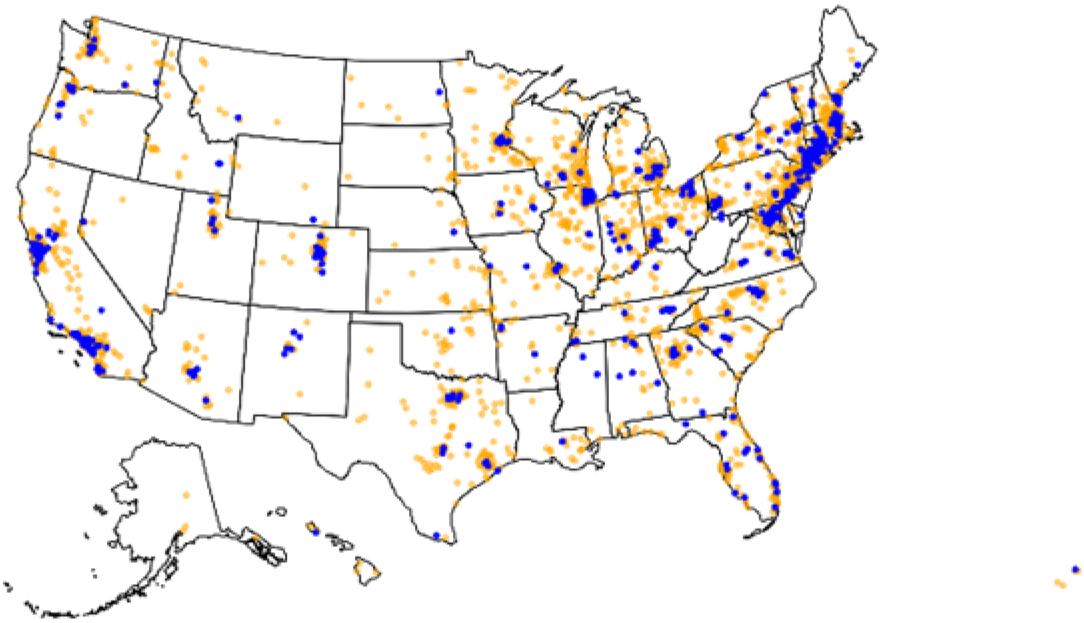

Figure 29: Geography of publicly funded and private patents in Clean Energy Technology in 2020.
Notes: Geographic location is based on the address of the first-named inventor. Government-funded patents (in blue) are patents that have been funded by one or several governmental agencies. Private patents (in orange) are those that have not been directly funded by any governmental agencies.
Data Source: USPTO.

I argue that counties "treated" with higher levels of public R&D are more likely to attract private R&D investment. Thus, I expect counties with higher *Public Y02* patents to feature higher numbers of private patenting. Public R&D outputs increase private R&D outputs.

To test if the observed relationship in Figure 29 is driven by the fact that federally funded research and development efforts in clean energy have spurred private follow-on innovation, or whether there are confounding factors that account for this pattern, I fit a series of regression models estimated via OLS that take the following shape:

$$PrivateY02_{i,t} = \beta_{0i,t} + \beta_1 PublicY02_{i,t} + \alpha_i + \gamma_t + \delta_{it} + \epsilon_{it} \qquad (2)$$

where,

- $PrivateY02$ is the number of privaste patents granted to inventors within county i in year t,
- β_0 is the intercept,
- β_1 is the coefficient for *Public Y02* granted to inventors within county i in year t,
- α captures all unobserved, time-invariant characteristics of county i ,
- γ captures any unobserved effects that vary across time but are constant across counties,
- δ is a vector of additional control variables measured for county i in year t
- ϵ is the error term.

I estimate all models with Driscoll-Kraay standard errors to account for cross-sectional dependence and serial correlation in panel data (Driscoll and Kraay, 1998).[82]

I pool all county-year observations for 3147 US counties over the timeframe between 2000-2020. The dependent variable is the number of privately funded patents in county i in year t, where the main independent variable is the number of publicly funded patents in county i in year t.[83] The models fitted below control for economic, population, and innovation-related confounders. I also control for county and year-fixed effects in all models.

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[82] Driscoll-Kraay standard errors are robust to heteroskedasticity (variability in a measure that is unequal over time), serial correlation (errors in the regression model are correlated over time), and cross-sectional dependence (errors across different entities, like firms of geographical areas, are correlated at a given point in time). Driscoll-Kraay standard errors allow to correct for the presence of an of these issues, allowing more reliable estimation of quantities of interest.

[83] In the full sample, the average number of private Y02 patents is 1.966, the minimum is zero, and the maximum is 1011. The median is 0, the standard deviation is 15.9. In the sample restricted on patenting counties, the average number of patents is 3.675, the minimum is 0, and the maximum is 1011. The median number is zero, the standard deviation is 28.3.

Table 9: OLS Models Estimated with Driscoll-Kraay Standard Errors

	DV: Private Y02 Patents						
	Full Sample (1)	Lagged Sample (2-4)			Patenting Counties (5-7)		
Public Y02	1.56^{***} [0.36]						
2-Year Lag		1.44^{***} [0.33]			1.42^{***} [0.33]		
5-Year Lag			0.93^{**} [0.32]			0.91^{**} [0.32]	
10-Year Lag				0.47^{*} [0.27]			0.47^{*} [0.27]
Economic Controls	Y	Y	Y	Y	Y	Y	Y
Innovation Control	Y	Y	Y	Y	Y	Y	Y
Population Control	Y	Y	Y	Y	Y	Y	Y
County FE	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y
Observations	64,430	58,258	49,000	33,574	31,168	26,215	17,962
R2	0.78	0.78	0.77	0.61	0.78	0.77	0.61
Adj. R2	0.77	0.77	0.75	0.57	0.77	0.75	0.57

*** Significance at the 1% level. ** Significance at the 5% level. * Significance at the 10% level. Note: Standard errors are in brackets. Economic controls are the annual unemployment rate and personal income per capita to capture the economic conditions of a county each year. Innovation Control is the count of all non-Y02-related patents granted in a year. Population control is the population size of a county. Data Sources: USPTO, US Census, Bureau of Economic Analysis, US Department of Agriculture Economic Research Service.

Table 9 displays the result of OLS models for all county years between 2000-2020. Column 1 in Table 9 shows that *Public Y02 Patents* has a significant and substantial positive effect on *Private Y02 Patents*. This suggests that counties that feature more publicly funded patenting also experience higher rates of private patenting in the CPC subgroup Y02. This effect is robust to controlling for time trends through year-fixed effects as well as all county-specific characteristics by controlling for county-fixed effects.

Patents are a lagging indicator of innovation, in the sense that patents granted in any given year are the result of past R&D spending. Further, inference from the specification in column 1 of Table 9 might be susceptible to reverse causality. Areas that are more innovative due to private R&D efforts might attract public R&D spending. I thus create lagged versions of *Public Y02 Patents* by lagging the variable by two years, five years, and ten years and use these lags as the independent variables. The estimated coefficients on the lagged versions of *Public Y02 Patents* remain both statistically and substantively robust.

Finally, many counties do not produce any patents in clean energy-related technologies over the entire timeframe under observation. In statistical terms, this leads to zero-inflation. Columns 5-7 report the results of models that omit all county observations that never produce any private Y02 patents or public Y02 patents. These counties can be considered "structural zeros" within the studied timeframe, in that they are never at risk of producing any patents due to some underlying demographic, economic, or other reason. The models that focus exclusively on those counties that experience some patenting at some point between 2000 – 2020 retains the positive effect of the lagged *Public Y02 Patents* variables.

Alternative specifications

It is likely the case that more populous counties are generally more likely to host inventors and/or research networks. Simply controlling the size of counties as I have done so far might not fully account for this. Hence, I present alternative specifications of both my dependent and independent variables below. I express both*Private Y02 Patents* and *Public Y02 Patents* in per capita form, and then take the logarithm of these variables to reduce the impact of the skew between highly innovative and other areas.[84] I report OLS models including the same sets of controls as in Table 9 below. All models indicate that federal R&D increases the amount of private clean energy innovation at the county level.[85]

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[84] In the full sample with logged variables, the mean of log(private Y02 patents per capita) is -10.024, the minimum is -14.816, the maximum is -4.007. The median is -10.044, the standard deviation is 1.22. In the sample restricted on patenting counties, the mean of the dependent variable is -10.895, the minimum is -14.816, the maximum is -4.007, and the median is -10.903, the standard deviation is 1.029.

[85] The results of these models are not dependent on aggregating measures at the county level. Models estimated with all measures aggregated at the commuting zone level instead show analogous results.

Table 10: OLS Models Estimated with Driscoll-Kraay Standard Errors

	DV: Log (Private Y02 Patents per Capita)						
	Full Sample	Lagged Sample			Only Patenting Counties		
Log (Public Y02 per Capita)	0.28***						
	[0.03]						
2-Year Lag		0.24***			0.20***		
		[0.03]			[0.03]		
5-Year Lag			0.13***			0.11***	
			[0.03]			[0.02]	
10-Year Lag				0.03*			0.03
				[0.02]			[0.02]
Economic Controls	Y	Y	Y	Y	Y	Y	Y
Innovation Control	Y	Y	Y	Y	Y	Y	Y
County FE	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y
Observations	64,430	58,258	49,000	33,574	31,168	26,215	17,962
Adj. R2	0.94	0.93	0.94	0.94	0.84	0.84	0.85

*** Significance at the 1% level. ** Significance at the 5% level. * Significance at the 10% level. Notes: Standard errors are in brackets. Economic controls are the annual unemployment rate and personal income per capita to capture the economic conditions of a county each year. Innovation Control is the count of all non-Y02-related patents granted in a year. Population control is the population size of a county.

Data Sources: USPTO, US Census, Bureau of Economic Analysis, US Department of Agriculture Economic Research Service.

Count Model

As an additional alternative specification, I also provide the model estimate from a Zero-Inflated Negative Binomial model below. This model is arguably more appropriate given that the dependent variable, *Private Y02 Patents*, is an annual, county-level count. Further, as discussed above, many counties record no patent grants at all in many years, which in statistical terms leads to zero inflation. Hence, the Zero-Inflated Negative Binomial model accounts for these characteristics of the underlying data the best. Figure 30 below shows the exponentiated coefficient value for a two-year lag of *Public Y02* when the model is are estimated using a Zero-Inflated Negative Binomial Model.

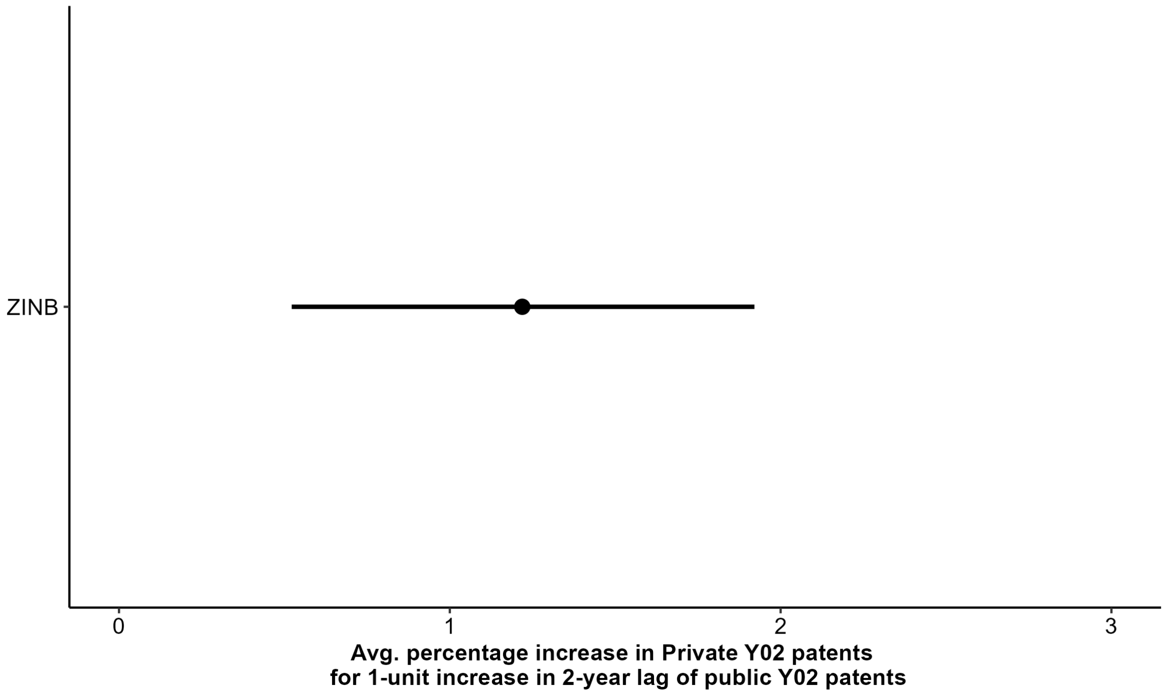

Figure 30: Count Model Coefficients and 95% Confidence Intervals.
Notes: I display the exponentiated coefficient value and 95% confidence intervals for the Zero-inflated Negative Binomial Model, using a 2-year lag of Public Y02 as the independent variable. The dependent variable is the county of Private Y02 Patents. The models are estimated with county and year-fixed effects and cluster-robust standard errors.
Data Source: USPTO, Author's calculations.

The Zero-Inflated Negative Binomial model suggests that on average, a one-unit increase in the 2-year lag of *Public Y02* is associated with an estimated 1.2% increase in the expected number of *Private Y02 Patents.* The model is estimated with county and year-fixed effects and cluster-robust standard errors.

Hence, the models presented above of the relationship between Public Y02 Patents and Private Y02 Patents indicate that increased federal R&D funding results in increased private innovative activity in related technologies. This effect is resilient to county and year-fixed effects, as well as lagging my main independent variable. Hence, larger levels of past federal R&D investments result in higher rates of private innovation. As a result, federal R&D appears to have contributed significantly to the creation and amplification of research clusters in clean energy technology throughout the 2000 – 2020 timeframe.

3.5 Discussion and Conclusion

In this Chapter, I have described an empirical pattern in which the most innovative counties in the United States have monopolized a growing share of all clean energy innovation in the 2000s. Further, I have suggested that this pattern is at least partly connected to the increase in clean energy R&D funding in the 2000s that was itself strongly focused on a set of clean energy research clusters, thus reinforcing the advantages of more innovative regions over others.

Empirically, I take advantage of several pieces of information recorded in patent filings at the USPTO to create an output measure of the geographic variation in federal clean energy R&D efforts at the county-year level. I also create an annual county-level measure of privately funded innovation in clean energy technology, to link public R&D investments to private innovation in clean energy technology. I show that past public R&D investments are systematically associated with increased private patenting at the county level. I show that areas that featured higher federal R&D activity in the past feature higher levels of privately funded innovation in later periods. Federal funding has thus contributed to the creation of regional clean energy innovation clusters that feature higher rates of company formation and higher rates of VC investment in clean energy companies.

The uneven technological focus of different regions has potentially important political implications (Short, 2022). Areas with less of a stake in new technologies might be unwilling to invest public resources in their further development (Menaldo and Wittstock, 2024). This Chapter thus relates to the influence of federal innovation policy on the polarization of areas in their orientation towards technology. These dynamics are especially important in the context of clean energy, which will likely require further innovation policy to successfully diffuse associated technologies.

Chapter 4: Technology-Targeted Innovation Policy - the Case of ARPA-E

4.1 Introduction

In 2007, the outgoing Bush administration created ARPA-E, a research agency modeled after the Defense Advanced Research Projects Agency (DARPA) and housed within the Department of Energy. The stated goal of ARPA-E has been to advance basic R&D in energy-related technologies, with an explicit focus on improving US energy security through technological progress. Building on the successes of DARPA, which included stealth technology, computing, microelectronics, the Global Positioning System, and unmanned aerial vehicles (drones), ARPA-E was part of a set of efforts intended to leverage US science and technology capabilities for advancement in specific areas deemed critical to national security. Among federal innovation policies focused on energy, ARPA-E is one of the flagship R&D initiatives of the last two decades.

As such, ARPA-E offers the opportunity to evaluate the impact of federal R&D efforts and gives insight into how federal innovation policy influences different regions in the country. In this Chapter, I evaluate the effect that ARPA-E has had on galvanizing the growth of US technology clusters focused on clean energy, discussed in Chapter 3. I suggest that participating in an ARPA-E project constitutes a geographically distinct treatment of the area hosting the participating entity. In doing so, this is the first study of the geographically distinct effect of ARPA-E that I am aware of. Creating a geo-located dataset on all organizations that have partnered on ARPA-E projects, I investigate the effect that this program has had on the relative innovativeness of the regions that host organizations participating in ARPA-E compared to those that do not. I show that areas that have hosted ARPA-E projects have subsequently increased their privately funded innovation in clean energy more than other areas. I also find evidence that these areas increasingly focus on clean energy innovation as the share of clean energy patents of all patents granted to the area increases. This Chapter thus presents new evidence on the spatial effect of American innovation policy related to clean energy.

4.2 Technology-Targeted Innovation Initiatives in Energy

US inventors and firms have been the primary drivers of three successive waves of technological innovation since around 1875 (Perez, 2010). In recent memory, US firms have been at the forefront of new industries based on Information and Communications Technologies (ICT and biotechnology)/ Concurrently, several scholars have argued that the US public policy has more actively focused on a technology-intensive economic growth model since 1980, which seeks to create competitive advantage through the development and mastery of technologies that are too advanced for firms of other countries to compete in. American firms primarily derive value from being able to protect their intellectual property globally, while licensing their technology abroad (see especially Schwartz, 2019). While some scholars have argued that American political institutions have always relatively favored the production of new ideas and technology (Bessen, 2017; Lamoureux and Sokoloff, 2001; Menaldo and Wittstock, 2024), there have been several deliberate policy changes on this front in recent history (see Chapter 1, section 1.8).

Federal policy has contributed to and aided in creating technologically advanced industries in the United States (see Block, 2010; Mazzucato, 2011). While many scholars acknowledge the role played by policies that raise the technological capacity of the workforce as well as companies in a technology-agnostic way (STEM education or R&D tax credits) governments also engage in much more active, technology-targeted policies. Historically, governments have often targeted specific technologies with investment, typically for reasons of geostrategic competition, or to overcome enduring societal challenges (see Chapter 1). Gross and Sampat (2023) demonstrate the effect of WW2-related research funding on the economic trajectory of US counties. It remains the case that some areas in the US are substantially more innovative than others. However, these regional differences vary somewhat depending on the technology class under consideration. Chapter 3 investigated the impact of federal R&D initiatives on the geography of US innovation in clean energy. In this Chapter, I use ARPA-E as a key example of federal R&D efforts to further investigate how the relative innovative capacity of regions is shaped by federal, technology-targeted innovation initiatives.

ARPA-E as a model for US Clean Energy Innovation Policy

In the mid-2000s, federal funding for clean energy technology increased (Chapter 2). ARPA-E is one of the flagship federal initiatives intended to raise US technological capacity in energy technology to ensure US national security. ARPA-E was conceived under the Bush administration with the explicit belief that private actors would be reluctant to invest in high-risk projects with uncertain outcomes in energy technology (Weiss, 2014, Chapter 1).

In 2005, Congress tasked the National Academy of Sciences to assess the most urgent challenges the US faces in "*maintaining leadership in key areas of science and technology*" (NAS, 2007). The National Academy subsequently released the report *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future.* The report echoed many concerns that had been voiced during the debates about industrial policy in the 1970s and 1980s and that have been politicized again in dramatic fashion since 2015 by the Presidential campaign and Presidency of Donald Trump (Lichtenstein and Stein, 2023; Chapter 1). Namely, the National Academy assessed that US firms were experiencing increasingly fierce economic competition in several industries from low-wage countries, especially in East Asia. As a result, companies were either outsourcing production or offshoring workforces. The National Academy's report averred that to ensure economic growth for companies within the United States, it would be necessary to leverage the American competitive advantage in specific advanced technologies more deliberately (National Academy of Sciences, 2007). In effect, the report re-articulated a commitment to a growth model based on heavy reliance on highly educated workers, and firms focused on developing and commercializing advanced technology (see Chapter 3; Short, 2022). A letter from the leadership of the National Science Foundation to the President's Council of Advisors on Science and Technology put the case bluntly: "*Civilization is on the brink of a new industrial order. The big winners in the increasingly* *fierce global scramble for supremacy will not be those who simply make commodities faster and cheaper than the competition. They will be those who develop talent, techniques, and tools so advanced that there is no competition.*" (quoted in National Academy of Sciences, 2007: 26).

While the report did not explicitly call for an industrial policy to support this orientation of the US economy, the report considered the US federal government to play a key role in enabling US firms to be able to "*develop talent, techniques, and tools*" sufficiently advanced.[86] To do so, the report made a range of recommendations, many of which were in some manner implemented in the 2007 America COMPETES Act passed by the Bush administration. The legislation included a variety of education provisions intended to raise standards and outcomes in STEM education, as well as a grant program for education in advanced manufacturing. Further, the Act also raised budgets for several federal agencies including NIST, NASA, DOE, and NSF – and featured provisions enlisting these agencies in efforts to raise human capital as well as the technologies for US firms to draw from (Stine, 2008).

One recommendation made in the report was the creation of an Advanced Research Projects Agency within the Department of Energy (DOE) modeled after the Defense Advanced Research Projects Agency (DARPA). The report articulated access to cheap, reliable, and clean energy as critical for future US economic competitiveness and national security. Here, the authors of the report combined an assessment of the national security risks associated with reliance on fossil fuels with the potential of clean energy sources to be ultimately cheaper and more stable in price, which was expected to yield economic benefits for US firms. The report acknowledged that DOE was already spending considerable sums on energy research but posited that a small and nimble agency modeled on DARPA would be better positioned to both galvanize innovation as well as aid in commercializing attendant technologies (National Academy of Sciences, 2007).

ARPA-E is thus clearly an instance of a technology-targeted innovation policy. The

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[86] Notably, while the 2007 report clearly recommends a set of policy actions that would form the basis of an industrial strategy focused on high-tech industries, the report does not mention the terms "industrial policy" or "industrial strategy" even once.

program seeks to raise American capacity in a specific technology domain, which was mainly motivated by a combination of national security and industrial policy considerations. That said, ARPA-E is not unique in the sense that the federal US government is engaged in a variety of programs that seek to raise innovation in specific technologies (DARPA being the classic example, also see Chapter 1). More recent examples are the Energy Frontier Research Centres implemented by the Obama administration or the Earth Shot initiative implemented by the Biden administration.

Thus, ARPA-E offers insight into the mode and effect of federal innovation policy in the United States. By all assessments, ARPA-E has been strikingly successful. By 2023, ARPA-E had provided \$3.27bn to 1415 projects, spurring more than \$11bn in private follow-on investment.[87] Further, 131 companies have been formed, 6257 academic articles published, 934 patents issued, and 289 licenses reported from ARPA-E projects (ARPA-E, 2023). There have been past attempts to evaluate the impact of ARPA-E on participating organizations, generally finding that participating entities benefit considerably (see Beaton and Khosla, 2017). Yet, no studies have evaluated whether the geographic region that houses participants is impacted by ARPA-E.

Setup of ARPA-E

ARPA-E was initially created in 2007 through the America COMPETES Act by the outgoing Bush administration. However, the program was first funded in 2009 by the Obama Administration as part of the stimulus spending of the American Recovery and Reinvestment Act. Since then, the program has launched 1415 research projects that feature a lead institution and several partner institutions each. ARPA-E periodically issues funding opportunities that are focused on specific technical problems, which are identified by the program administrators (Beaton and Khosla, 2017). ARPA-E thus allocates research funds based on its own mission-based technology goals. Some projects have also been funded as the result of open opportunities that do not specify a specific issue area. Applicants present concept papers, technical information, and a budget justification in

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[87] Values expressed in 2021\$.

grant applications (ARPA-E website). Applicants must justify their projects in terms of their potential benefits to American energy security, their beneficial environmental impacts, and their economic relevance.

Project participants can include individual researchers, teams at universities, and firms of various sizes. In practice, the main executor of ARPA-E projects is usually a small firm. Chosen projects then receive federal funding. The administrators of ARPA-E will typically pair the main research team with project partners. These often include universities or National Laboratories. ARPA-E administrators actively seek to create synergies between groups that work on similar projects or will benefit from the expertise of others, as well as access to scientific resources or installations necessary. Here, the system of National Laboratories overseen by the Department of Energy plays an important role. Many ARPA-E projects are partnered with teams from National Laboratories, which often provide lab space or technical expertise that would be out of reach for many smaller research ventures. Federal R&D installations thus serve as crucial force multipliers for individual researchers, university labs, or small companies that seek to develop a technological idea that might otherwise never be explored due to prohibitive costs. Universities also play a key role, either being selected as the main executors of research projects or partnering with companies and/or National Laboratories, providing topic-specific expertise.

The partnering of different organizations thus creates a network between different ARPA-E partners. Figure 31 displays the connections between different ARPA-E partners that emerge from all ARPA-E projects between the 2009 – 2022 period.

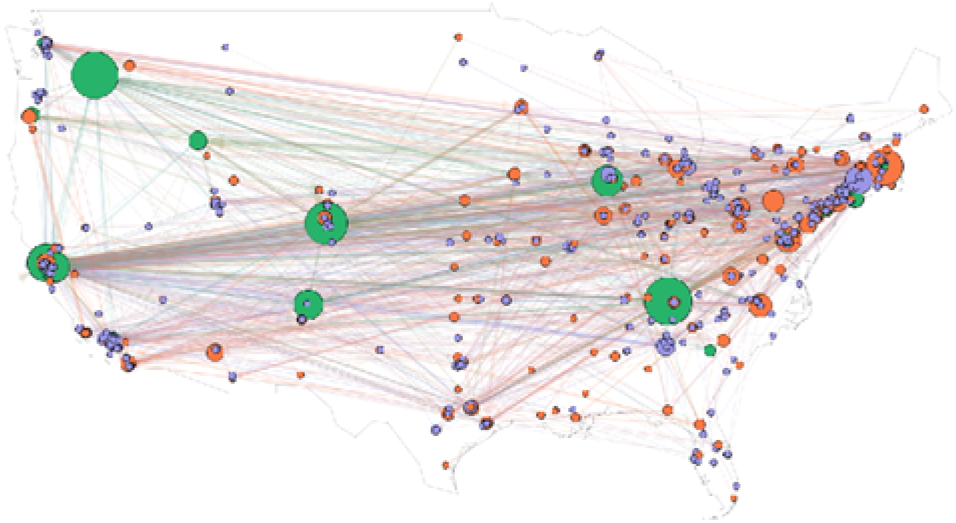

Figure 31: The ARPA-E R&D Network.
Notes: This network graph is based on geo-located information of all participant organizations of ARPA-E research projects since 2009 and their partner institutions. National Laboratories and other Government agencies are in green, Universities in Orange, and companies in purple. I have omitted the University of Alaska, as well as three Hawaiian companies and utilities from this graph to improve clarity. The connections between nodes indicate that the respective organizations cooperate on an ARPA-E project. Node size is based on the node degree (the number of total connections to other nodes – or R&D partnerships under ARPA-E).
Data Source: ARPA-E Website. Author's calculations.

Figure 31 shows higher degree values of nodes to illustrate that certain entities partner on a larger number of different projects with various project partners. The high degree values of national laboratories show that many projects draw on the technical expertise and facilities of the National Labs system. Important here are especially the Pacific Northwest National Laboratory in Benton, WA; the National Renewable Energy Laboratory in Golden, CO; Oak Ridge National Laboratory in Oak Ridge, TN; as well as Los Alamos in NM and the Lawrence Berkeley National Laboratory in CA. Universities like MIT, Duke, and the University of Chicago have also been frequent partners on ARPA-E projects. ARPA-E deliberately leverages the scientific expertise and infrastructure within these installations, pairing this with motivated research groups working on concrete proposals for technology development.

These networks are emblematic of the mode in which federal agencies influence innovation in the US (also see Chapter 1 section 8; Schrank and Whitford, 2015). Federal agencies set specific goals, they provide research funding to firms, universities, or teams of researchers. They solve coordination and search problems by pairing researchers who work on similar problems, they provide the lab space or scientific installations necessary either through university partners or national laboratories. Further, ARPA-E is actively engaged in building communities around specific technologies by organizing meetings and conferences. Such events typiclaly also include financiers and larger private companies that may be interested in commercializing these technologies.

How ARPA-E Impacts Regions that Host Projects

I suggest that initiatives like ARPA-E affect the geographic areas that host associated projects by creating R&D hubs with an increased focus on specific technologies that are connected to country-wide communities focused on related technologies. ARPA-E and other federal initiatives like it are not simply funding research, they are explicit attempts at network building. ARPA-E connects participants to finance, to other researchers working in related fields and gives participants access to technical resources and infrastructure that allows the research teams to work more effectively. By funding R&D projects and connecting them to other entities that conduct similar research, ARPA-E in effect creates a link between local teams and a wider, federal effort to create technological innovation in Clean Energy that is conducted by various federal agencies, firms, and universities (see Chapters 2 and 3). ARPA-E explicitly seeks to include treated organizations, as well as their researchers, in a federal network of researchers and organizations that are focused on these specific technologies.

I suggest that ARPA-E raises the productivity of researchers within the targeted technology class, beyond the project directly associated with ARPA-E. It is not just the legal entities directly involved, but rather the people in the area that are treated. Researchers might leave the organizations that initially received ARPA-E grants or continue working privately on related projects once their ARPA-E-related work is finished.

ARPA-E explicitly seeks to include treated organizations, as well as their researchers, into a federal network of researchers and organizations that are focused on these specific technologies. These connections are likely to become more open also to colleagues or students of researchers who are themselves not directly involved in the funded projects.

Thus, I suggest that each ARPA-E project can be considered a geographically distinct treatment of the area that houses every partner organization. The treatment consists of being recruited into a federal R&D network focused on clean energy. Researchers associated with ARPA-E gain access to funding, but also get connected to resources and assistance from National Laboratories and other research groups in similar areas, but also potential sources of private funding (either for research or to commercialize technologies). As a result, I expect the geographical areas surrounding ARPA-E partners to increase their patenting in clean energy as a result of becoming recruited into this federal network.

4.3 Empirically Testing the Theoretical Assertions

To empirically test the effect of ARPA-E on the relative innovativeness of different areas in clean Energy technologies, I collect data on all ARPA-E projects funded between 2009 and 2023[88], and the location of the organizations partnering on each project. I then match each location to the corresponding county. I suggest that each ARPA-E project can be considered a geographically distinct treatment to the county that houses every partner organization. I hypothesize that counties treated with hosting an ARPA-E project increase their subsequent innovation output in clean energy-related technologies - even beyond those patents directly associated with ARPA-E.

I test these theoretical predictions using a difference-in-difference (DiD) design with multiple treatment periods and variation in treatment timing (Callaway and Sant'Anna, 2021; 2020).

The dependent variable of interest is the number of clean energy-related patents granted at the county level each year. I further collect patent data from the USPTO,

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[88] Data collection from the ARPA-E website was completed in March 2023. Any projects implemented afterward are not included. I thank Huong Ngo for invaluable research assistance in scraping the ARPA-E website.

which I filter for patents tagged with the CPC classification Y02, which denotes technologies related to clean energy.[89] I aggregate patents granted within the CPC category Y02 at the county level as my measure of the dependent variable - the amount of innovation in clean energy technology originating in each region. I use the address of the first-named inventor noted on the patent to establish the location or innovation.

Additionally, patents granted at the USPTO are required to disclose federal funding, which allows me to distinguish between patents that are directly associated with ARPA-E or other federal R&D, and patents that are the result of privately funded R&D. To measure county-level innovation in clean energy, I exclusively focus on privately funded patents. This means that I exclude all patents that feature government-interest statements. Thus, any patents that are directly related to ARPA-E-funded research or any other federal research program do not count towards my measurement of clean energy innovation at the country level. Thus, the key dependent variable of interest here is the annual number of clean energy patents (Y02) that are privately funded.

I consider the earliest year that a county hosts an ARPA-E partner organization as the time that this county first enters treatment. I create a panel of county-years that denotes when a given county enters treatment by starting to host an ARPA-E project partner.[90] In the DiD design, I effectively compare annual levels of clean energy patenting between counties that host ARPA-E partners and those that do not. The design eliminates time-invariant differences between counties – a critical source of potential bias in estimating the relationship between hosting ARPA-E partners and the level of private clean energy innovation.

There are a total of 172 different counties that are treated with hosting or being partners to an ARPA-E project between 2009 and 2022. Figure 32 below shows the number of different counties that host new ARPA-E project partners on an annual basis.

From the following analysis, I exclude the two counties treated in 2022 – because

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[89] The Cooperative Patent Classification Category Y02 is defined by the USPTO as: Technologies or applications for mitigation or adaptation against climate change. This technology class is inclusive of emission reductions technologies, alternative energy sources, technologies intended to reduce energy use, and various attendant technologies.

[90] I consider counties to remain treated once they host an ARPA-E project partner – meaning that treatment does not “turn off”.

they do not have a post-period to evaluate. This leaves me with 170 treated counties in 48 different states. As shown in Figure 32, these counties enter treatment at different times.

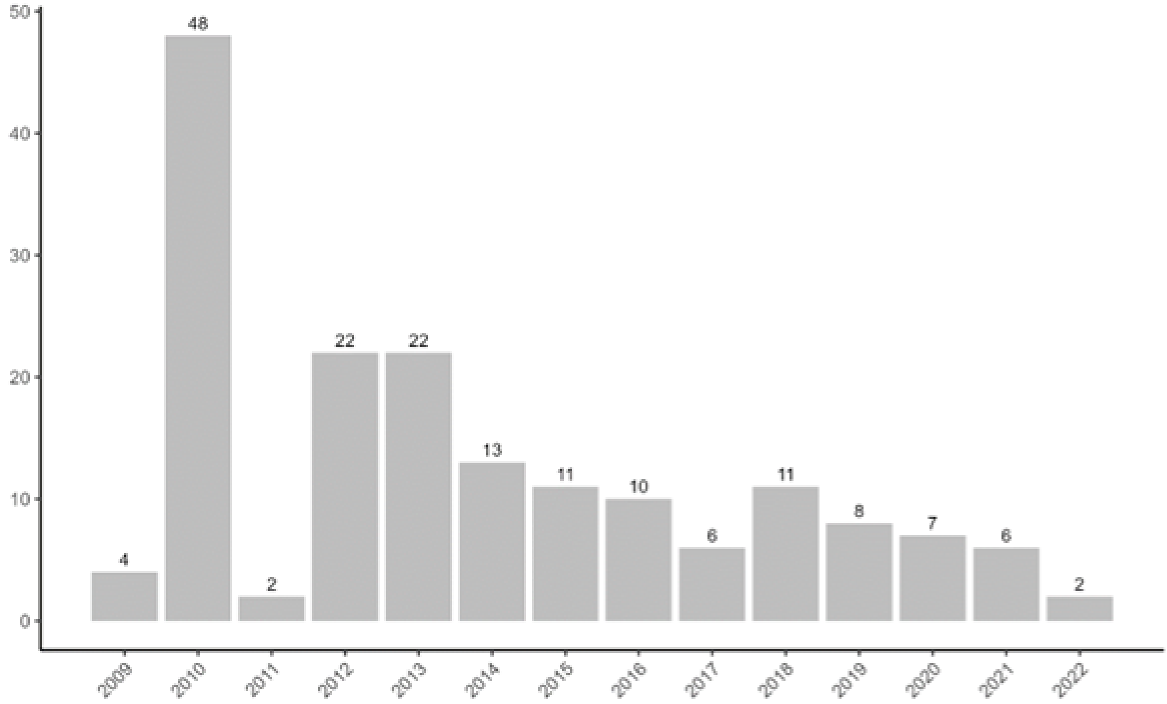

Figure 32: Number of Different Counties Hosting Partners for New ARPA-E Projects per Year.
Data Source: ARPA-E Website.

Matching design

Most counties in the United States do not innovate in clean energy technology. Innovation in general is highly unequally distributed across US counties (see Menaldo and Wittstock, 2024). Only a small number of places within the United States house inventors who produce technology advancements. Hence, it makes little sense to compare counties that host ARPA-E partner organizations to all other counties in their clean energy innovation output.[91] Most counties can be considered "structural zeros" on this metric, in that they lack the infrastructure, and private, or public organizations to engage

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[91] The results presented below hold also when comparing treated counties to all other US counties. I explain why I do not think this is a good comparison group above.

in clean energy innovation.

Hence, I use a matching algorithm to find counties most alike to those treated with hosting ARPA-E project partners at some point after 2009 on relevant pretreatment characteristics. I use the pretreatment period of 2000 – 2008 to find matches for the 170 ARPA-E partner counties. In my main specification, I match treated counties with two counties most similar to the treated county in their level of Y02 patenting prior to the creation of ARPA-E (measured as annual granted privately funded Y02 patents), as well as the size of the county's population.[92] I obtain matches for treated counties using the nearest neighbor algorithm[93]. I thus obtain 340 control units to the 170 treated counties.

I estimate a DiD model with staggered treatment adoption (Callaway and Sant'Anna, 2021), which takes the following form:

The equation is given by:

$$Y_{it} = \alpha + \sum_{g} \gamma_g \cdot \text{Post}_{gt} \cdot D_{ig} + \lambda_t + \mu_i + \epsilon_{it} \tag{3}$$

Where:

- Y_{it} is the number of Y02 patents in county i at time t.
- α is the intercept.
- γ_g captures the effect of the treatment for cohort g (ATT for group g in period t).
- Post_{gt} is an indicator that is 1 if period t is after the beginning of the treatment for group g, and 0 otherwise.

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[92] In additional specifications presented as robustness checks in the appendix, I match counties on wider vectors of pre-treatment covariates, including restricting matches to counties within the same state. The results do not meaningfully change. Further, it does not matter if I use genetic, nearest, or optimal matching to create the control groups. The size of the control group also does not matter. Matching on 1, 2, or three comparable countries does not make a substantive difference to the results. Restricting control units to the same state also does not change results.

[93] For each county, the nearest neighbor algorithm calculates the distance between it and all other counties based on average patenting rates in clean energy from 2000 to 2008, and the size of the population, using the Euclidean distance, which measures the straight-line distance between two points in multi-dimensional space. After calculating these distances, the algorithm identifies the nearest neighbor for each county. This means it finds the county that is most similar based on the smallest distance calculated. The result is a set of matched pairs of counties, where each county is paired with its nearest neighbor. These matches indicate which counties are most similar to each other based on the selected metrics.

- D_{ig} is an indicator for whether unit i belongs to group g.
- λ_t and μ_i represent year and county fixed effects, respectively.
- ϵ_{it} is the error term.

I estimate all models with cluster-robust standard errors, thereby accounting for both heteroskedasticity and contemporaneous correlation in the residuals. The estimated treatment effects γ_g for each group g can be aggregated into an Average Treatment Effect on the Treated (ATT) in different ways. I present three different aggregations below.

Results

Below, I present the results of a DiD regression model with staggered treatment adoption using the Callaway and Sant'Anna estimator (from Callaway and Sant'Anna, 2021). The dependent variable in this model is the number of Y02 patents granted at the county level.[94]

The Average Treatment Effect on the Treated units (ATT) can be interpreted as the relative increase in clean energy patenting experienced by treated units compared to untreated units.

In Figure 33, I plot the results from three separate ways to aggregate the ATT from the Callaway and Sant'Anna (2021) DiD estimator: *Dynamic*, *Group*, and *Group-Time*. *Group* refers to the average effect of participating in the treatment that was experienced across all units that are ever treated. *Dynamic* refers to the average treatment effects at different lengths of exposure. *Group-Time* is a weighted average of all group-time average treatment effects with weights proportional to the group size (a group in this context is a set of counties treated with hosting ARPA-E projects for the first time in the same year). In addition to using different aggregation procedures, the model drops counties that were "treated" (i.e., hosting an ARPA-E project partner) in the first period, the year 2009.

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[94] My main dependent variable in the first model I report in figures 4.3 and 4.4, the number of annual Y02 patents at the county level, has a minimum of 0, a maximum of 1011, a median of 2, and an average of 15.46.

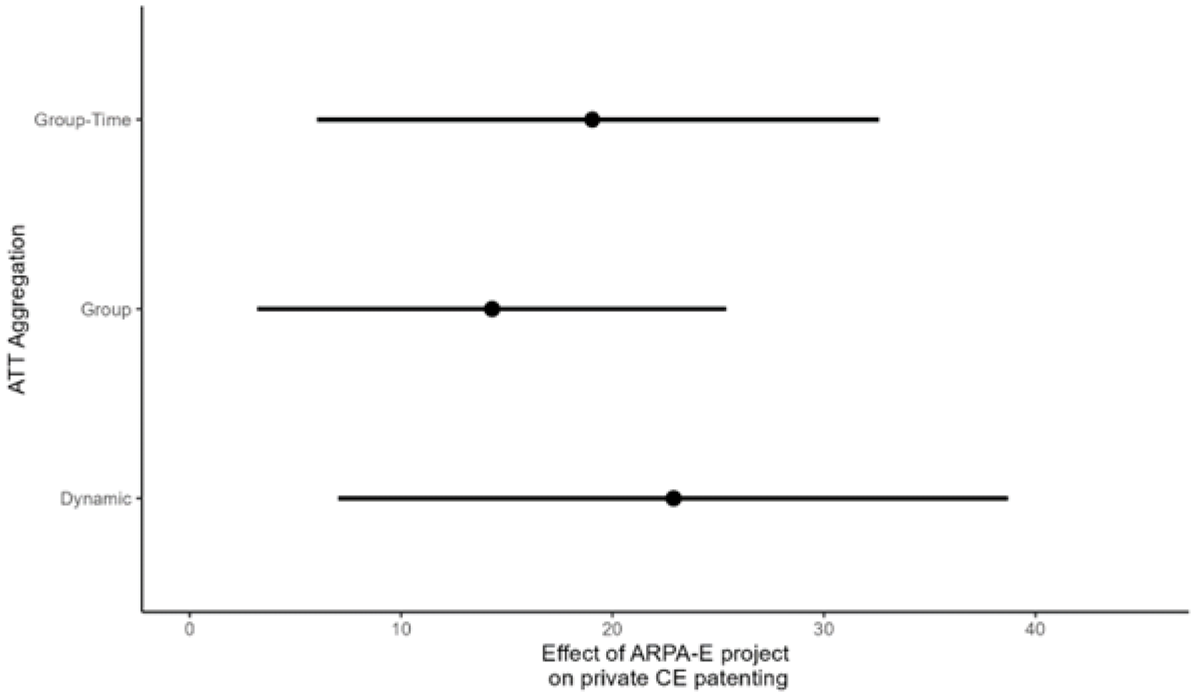

Figure 33: ARPA-E Effect on Annual Private Y02 Patents.
Notes: I display three different ways to aggregate the Average Treatment Effect on the Treated (ATT) using Callaway and Sant'Anna Estimator. Group: The average effect of participating in the treatment that was experienced across all units that are ever treated. Dynamic: Average treatment effects at different lengths of exposure. Group-Time: Weighted average of all group-time average treatment effects with weights proportional to the group size. The control group consists of two matches per treated county, matched on private Y02 patents before 2008 and the county's population size. I do not restrict matches to being from the same state. The matching algorithm used is nearest neighbor matching. I estimate the model using cluster-robust standard errors.

All three ways to aggregate the ATT estimated by this DiD model suggest a sizable treatment effect of hosting an ARPA-E project on subsequent private patenting in clean energy-related technologies. The smallest point estimate is 14.3, whereas the largest point estimate is 22.9. While the point estimates and standard errors will change slightly, these results are not sensitive to the number of comparison counties and are also robust to comparing treated counties to not-yet-treated counties.[95]

I additionally present a graphed version of the average effect by the length of exposure to the treatment (Dynamic effect) below.

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[95] See tables 33.2 and 33.3 in Appendix. Comparing counties to not-yet-treated counties represents a different approach in finding a suitable control group for the counties that become treated

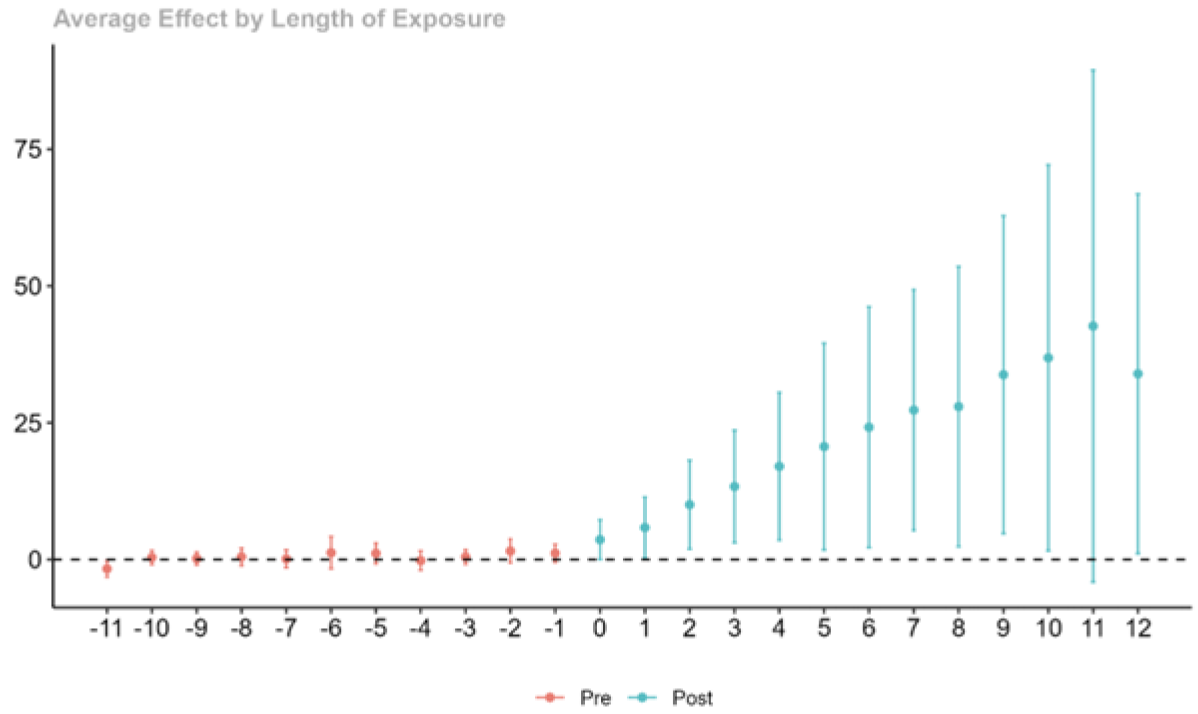

Figure 34: Staggered DID – Average Effect by Length of Exposure to Treatment.
Notes: The control group consists of two matches per treated county, matched on private Y02 patents before 2008 and the county's population size. I allow matches to be from separate states. The matching algorithm used is nearest neighbor matching. This graph shows the average effect size and the average treatment effects at different lengths of exposure. I estimate the model using cluster-robust standard errors.

It is also important to note the lack of a difference before treatment (displayed in red in Figure 34), which suggests that the parallel trends assumption is satisfied here[96], or that the matching procedure described above identified a set of counties that are good comparisons to the treated counties. Hence, this model suggests that ARPA-E indeed results in significantly stronger increases in private patenting in areas that host ARPA-E partners compared to similar areas that do not.

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[96] The parallel trends assumption is a crucial requirement in Difference-in-Differences (DID) designs. It states that, in the absence of the treatment, the average difference between the treated and control groups would have remained constant over time. This assumption ensures that any observed differences in outcomes between the treated and control groups after the treatment can be attributed to the treatment itself rather than to other confounding factors. The pretreatment difference estimates provided by the Callaway and Sant'Anna estimator (shown in red in Figure 34) suggest that in the absence of treatment, the average difference between the treated and control groups would have remained constant.

Alternative Specification

I use the percentage of Y02 patents of all patents granted in a county per year as an alternative measurement of the focus of a county on generating innovation in clean energy-related technologies. To do so, I create the dependent variable by dividing the number of clean energy-related patents by the total number of patents granted to inventors within the county for each county-year.[97]

Then, I again match counties to control units in the way presented above. I use nearest-neighbor matching to identify two comparison counties for every treated county that are most similar in terms of their average pre-treatment percentage of Y02 patents, and their population size. I implement an analogous DiD design as above noted in equation 3, but change the dependent variable. Figure 35 below summarizes the results.

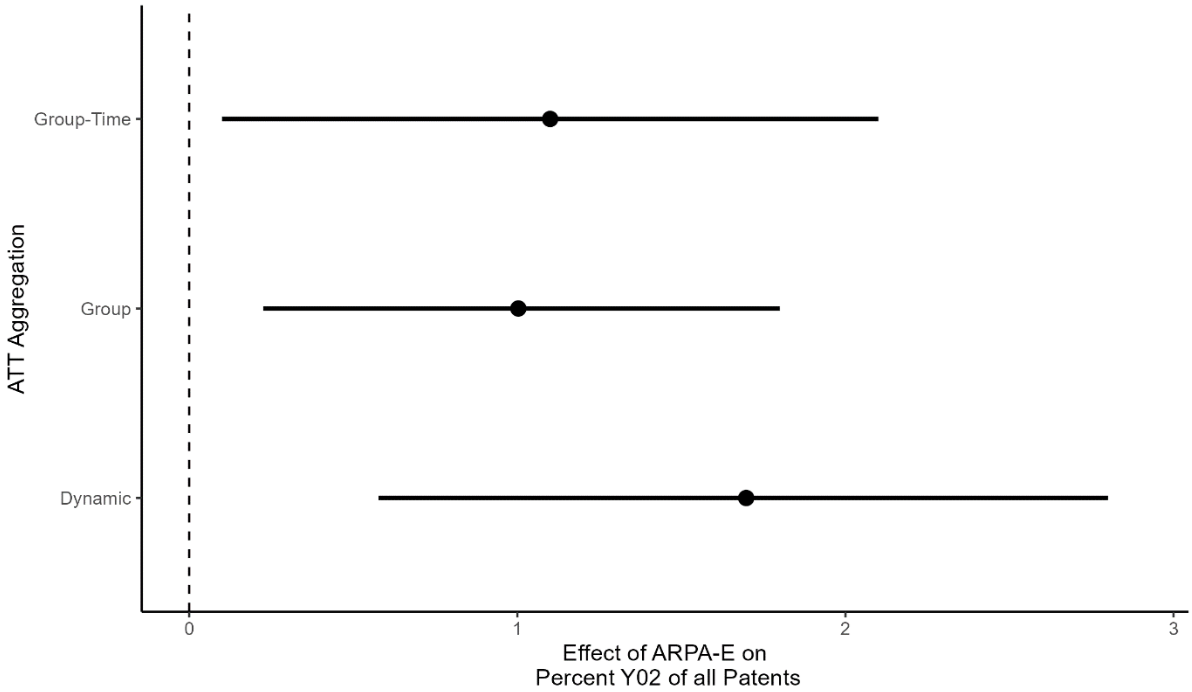

Figure 35: ARPA-E Effect on the Share of Clean Energy Patents.
Notes: I display three different ways to aggregate the Average Treatment Effect on the Treated (ATT) using the Callaway and Sant'Anna Estimator. Group: The average effect of participating in the treatment that was experienced across all units that are ever treated. Dynamic: Average treatment effects at different lengths of exposure. Group-Time: Weighted average of all group-time average treatment effects with weights proportional to the group size. I estimate the model using cluster-robust standard errors.

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[97] This new variable with denotes the share of Y02 of all patents granted within a county ranges from 0 to 100, the mean is 5.9, median is 3.8., SD is 9.2.

Figure 35 shows that there is a consistently positive effect on the share of Y02 of all patents variables. The point estimates range from a 1.05% to 1.8% increase in the percentage of clean energy-related patents that are granted to private inventors in a county. Even being conservative, the lower 95% confidence interval estimates of the ATT range from a 0.1 to 0.58% increase in the percentage of Y02 patents of all patents granted within a county as a result of hosting an ARPA-E partner. Thus, both my main and alternative specifications suggest that counties that host ARPA-E project partners subsequently increase their privately funded Patenting in clean energy technologies more than comparable counties that do not host such projects.

4.4 Conclusion

ARPA-E is one of the flagship federal energy R&D initiatives implemented during the late 2000s. The program has leveraged scientific expertise and infrastructure embedded in the National Laboratories in conjunction with private and university research groups to advance technological development in areas that are intended to boost US national security and provide economic benefits to the US

Federal agencies and R&D initiatives often deliberately target specific technologies for mission-related reasons. I have suggested that federal agencies are actively engaged in building research networks between federal research groups, universities, and private actors. As a result, federal agencies raise privately funded technological innovation in areas that become connected to a wider country-wide research network focused on specific technologies.

I show that counties that have housed ARPA-E partner projects have increased their output in privately funded clean energy innovation faster than comparable counties that have not housed ARPA-E projects. I interpret this as evidence for my contention that federal agencies boost the innovative capacity and focus of entire local research communities by including them in wider federal efforts to advance specific technologies. By funding specific lines of inquiry, programs like ARPA-E raise the focus of researchers on specific technologies. This extends beyond the direct effect of ARPA-E. The program has itself generated useful technological innovations, in the form of patents, scientific articles, and researcher know-how. My analysis suggests that ARPA-E has further raised the productivity of the research communities that exist in those areas that have previously hosted ARPA-E projects.

Chapter 5: The Politics of US Clean Energy Hubs - Evidence From Campaign Donations

5.1 Introduction

In this Chapter, I turn toward the local political effects of the growing innovation and commercialization of clean energy technologies. As Chapter 2 has argued, the US has implemented a set of very technology-oriented policy initiatives. Until 2022, there have been comparatively few policies intended to support the domestic manufacturing capacity of US businesses in clean energy. Further Chapters 3 and 4 examined the uneven geographic impacts of federal innovation policy in clean energy. This Chapter investigates the political outcomes of this uneven geographic pattern.

US firms have often focused on prototyping and selling cutting-edge technologies related to clean energy instead of focusing on in-house manufacturing (Nahm, 2021). Even companies with some significant ambition to manufacture in-house decided to mainly do so outside of the US[98] Hence, the US lacks a considerable domestic manufacturing footprint in many clean energy technologies, which grew into a point of contention during the Trump administration. As part of President Trump's critical stance towards trade with China, he problematized the relative dearth of US manufacturing in sectors like solar panels. Large numbers of those employed in the growing US clean energy industry work in installation and maintenance, while a much smaller group of people works for companies engaged in developing and prototyping innovative applications of novel clean energy technologies.

Technology-oriented federal policy discussed in Chapters 2 and 3 has created small clusters focused on producing innovative technologies but has not provided incentives at a similar scale to build domestic manufacturing industries that would concentrate employment within the United States and across the country, enabling the rise of a sizable domestic political constituency pushing for more accommodating climate policy.

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[98] SunPower Corporation, long one of the leading US solar companies mainly manufactured in Indonesia. In 2019, SunPower announced that it would spin out its solar panel manufacturing business into a separate entity called Maxeon Solar to exclusively focus on selling rooftop solar systems.

Instead, technology-focused federal policy has amplified the development of technology clusters (see Chapters 3 and 4).

Technology clusters concentrate people and spawn businesses with specific economic interests (Menaldo and Wittstock, 2024). This might lead political representatives of these regions to favor specific policies to aid these industries. In recent history, US politicians have often become major proponents of industries located in their home districts. An often-invoked example is the relationship between Senator Paul Tsongas of Massachusetts and Wang Industries and other innovative businesses in Middlesex County, MA. More recently, Representative Zoe Lofgren, representing California's 18th district, which includes Santa Clara County, the most patent-intensive place in the US, has been a key advocate for US knowledge industries. Representative Anna Eshoo of California's 16th district is a similar case. Representatives Lofgren and Eshoo are highly influential in US science and technology policy, having sponsored and coordinated copious amounts of federal legislation with direct relevance to California technology companies. Senator Ed Markey, who was a member of Congress representing Massachusetts's 7th district from 1976 to 2013 has been a key advocate for federal climate policy. The wider Middlesex County area in Massachusetts is also one of the most innovative areas in the country in clean energy technology, also spawning many startups seeking to commercialize new clean energy technologies.

Yet, if the US clean energy industry and its related owners, financiers, and employees continue to be highly geographically concentrated, this growing constituency might be hamstrung in its ability to influence public policy effectively. Entrepreneurs might be especially important constituencies, pushing for policies congenial to their interests. The strong US focus on innovation and technological change as a solution to climate change gives these people a special role. However, if these people are strongly concentrated in specific areas, their political influence might also be primarily local.

What are the political affiliations and preferences of this emerging industry? On the one hand, Democrats should benefit due to climate policy polarization. Climate policy has been associated with Democrats, so we should expect deeper levels of support from this group. How has the overwhelming focus of federal policy on supporting cutting-edge technological innovation related to clean energy technologies impacted the geographical distribution of the fledgling US clean energy industry? Has the growth of the US clean energy industry created a constituency that demands certain policies? Are these constituencies geographically clustered? Have Democrats reaped electoral benefits from their relative embrace of climate policy?

To explore these questions, I combine data from several sources to study the political donation behavior of a sample of 1907 clean energy entrepreneurs and 36,666 workers employed in the US clean energy industry. This donation data spans 15 election cycles between 1990 – 2022. I use data from Crunchbase to obtain the names and associated organizations of entrepreneurs, financiers, and C-suite executives in the US clean energy industry and match this information with campaign contribution data from the Database on Ideology, Money in Politics (DIME) (Bonica, 2016) to capture the campaign donations and common-factor ideology scores imputed from those donations. Further, I use the organization names of 5002 US clean energy companies to identify 36,666 workers associated with the US clean energy industry within the DIME dataset.

My analysis shows that US clean energy entrepreneurs are considerably more Liberal in their imputed ideology values than comparable individuals from the Oil & Gas industry, as well as the average US entrepreneur. While the average clean energy entrepreneur has become more likely to donate to Democrats, as a group, these entrepreneurs continue to donate more to Republican candidates. US clean energy entrepreneurs are also overwhelmingly located in US innovation clusters. Further, those entrepreneurs that are located in such areas are also those that are most ideologically aligned with Democrats.

Further, workers within the US clean energy industry are significantly more geographically distributed than entrepreneurs, but still heavily clustered in high-tech areas. Also, US clean energy workers in more innovative areas are more likely to be Liberal as inferred from their donation behavior. As a group, clean energy workers are overwhelmingly supportive of Democrats.

I can thus show that the growing American clean energy industry has so far been mostly concentrated in high-technology clusters. Democrats have benefitted from their embrace of climate policy, but so far, the political support of this industry remains concentrated in a small number of geographical areas, which has likely undermined the level of political influence this industry can exert.

5.2 The Politics of US Technology Hubs

US innovation in clean energy is concentrated in a small number of highly innovative enclaves, while large parts of the country do neither house innovative labor nor innovative startups that commercialize new energy technologies (see Chapter 3). Highly innovative areas are also more likely to concentrate entrepreneurial activity. Figure 36 shows the connection between innovation in clean energy and the level of local receipts of investments in clean energy companies (including VC, Angel investments, and public funding). Innovation clusters tend to also be the places that receive more funding to commercialize innovative technologies.

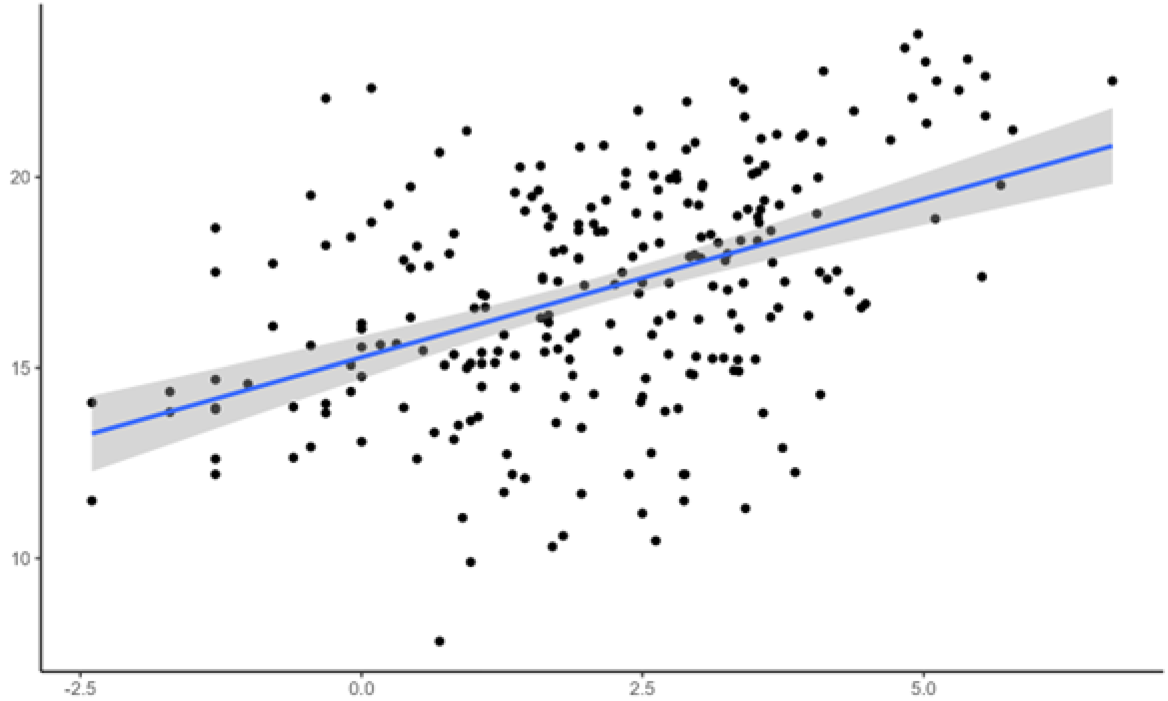

Figure 36: County-level Patenting in Clean Energy and Receipts of Private and Public Capital Investment.
Notes: I only show counties with patents and who have received funding. Both scales are logged. Data Sources: USPTO, Crunchbase, Author's calculations.

Figure 36 mirrors the wider dynamics of the American Knowledge Economy, in which a small number of urban agglomerations benefitted in an outsized manner from Cold War R&D projects and investments in universities, subsequently concentrating large amounts of highly skilled labor and investment capital, creating spatial concentrations of cutting-edge science, innovation, and entrepreneurship (Gross and Sampat, 2023; Glaeser and Hausman, 2020). A small number of technology clusters in California, Texas, Washington, and New England attract disproportional numbers of highly educated workers, federal R&D spending, as well as private spending on company formation and as a result account for most of US technological innovation and innovative start-ups (Glaeser and Hausman, 2020; Menaldo and Wittstock, 2024).

As a result of this increased spatial polarization in the focus of different US regions on producing and commercializing cutting-edge technologies, the political-economic preferences of regions' inhabitants have also diverged (also see Rodden, 2019; Menaldo and Wittstock, 2024).

Figure 37 demonstrates this dynamic by plotting the average two-party vote share of the Democratic party at the county level in Presidential elections since 1972 for counties within the 99th, 75th – 99th, and below the 75th percentile in terms of annual patents granted to inventors within each county. Figure 37 highlights that electoral support for Democrats in federal elections has declined among less innovative counties since the first Clinton Presidency in 1992 and has especially grown among the most innovative counties.

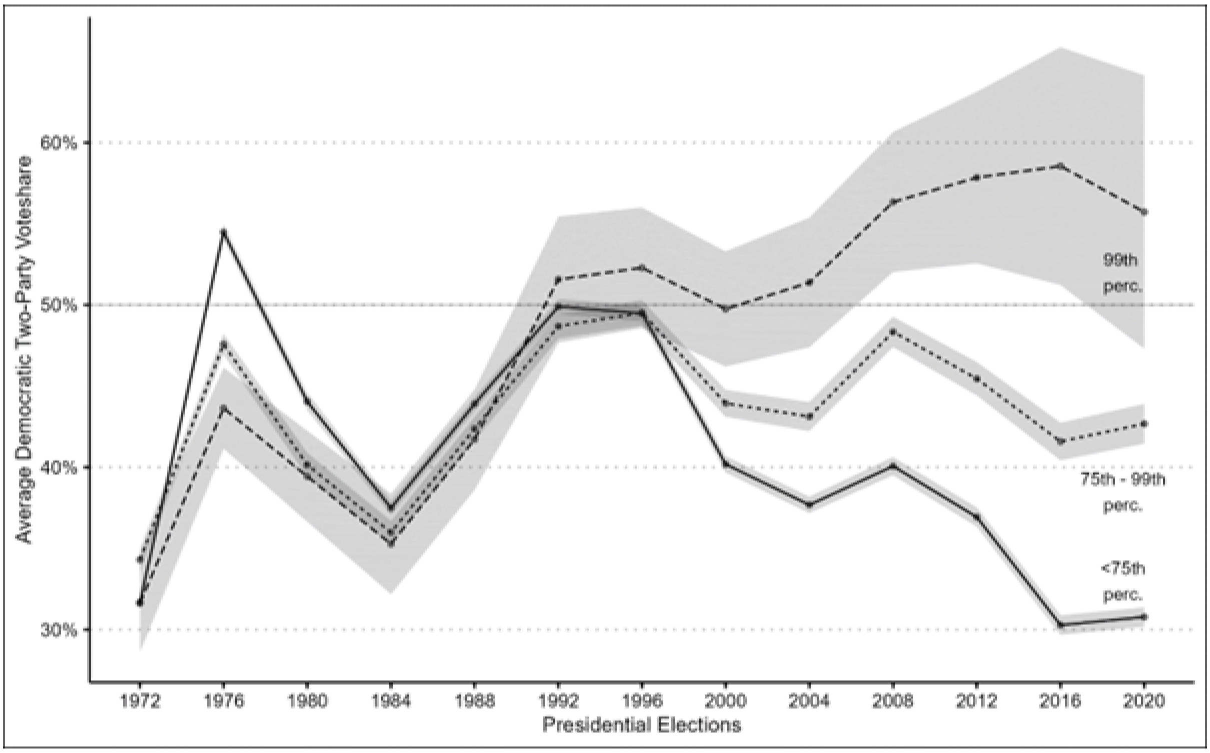

Figure 37: Average County-level Democrat Two-party Vote Share in Presidential Elections by Select Decadal Patenting Percentiles.
Note: I calculate the decadal patenting percentile that each county falls into by summing up all patents granted to inventors for each county, dividing by the closest decadal census population estimates, and multiplying by 10000 to obtain Patents per 10k inhabitants. I distinguish counties by the percentile they fall into for each decade on this measure. I display the average Democratic Two-party vote share for the 99th percentile, 75th -99th percentile, and counties below the 75th percentile.
Data Sources: USPTO, Algara and Amlani (2021); Author's calculations.

Because innovative activity is so spatially concentrated in the US, there is little practical difference between counties within the 50th percentile or 10th percentile of Patents Per 10k People. Figure 37 illustrates that the most innovative US areas and the rest of the country have diverged significantly in their policy preferences after the 1980s. Under Clinton, the ascendant "New Democrats" re-oriented the party away from its New Deal commitments, and towards a political embrace of the Knowledge Economy growth model (Short, 2022; Gerstle, 2023; Lichtenstein and Stein, 2023; Greene, 2021). This economic vision saw investment in education and worker skills, together with public investments in American science and technology as far more important to thrive in new industries than labor unions or welfare state spending. This political reorientation of Democrats partly explains the strong gains Democrats have made among knowledge workers employed in finance, high-tech industry, and academia (Short, 2022). The orientation of places in the US towards successfully producing and commercializing novel technologies has increasingly turned into the driver of diverging economic preferences within the country. Menaldo and Wittstock (2024) show that relative rates of innovation at the county level were systematically tied to the local electoral support of Candidate Trump in the 2016 and 2020 Presidential elections.

Illustrating this point further, Figure 38 shows the estimated coefficients for the average effect of the county's annual patenting percentile on the average common-factor ideology scores inferred from political campaign donations made by people within the same county.

To produce this graph, I aggregated all campaign donations made by donors within a given county for each election cycle and estimated average common-factor ideology scores at the county level, using data from the DIME database (Bonica, 2023). I then regress these county-level Ideology Scores on the Patenting Percentile separately for each election cycle, controlling for state-fixed effects.[99] The coefficient captures the average effect of increasing a county's patenting percentile by one unit on the average ideology score attributed to the political donations made by people within that county. Figure 38 thus shows that a county's level of innovation intensity has grown into a stronger predictor of population political ideology. The coefficient estimates become more negative over time, suggesting that more innovative areas have increased the number of donors with political ideologies aligned with Democrats. This development has only become apparent since the 2002 election cycle. Until then, there was no consistent connection between a county's patenting percentile and the average ideology of political donations.

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[99] I aggregate all patents granted each year at the county level and express this value in Patents per 10k people using the closest decadal Census population estimates for every given year. I then distinguish counties by their annual percentile in terms of Patents per 10k People. The CF score ranges from -2 to +2, measuring the distance in political ideal points. I fit annual regression models estimated via OLS, controlling for state fixed effects.

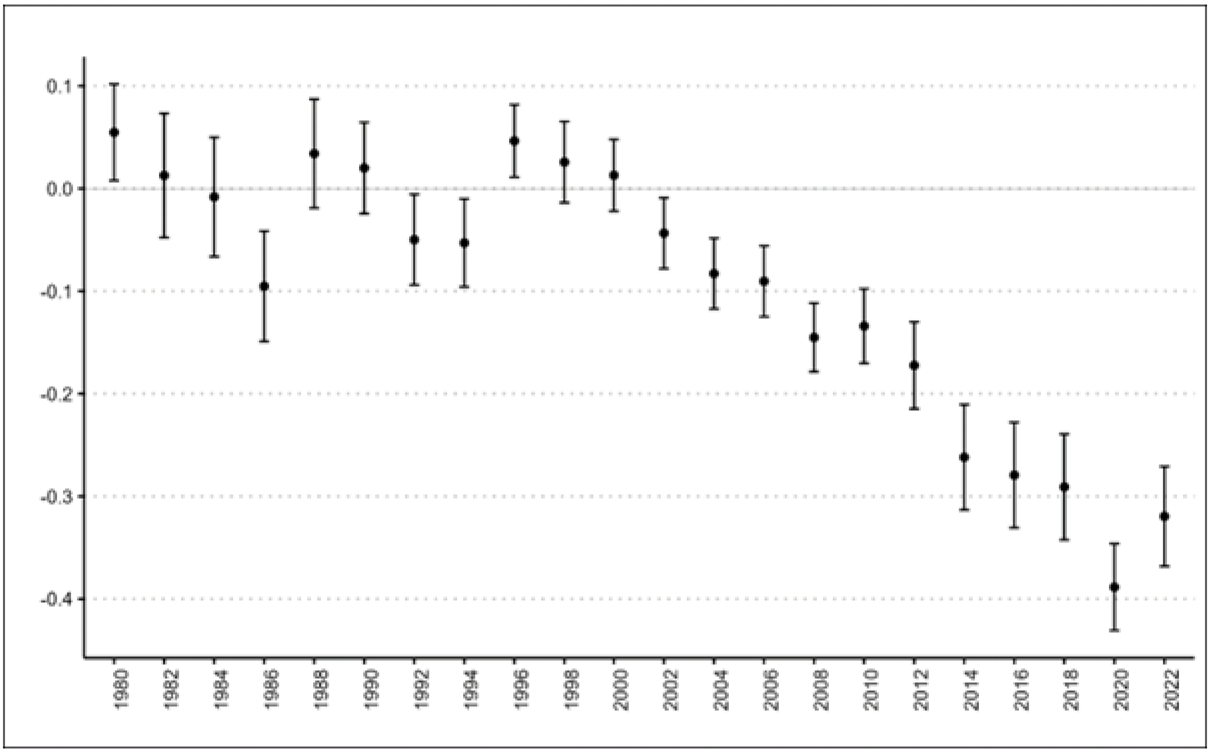

Figure 38: Effect and Confidence Intervals for Patent Percentile on Average Common-Factor Ideology Score at the County Level.
Notes: I aggregate all patents granted each year at the county level and express this value in Patents per 10k people using the closest decadal Census population estimates for every given year. I then distinguish counties by their annual percentile in terms of Patents per 10k People. The CF score ranges from -2 to +2, measuring the distance in political ideal points. I fit annual regression models estimated via OLS, controlling for state-fixed effects.
Data Sources: DIME (Bonica, 2023); USPTO; Author's calculations.

This thus corroborates the impression from Figure 37. Being technologically innovative has grown into a stronger predictor of political ideology over time. Innovative regions in the US have been the main winners of the US economic orientation towards industries "*so advanced that there is no competition*" (National Academy of Sciences, 2007: 26). These regions have also grown more politically connected to the Democratic party (also see Short, 2022).

Yet, the number of highly innovative areas in the US is small. Some scholars have argued that because the winners of the contemporary US growth model have become so concentrated in a few urban agglomerations, the American Knowledge Economy is politically unsustainable (Hacker et al. 2021; Short, 2022, Rodden 2019). Cities, or rather specific urban agglomerations, are economically favored in the knowledge economy but are systematically politically penalized in several instances by the US election system (see Rodden, 2019). As a result, the fact that innovation clusters concentrate the economic winners of the US Knowledge Economy leaves an abundance of Congressional Districts and entire States that will follow different economic preferences in their political decision-making, pushing for policies possibly anathema to the economic prospects of US innovation clusters (Menaldo and Wittstock, 2024).

How has the overwhelming focus of federal policy on supporting cutting-edge technological innovation related to clean energy technologies impacted the geographical distribution of the fledgling US clean energy industry? Has the growth of this industry created a constituency that demands specific policies? Are these constituencies geographically clustered? Have Democrats reaped electoral benefits from their relative embrace of climate policy?

By investigating these questions, this Chapter contributes to studies of the contemporary US focus on generating competitive advantage through technological superiority and its effects on US politics (see Chapters 3 and 4; Menaldo and Wittstock, 2024; Short, 2022). In doing so, this study also relates to a wider literature on the interaction of economic inequality and political polarization in the US (McCarty, Poole, and Rosenthal, 2016; Rodden, 2019)

5.3 The Politics of the US Clean Energy Industry

Climate policy and support for the emerging clean energy industry has become an increasingly partisan issue in US politics. Over the last two decades, state-level governments in the US have become major policymakers in climate-related areas. Several states have implemented a variety of climate policy tools, including net-metering laws and renewable portfolio standards (Bergquist and Warshaw, 2023, Trachtman, 2020). Yet some states have moved much more than others, creating substantial policy distance between them. One way to capture this distance comes from Bergquist and Warshaw (2023), who compiled a set of twenty-five policies that multiple states have implemented to reduce greenhouse gas emissions, increase domestic clean energy production, and boost energy efficiency. Based on these policies, Berquist and Warshaw (2023) use a Bayesian factor analysis model to estimate the state-level climate policy stringency as a continuous variable. Previous work in this area has often focused on the presence or implementation of single policies. Bergquist and Warshaw's (2023) Climate Policy Score allows comparisons of states across time along a more holistic dimension of climate policy stringency. Figure 39 displays the state-level values of the combined Climate Policy Score from 1999 – 2020.

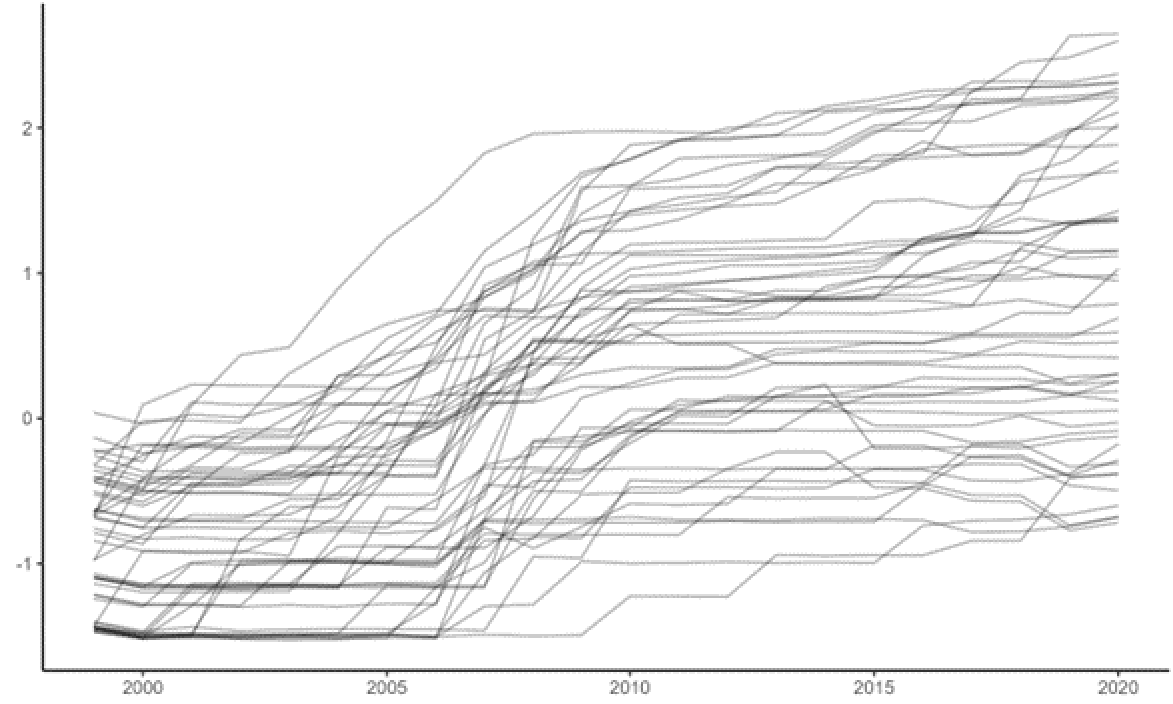

Figure 39: Annual State Climate Policy Score.
Notes: The State Climate Policy Score is based on a Bayesian factor analysis model that uses a set of 25 state-level policies to provide a ranking of state climate policy efforts on the dimensions across which states are comparable, from 2000 to 2020.
Data Source: Bergquist and Warshaw (2023).

Figure 39 thus depicts an estimate of the increasing distance in the combined climate policy commitments between states. While states have generally increased their Climate Policy Scores during the pictured timeframe, the distance between states has increased on average.[100] This increased distance can be ascribed to Republican disinterest in climate policy paired with Democratic initiative on this issue (Trachtman, 2020). As a result, climate policy has grown into an increasingly partisan issue. This is easily demonstrated through a regression model.

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[100] The maximum of this index in 2000 was Vermont (0.09), the minimum was Idaho (-1.5). Maximum in 2020 was NY (2.64), Min in 2020 was WV with (-0.72).

I use data from Philip Thomas's GitHub Library on state partisan composition to create an annual measure of partisan state legislative control and regress this on Bergquist and Warshaw's Climate Policy Score. I differentiate between Democrat Control, Divided Government (no one party majority in both houses of state congress), and Republican Control. Using the legislative control of the state legislature as an independent variable, I estimate simple fixed effects and OLS regression models to show the negative effect of Republican state legislative control on the above-discussed Climate Policy Index.

Table 11: Regression Results

	Climate Policy Index		Clean Energy Gen.	
	FE (1)	OLS (2)	FE (3)	OLS (4)
Divided Gov.	-0.15***	-0.15***	-2.01	-0.20
	(0.05)	(0.06)	(1.40)	(0.66)
Republican Control	-0.12**	-0.32***	2.12	-0.29
	(0.06)	(0.06)	(1.53)	(0.78)
BEA Region Controls	N	Y	N	Y
GDP Per Capita	Y	Y	Y	Y
Population	Y	Y	Y	Y
CO2 Per Capita	Y	Y	Y	Y
Observations	1,259	1,259	1,259	1,259
Adjusted R2	0.38	0.49	0.35	0.15

*** Significance at the 1% level. ** Significance at the 5% level. * Significance at the 10% level. Note: Standard errors are in parentheses. The models control for annual GDP per capita, Annual C02 emissions per capita, and the annual population numbers of the state. The OLS model additionally controls for BEA region-fixed effects. Data Source: Bergquist and Warshaw (2023); Author's calculations.

Columns 1 and 2 of Table 11 show the results of Fixed-Effects and OLS models, respectively. Moving away from Democratic State Legislative control significantly reduces the Climate Policy Score. Thus, the holistic climate policy measurement created by Bergquist and Warshaw (2023) shows that over the 1999 – 2020 period, state-level legislative control by Democrats has been associated with systematically more stringent climate policy than state-level governments with divided or Republican legislative control.

The partisan polarization on climate policy issues is also evident at the federal level. Figure 40 shows the distribution of Climate Scorecard scores of Congressional Representatives which the League of Conservation Voters produces annually, for 1976 and 2022. These scores are based on the voting record of Congressional Representatives on a set of bills selected by the League of Conservation Voters. Already in 1976, Republicans received lower scores on average, which corresponds to less concern for environmental issues, fostering renewable energy companies, and more policy support for fossil fuel industries.

However, in 2022, partisanship almost produces perfect separation of Congressional Representatives into scores either indicating highly accommodating policy on climate and clean energy in the case of Democrats and the complete opposite for Republicans.[101]

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[101] Admittedly, the League of Conservation Voters has recently included bills into their scoring scheme that do not obviously relate to climate policy, and arguably betray a partisan bias. However, the general pattern depicted in Figure 40 does not change if one focuses specifically on the Congressional Voting record on bills that are explicitly related to energy policy.

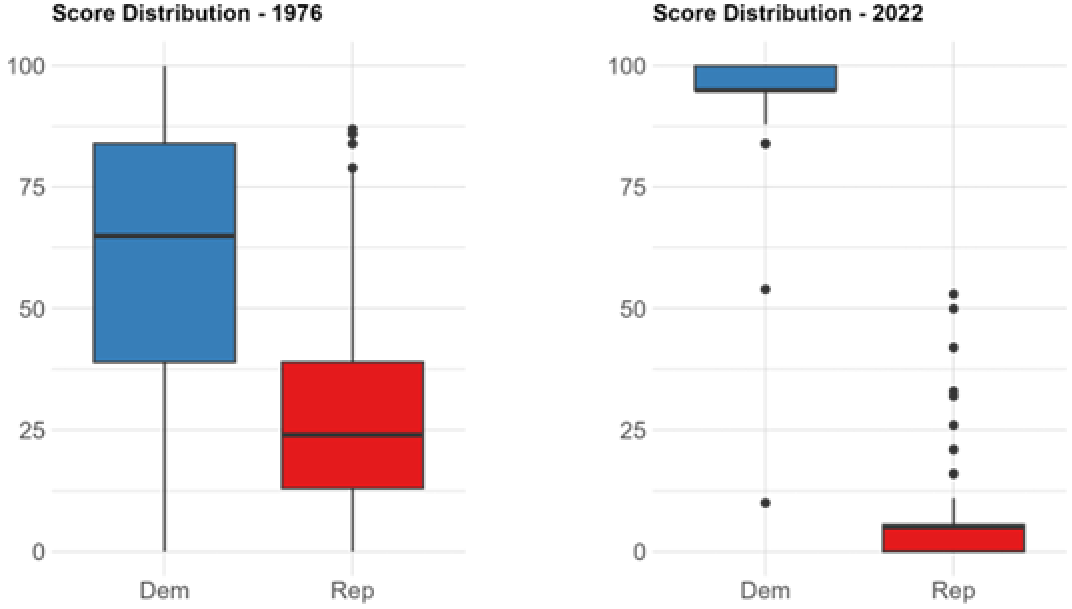

Figure 40: League of Conservation Voters Climate Scorecard for Congressional Representatives.
Notes: LCV scores the legislative actions of each Congressional Representative for every year based on a set of bills chosen by LCV. Higher scores indicate a voting record more in line with what the LCV considers to be pro-environmental legislation.
Data Source: League of Conservation Voters Scorecard Archive; Author's calculations.

These two examples illustrate that Republican lawmakers at both the state and federal levels have been less accommodating of climate policy. This suggests that the Democrats are the clear political ally of the emerging clean energy industry in the US.

Importantly, it is empirically not the case that Republican-controlled states generate less renewable energy than Democrat-controlled states on average. Columns 3 and 4 in Table 11 above show the results of Fixed Effects and OLS regressions that estimate the effect of Partisan legislative control on the amount of clean energy generation at the state level. Both models show that there is no clear relationship between these two variables.[102] The point estimate on Republican Control is even positive in the Fixed Effects specification, albeit not statistically significant.

Thus, while it is intuitive to assume that more accommodating policy would boost

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[102] This result is not sensitive to the inclusion of the state of Texas, which is both a Republican-run state and the largest generator of renewable energy among US states. I use estimates from Berquist and Warshaw (2023) on the annual clean energy generation capacity across states.

renewable energy capacity in Democrat-run states, this is not a clear empirical pattern. At least, it is not the case that renewable energy generation is highly concentrated in Democrat-run states. At a minimum, states that are legislatively controlled by Republicans do not have systematically smaller clean energy capacity, suggesting that these states do have markets for clean energy technology.

It is plausible that Republican states have found policy tools other than climate policy to incentivize the growth of clean energy industries. It is thus ex-ante not obvious if Democrats have benefited politically in an unequivocal way within the emerging clean energy industry from their embrace of climate policy. Further, the strong federal policy focus on technological innovation in clean energy has amplified the clustering of innovation and commercialization of high-tech businesses in a small number of areas. The business constituency interested in accommodating public policy might be similarly spatially concentrated. This geographic clustering of the US clean energy Industry might undermine its ability to influence policy. To understand more about the political affiliations and preferences of the growing US clean energy industry as well as its spatial distribution, I now turn to evidence from political campaign donations.

5.4 Political Donations of the Clean Energy Industry

I use the Crunchbase dataset to obtain a list of 11296 individuals listed either as founders, owners, key investors, or C-suite executives within the US clean energy industry.[103] I henceforth refer to this group of people as clean energy entrepreneurs. I use the first and last names, as well as the primary company[104] that these people are associated with to match these entrepreneurs with political donations records from the DIME database (Bonica, 2023). DIME provides information on the first and last names, as well as the self-provided employer of the donor. I use these three pieces of information to match individuals across the DIME database and the Crunchbase list of clean energy

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[103] Crunchbase identifies owners, founders, active financiers, or Venture Capitalists, as well as C-suite executives, Partners, and other influential individuals within an array of industries. Crunchbase provides their own industry classification scheme. I select entrepreneurs based on whether they are active within the Crunchbase-provided industries of Solar, Battery, Biofuel, Biomass, Clean Energy, Energy Storage, Fuel Cell, Geothermal, Hydroelectric, Renewable, or Wind industries.

[104] I use the Primary Organization as listed by Crunchbase connected with the people I identify.

entrepreneurs. To supplement, I additionally extract the campaign donations made by all people employed by a list of 5002 US clean energy companies over the same timeframe.[105] For the analysis below, I filter this list for all donors who list their occupation as either "owner", "ceo", or "president". I add the individuals identified in this manner to the sample described above.

In this manner, I identify the campaign donation records of a total of 1907 clean energy entrepreneurs over the 1992 – 2022 election cycles. Table 12 below offers summary statistics:

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[105] I again use Crunchbase to create this list of US clean energy companies.

Election Cycle	Number of Donors	Number of Donations	Percent Democrat Donations	Total Dollars Spent	Two-Party Democrat Dollar Share
1992	11	42	63.9	69,175	59.9
1994	16	54	28.3	70,940	29.2
1996	17	90	17.1	82,127	17.8
1998	29	91	27.7	86,543	23.6
2000	61	265	37.7	693,333	41.4
2002	127	714	36.0	2,028,950	24.6
2004	182	1,045	44.3	5,633,693	15.0
2006	184	1,318	44.8	3,171,313	33.2
2008	378	2,764	55.9	5,515,341	35.7
2010	497	3,935	59.5	7,716,995	39.1
2012	641	5,669	56.1	13,391,879	25.5
2014	688	6,085	57.5	19,574,995	36.2
2016	903	8,326	67.1	28,416,958	37.7
2018	990	10,580	74.7	32,773,004	29.5
2020	1,753	27,679	74.4	45,298,116	50.9
2022	1,129	15,722	72.9	50,486,012	27.3

Table 12: Summary Statistics of Clean Energy Entrepreneur Political Donations
Notes: I identify a total of 1907 clean energy entrepreneurs from the DIME political donation database. I use first and last names and associated organizations from 11296 people listed on Crunchbase as associated with the US clean energy industry. I match these with records from DIME. Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

In addition to this group of clean energy entrepreneurs[106], I additionally identify 36,666 individuals who are employed by one of the 5002 US clean energy companies listed in the Crunchbase dataset but are not themselves clean energy entrepreneurs. I refer to this group as clean energy workers.

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[106] I identify this group by filtering the DIME dataset for donations by individuals that list one of the clean energy companies as their employer.

Election Cycle	Number of Donors	Number of Donations	Percent Democrat Donations	Total Dollars Spent	Two-Party Democrat Dollar Share
1992	70	89	72.0	53,490	65.9
1994	62	82	47.5	57,245	48.4
1996	120	164	39.4	97,033	43.7
1998	145	205	51.6	134,370	42.8
2000	252	361	38.2	460,629	36.3
2002	357	823	57.5	343,867	35.9
2004	618	1,305	65.0	586,797	42.3
2006	511	984	60.7	438,462	49.1
2008	1,483	4,106	77.3	1,319,240	76.5
2010	1,341	9,181	71.0	1,847,752	57.6
2012	2,412	13,120	82.7	2,458,048	52.9
2014	1,806	6,914	88.1	1,852,236	46.1
2016	4,221	22,735	93.7	2,677,703	55.7
2018	4,268	22,442	93.6	3,416,538	53.5
2020	20,739	150,609	86.3	10,942,239	82.4
2022	9,540	64,413	81.2	6,287,258	68.9

Table 13: Summary Statistics of Clean Energy Worker's Political Donations

Notes: I identify a total of 36,666 from the DIME political donation database. I use first and last names and associated organizations from 11296 people listed on Crunchbase as associated with the US Clean Energy industry. I match these with records from DIME. Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Political Affiliations of Clean Energy Entrepreneurs

What are the political affiliations of clean energy entrepreneurs? The increasing association of climate policy with the Democratic party suggests that this group of people should be much more likely to be political supporters of the Democrats. The DIME database includes information on the partisanship of the recipients of donations, which allows me to ascertain the partisan support of clean energy entrepreneurs. The summary statistics tables 12 and 13 indicate that increasing percentages of donations for both clean energy entrepreneurs and workers have gone to Democrats, while the aggregate number of dollars has been more directed towards Republicans. Figure 41 visualizes this for the sample of clean energy entrepreneurs by simply aggregating all donations for each election cycle by the partisanship of the recipient.

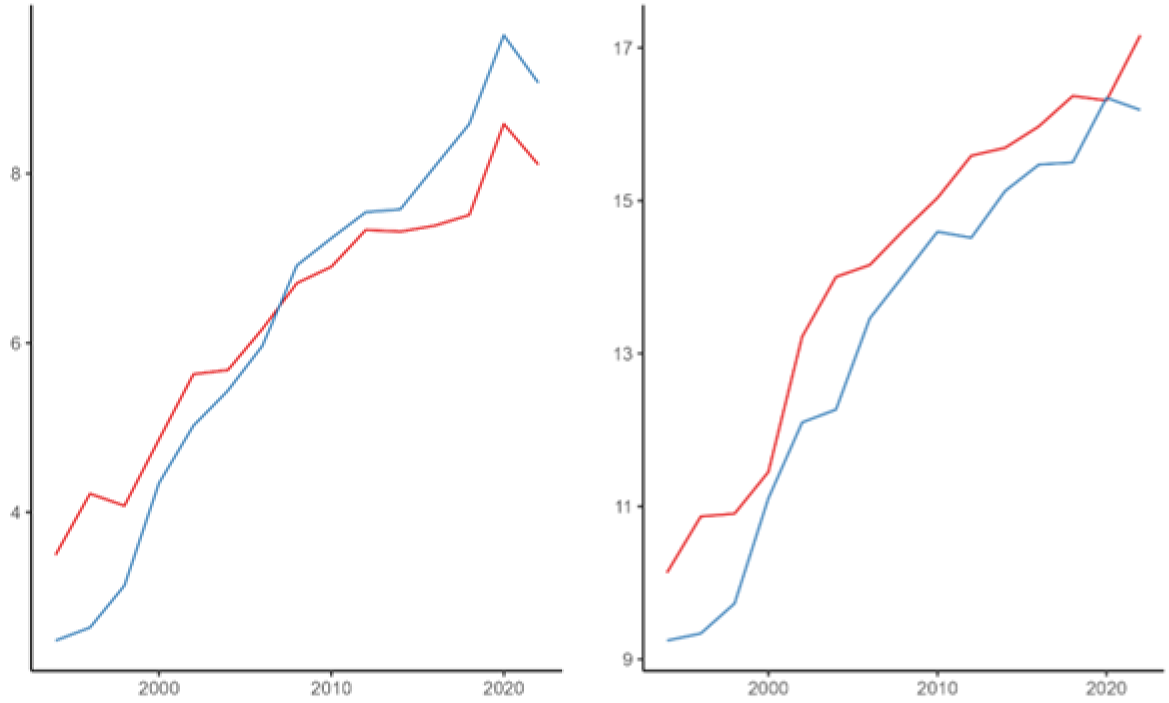

Figure 41: Number of Donations (left) and Total Spending (right) from CE Entrepreneurs to Democrats (blue) and Republicans (red) Between 1992 – 2022.
Notes: Both y-axes are on logged scales.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Interestingly, Figure 41 shows that in terms of the number of donations, Democrats have been able to overtake Republican early advantages among this group. However, in terms of the total dollars spent, Republicans still receive a larger share of donations from clean energy entrepreneurs.

Democrats have created a lead in donation receipts, less so in the total amount. But support seems to favor Democrats. The donation-imputed common-factor ideology scores of clean energy entrepreneurs corroborate this picture. Figure 42 displays that the average CF score of clean energy entrepreneurs has consistently declined over the period of observation.

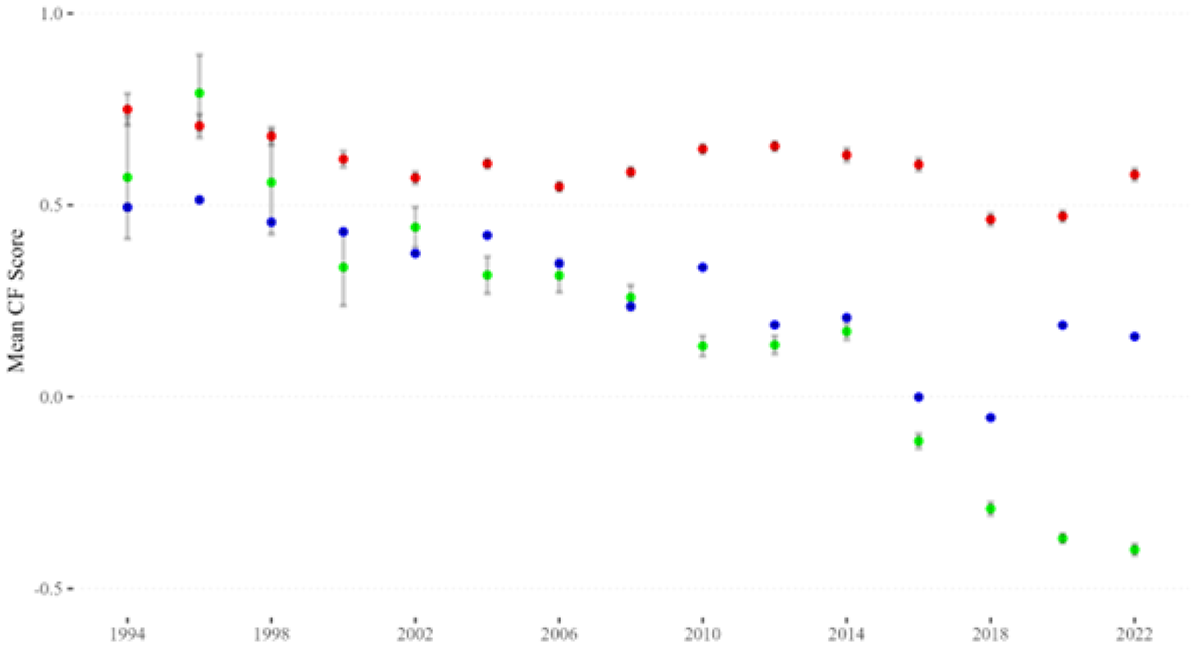

Figure 42: Common-factor Ideology scores of CE Entrepreneurs (Green), Oil & Gas (Red); and all other Entrepreneurs (blue) Between the 1994 – 2022 Election Cycles.
Notes: I calculate average CF scores for each group and election cycle by averaging across unique donations. Additionally, I provide 95% confidence intervals based on the standard deviation of the CF score for each group-cycle. The CF score ranges from -2 to +2, measuring the distance in political ideal points. Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

To provide relevant comparison groups, I also include the average CF score of a group of owners, C-suite executives, and company presidents of the Oil & Gas industry, as a stand-in for the fossil fuel industry. I also calculate average CF scores of American CEOs, owners, and company presidents that fall into neither industry to provide information on the ideological position of American dntrepreneurs outside of the energy industry.

Figure 42 shows that clean energy entrepreneurs have grown to be on average much more Liberal than the average US entrepreneur. Further, entrepreneurs in other industries have not changed their ideology as much as those within the clean energy industry. Overall, the average CF scores within the group of Oil & Gas industry entrepreneurs have been stable. Importantly, the imputed ideological difference between all three groups was much less pronounced in the 1990s but has steadily increased throughout the 2000s and

10s. The campaign donations for clean energy entrepreneurs suggest that this group veered to the left in the mid-2000s. This mirrors the ideological movement of other entrepreneurs not associated with either industry until around 2016 when clean energy entrepreneurs appear to have moved further to the left.

The sample of clean energy entrepreneurs thus indicates that this group of people is on average substantially more ideologically aligned with Democrats and does donate to them more on average. However, there remain considerable numbers of high spenders in this group that donate to Republicans. On balance, this sample suggests that Democrats have politically benefitted from their stronger focus on climate policy.

Innovation Clusters and Campaign Donations

Given the clustering of innovative businesses in areas of technological innovation discussed in the previous section, is it the case that clean energy entrepreneurs mainly hail from such high-innovation areas? Do people in high-innovation areas somehow donate differently, suggesting that people in innovation clusters have different political preferences from those who live outside of them?

To determine if a donor lives in an innovation cluster focused on clean energy, I use USPTO data to measure the number of patents granted in CPC sub-group Y02 between 2010 and 2020. I aggregate these patents at the county level and express them in patents per 10k inhabitants using population estimates from the 2010 US census. This yields a measurement of the contemporary patent intensity of counties across the US related to clean energy technologies. Many counties do not produce any patents. I thus divide counties into different groups, one group for all those counties without any patents between 2010 and 2020, and, for positive counts, I divide counties into quartiles.

Figure 43 reports the number of donations and the total amount of dollars spent by each bucket across all election cycles between 1992 – 2022. Unsurprisingly, clean energy entrepreneur-donors are predominantly located in patent-intensive areas. The spending is also highest in the most innovative areas. Figure 43 shows that the group of counties in the highest quartile of patents per capita also records the largest number of campaign donations from clean energy entrepreneurs.

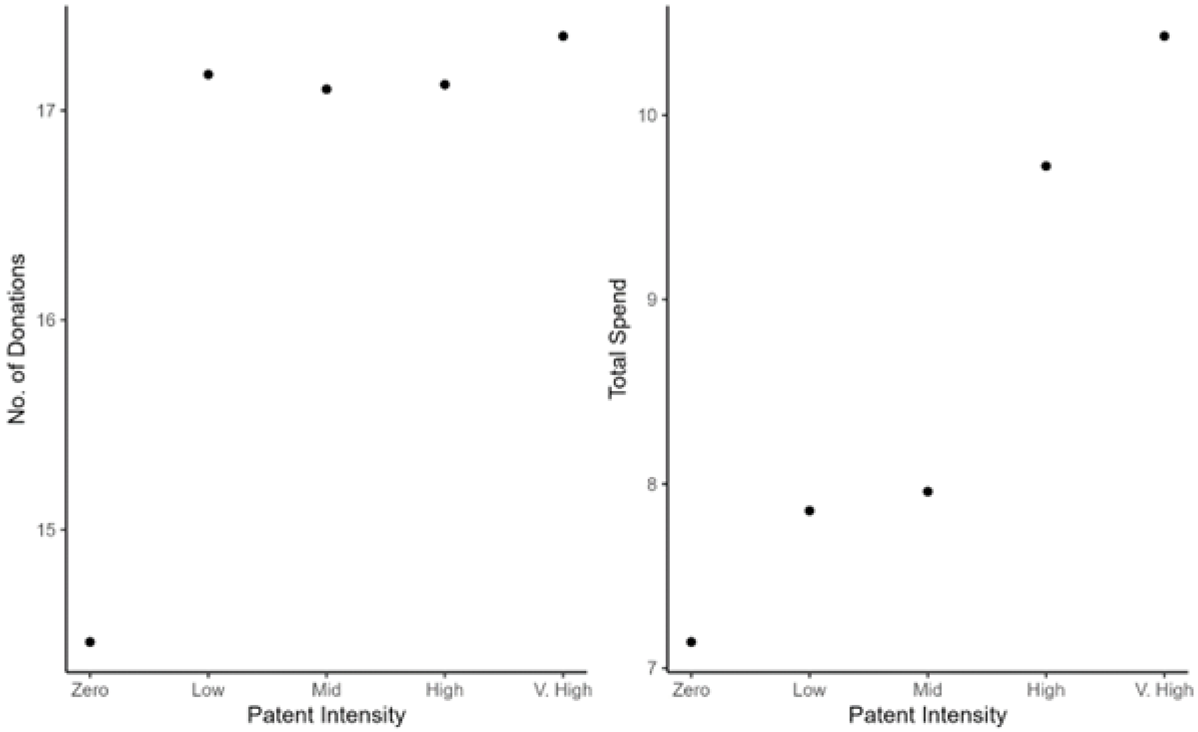

Figure 43: Clean Energy Entrepreneur-Donors are More Likely to Donate in Innovation Clusters and Donate Larger Amounts.
Notes: This graph is based on all election cycles after 2010 combined. Both y-axes are logged. Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

This geographical concentration of clean energy entrepreneur-donors has not attenuated over time. While the total number of donating districts or zip codes has increased in more recent election cycles, the total number of increasing donations remains concentrated on the top end. Before 2016, the top five Congressional districts accounted for roughly 21% of all donations from entrepreneur-donors. After 2016, they made almost 30%.

Figure 44 below shows this temporal dynamic differently. While the total number of entrepreneur donations has increased, these increases have mainly originated from innovation clusters. Figure 44 shows that the percentage of all donations originating from the most innovative counties (90th percentile) has increased since the mid-2000s. Since 2008, roughly 40% of all clean energy entrepreneur donations came from the most innovative decile of counties.

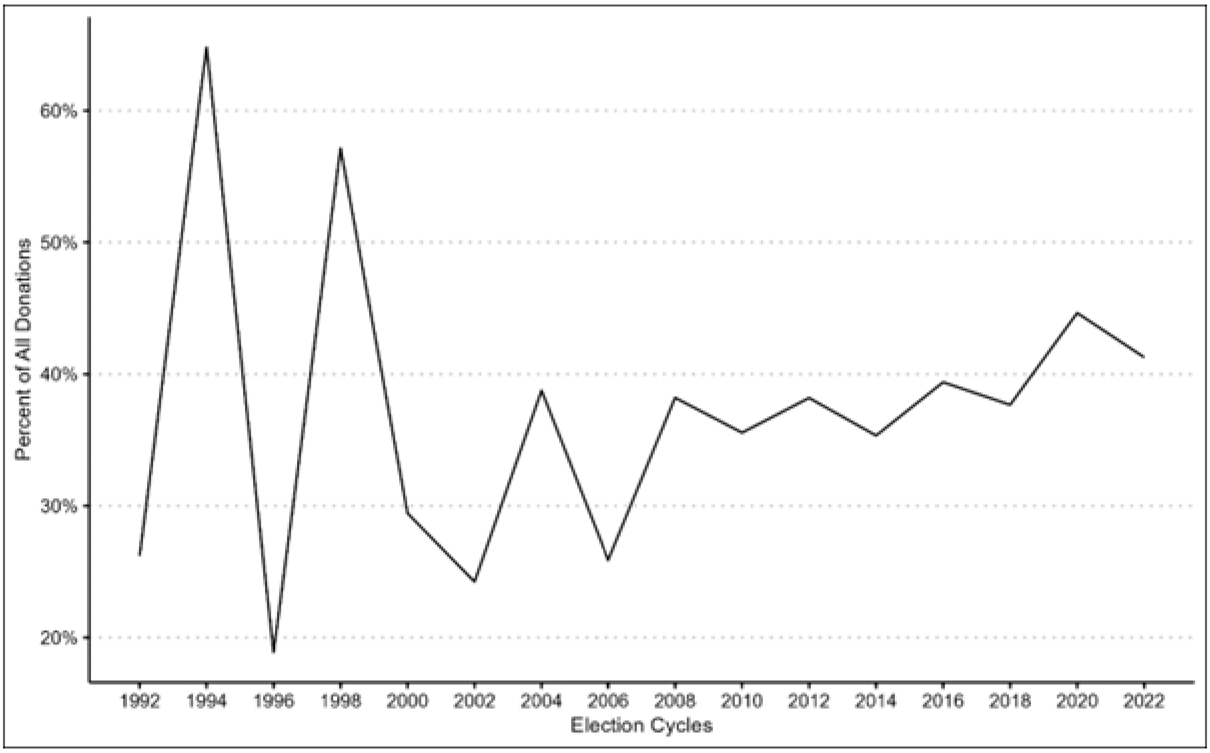

Figure 44: Percent Of All Clean Energy Entrepreneur Donations From Most Clean Energy Patent Intensive Decile.
Notes: I calculate the 90th percentile of Clean Energy Patents for every election cycle, based on the annual number of patents granted in Y02 per county, using the closest Census population estimate to express this as patents per 10k People. I then match donation records from DIME to counties of donor residence. I display the share of total donations per election cycle being made from Clean Energy Entrepreneurs residing in counties within the 90th percentile of Clean Energy Patents.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

It is thus indeed the case that clean energy entrepreneurs continue to be highly represented within clusters of innovative activity. This has not attenuated with the growth of the industry throughout the same period.

At the same time, the campaign donations made by this group have been primarily focused on federal offices. Table 14 below shows a breakdown of clean energy entrepreneur donations since 2000 by the seat of the race.

Seat	**Percent of all donations**
Federal Committee	34.0
Federal Senate	17.5
Federal House	16.9
President	10.8
State Committee	7.5
State Governor	3.6
State Lower House	3.5
State Upper House	2.1

Table 14: Donations by Recipient Office Since 2000
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Donations have been concentrated at the federal level with roughly 70% of all donations since 2000 being directed at federal offices. Hence, a surprisingly small amount of donations has been directed at state offices. Among those donations directed at state-level races, donations have been heavily tied to a small number of states, with more than 30% of donations going to races in Texas. Table 15 below provides an overview.

Recipient State	**Percent of all donations**
Texas	34.6
California	11.3
Massachusetts	5.7
Pennsylvania	4.8
North Carolina	3.2
Colorado	3.1
Wisconsin	2.8
Florida	2.6
All other states	31.9

Table 15: State-level Donations Since 2000 by Recipient State
Data Source: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Hence, the campaign donations of clean energy entrepreneurs tend to come from more innovative areas and are mainly directed at federal offices and a small number of state races.

Do Innovation Clusters Show Systematically Different Donation Patterns?

The previous section discussed the increasing divergence of political preferences between US innovation hubs and the rest of the country. Since clean energy entrepreneurs are heavily concentrated in innovative enclaves and have exhibited donation behaviors that indicate a growing orientation toward Democrats, it stands to reason that this has been driven by their locations of residence.

Indeed, Figure 45 shows that the average CF scores of donations from the most innovative quartile of counties are the lowest. Hence, Figure 45 suggests that even among the relatively Liberal group of clean energy entrepreneurs, those who reside in more innovative clusters tend to have even lower average CF scores.

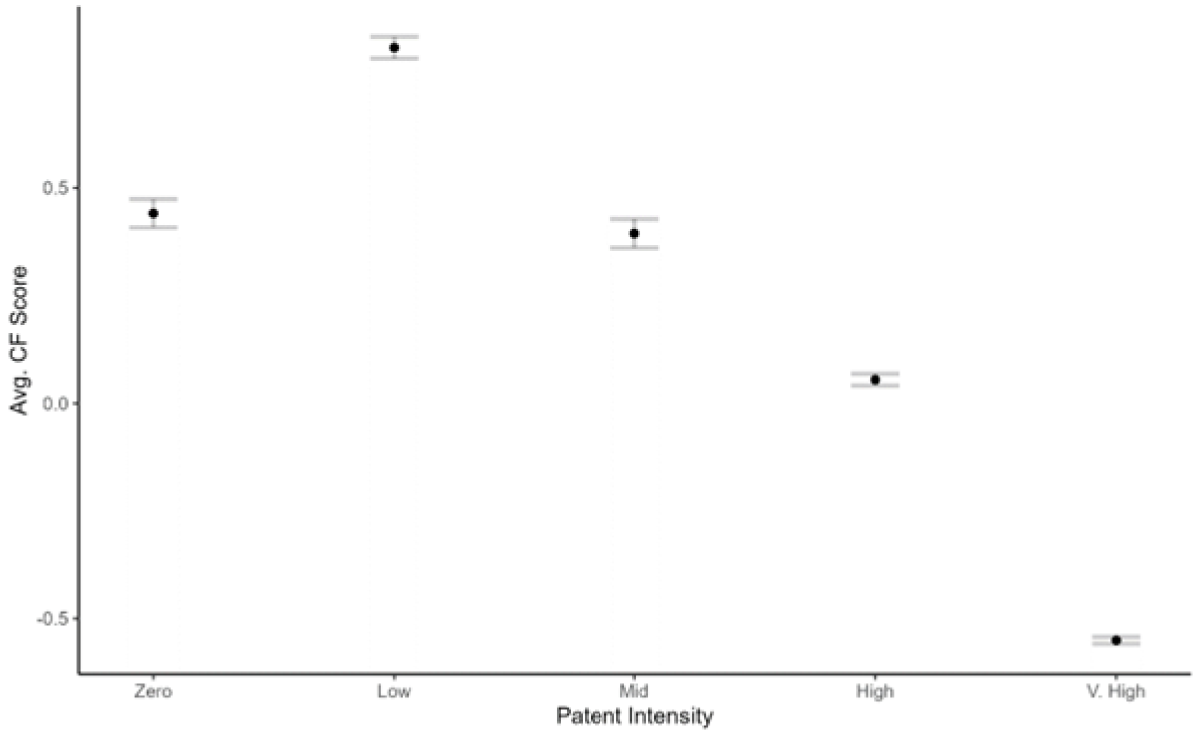

Figure 45: More Innovative Counties Display Lower Average CF Scores
Notes: I divide donations into their counties of origin and group them by the Clean Energy patent intensity of the counties. I then calculate average Common-Factor ideology scores for each group of counties.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Illustrating this point differently, I calculate annual clean energy patents per 10k people at the county level. I add this information to the individual donation data, to establish the clean energy patents per 10k of the county the donor resides in at the time of donation. I then fit regression models estimated via OLS for every election cycle since 2002 at the donation level. I regress the contributor's donation-inferred common-factor ideology score on clean energy patents per 10k people for the county of the donor's residence. I additionally control for state-fixed effects and the contributor's gender.

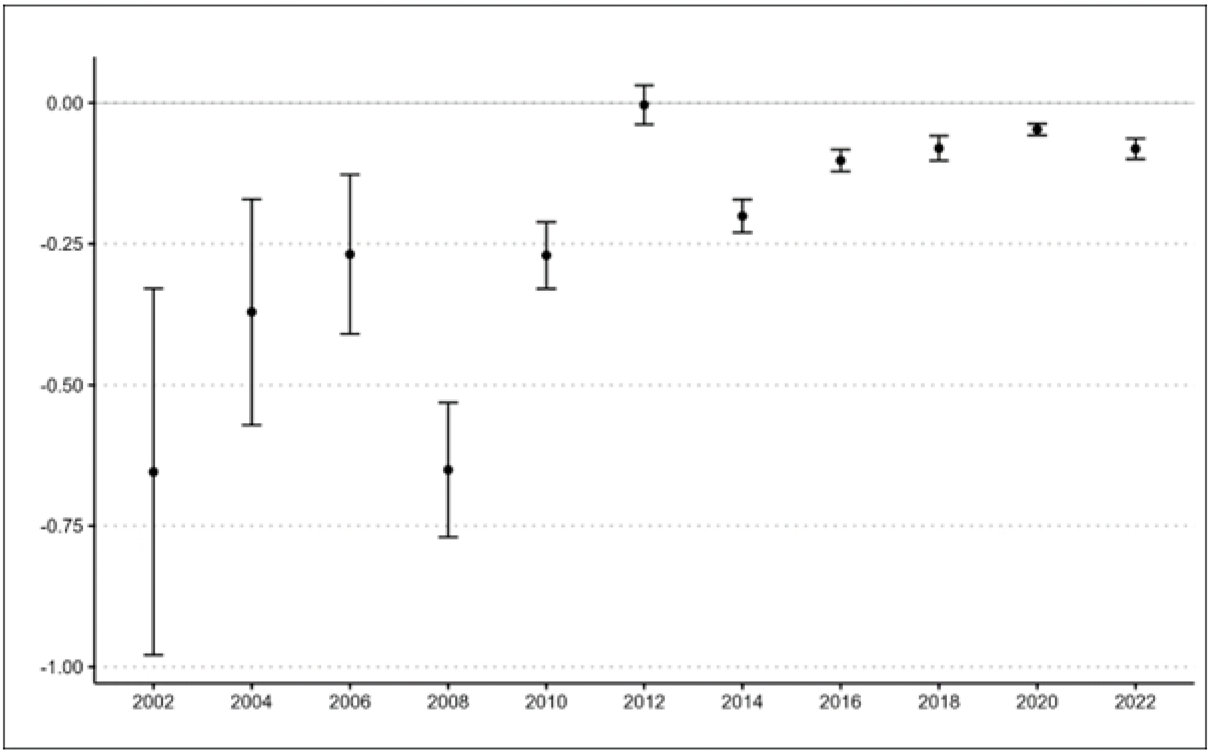

Figure 46: Regression Coefficients and Confidence Intervals for Donation Level Regressions of CF Score on Patents per capita in County of Donor.
Notes: I regress the contributor CF scores on Patents Per 10k People of the county the donor is in during the relevant year, controlling for state-fixed effects, and the gender of the contributor. I do so for each election cycle.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

On balance, Figure 46 shows that there is a persistent and considerable negative effect of the patent intensity of the entrepreneur-donor's county of residence on the donor's inferred ideology score. Hence, even within the group of clean energy entrepreneurs, those living in more innovative areas are more aligned ideologically with Democrats.

Do These Trends Hold for the Wider Clean Energy Industry?

I replicate the above analysis with 36,666 different donors from the US clean energy industry, which I have presented summary statistics for in Table 13. This sample excludes donors who indicate their job categories to be "ceo", "owner" or "president", to avoid duplicating the sample of clean energy entrepreneurs. I refer to this group as clean energy workers.

Figures 54 - 56 in the appendix show that this group of donors shows broadly analogous donation behavior to clean energy entrepreneurs. Importantly, clean energy workers are more aligned with Democrats as indicated by Figure 47 below. Compared to entrepreneur-donors, worker-donors' donations have been heavily tilted toward Democrats in terms of the number of donations. Democrats have also enjoyed slight advantages in the total amount of dollars spent.

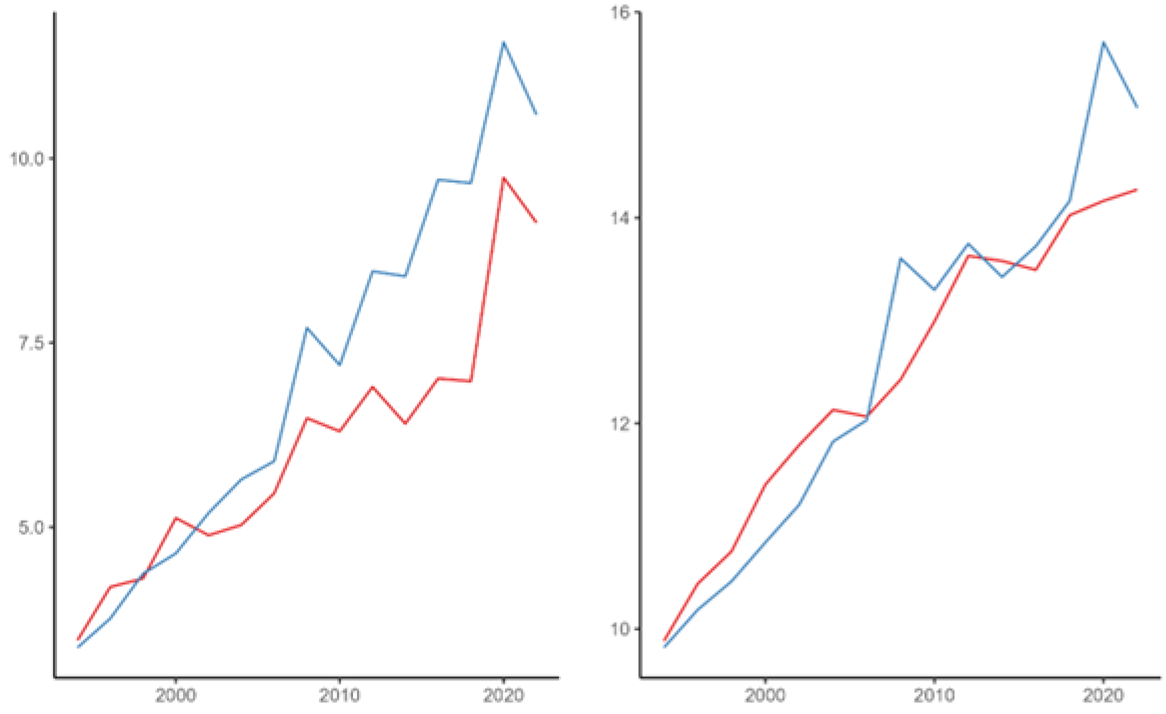

Figure 47: Number of Donations (left) and Total Spending (right) from CE Employees to Democrats (blue) and Republicans (red) between 1992 – 2022.
Notes: Both y-axes are on a log scale.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Figure 55 in the appendix shows that clean energy workers are also most concentrated in US innovation clusters. However, clean energy workers have become much less concentrated geographically over time, both in terms of the number of donations and the total money amount. Figure 48 plots the county-level GINI scores for clean energy workers. I additionally plot the GINI scores for a sample of 145,804 workers within the Oil & Gas industry.[107] I calculated GINI scores for counties, after aggregating the number of donations and total spending at the county level. The resulting GINI scores describe the level of inequality between US counties.

Figure 48 traces a substantial decline in the geographic concentration of clean energy workers' donations, suggesting that workers within this industry have spatially diffused considerably. In recent election cycles, the geographic concentration of donations from clean energy workers has been on par with those of the much more established Oil & Gas industry.

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[107] I identify the campaign donation records of 145,804 Oil & Gas workers by filtering the DIME database for donor's whose self-reported employer falls into the Oil & Gas industry as established by DIME (Bonica, 2023).

Figure 48: Geographical GINI in Donation Number (left) and Total Spending (right) for Clean Energy Workers (Green) and Oil & Gas (red) Workers.
Notes: I aggregate unique donations at the county level for each election cycle and calculate a GINI score for each election cycle across the donating counties.
Data Sources: DIME (Bonica, 2023; Crunchbase; Author's calculations.

While the GINI scores of donations within the clean energy workers have decreased, it is nevertheless the case that a sizable percentage of all donations originates from within innovation clusters. Figure 49 shows the percentage of all donations made by clean energy workers residing within the 90th percentile of clean energy patents per 10k people. While the share of donations coming from innovation clusters has steadily decreased since the 2010 election cycle, the lowest point in 2022 was nevertheless higher than 30% of all donations. Hence, while donations from clean energy workers are increasingly coming from a larger number of areas, a big share of them still originate from innovation clusters.

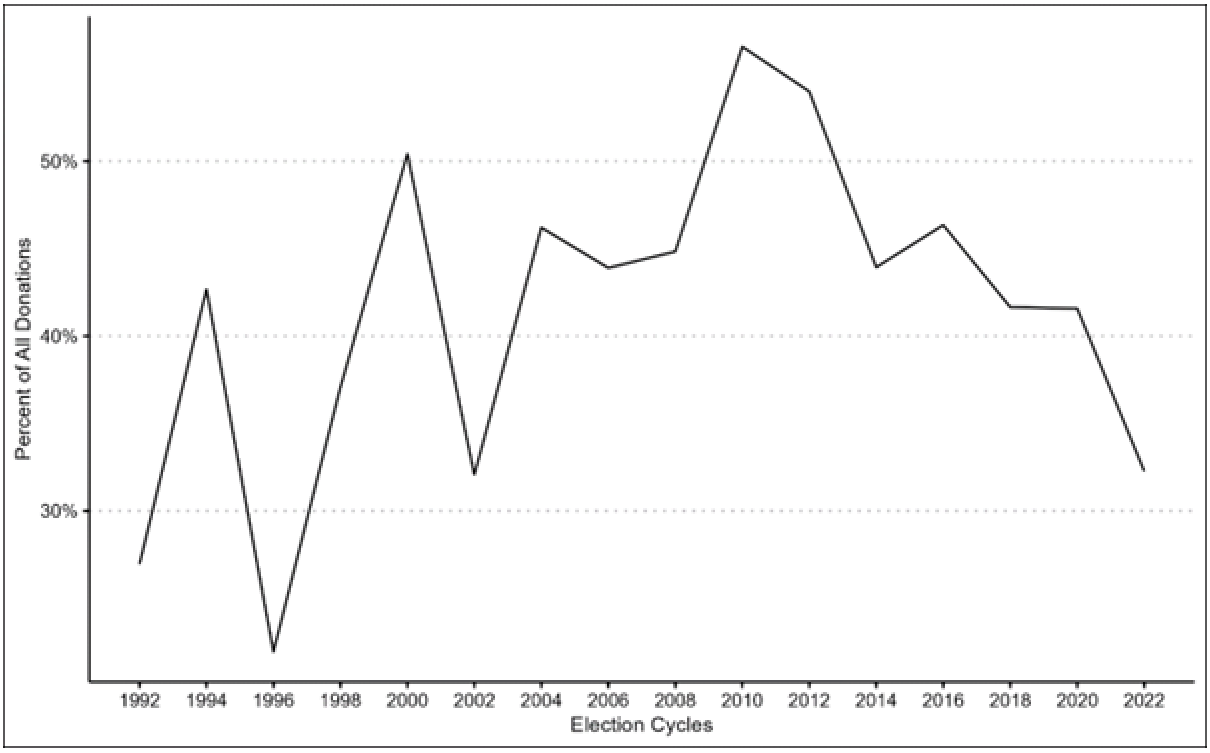

Figure 49: Percent Of All Clean Energy Worker Donations From Most Clean Energy Patent Intensive Decile.
Notes: I calculate the 90th percentile of clean energy patents for every election cycle, based on the annual number of patents granted in Y02 per county, using the closest Census population estimate to express this as patents per 10k People. I then match donation records from DIME to counties of donor residence. I display the share of total donations per election cycle being made from clean energy workers residing in counties within the 90th percentile of clean energy patents.
Data Sources: DIME (Bonica, 2023; Crunchbase; Author's calculations.

Further, the patenting intensity of the donor county is similarly related to the common-factor ideology scores of donors for clean energy workers as it appears to be for clean energy entrepreneurs. Figure 50 depicts the regression coefficients and confidence intervals for clean energy patents Per 10k people from OLS models of the contributor CF score. There is no clear time trend here, but on balance, more innovative areas appear to be associated with systematically lower CF scores.

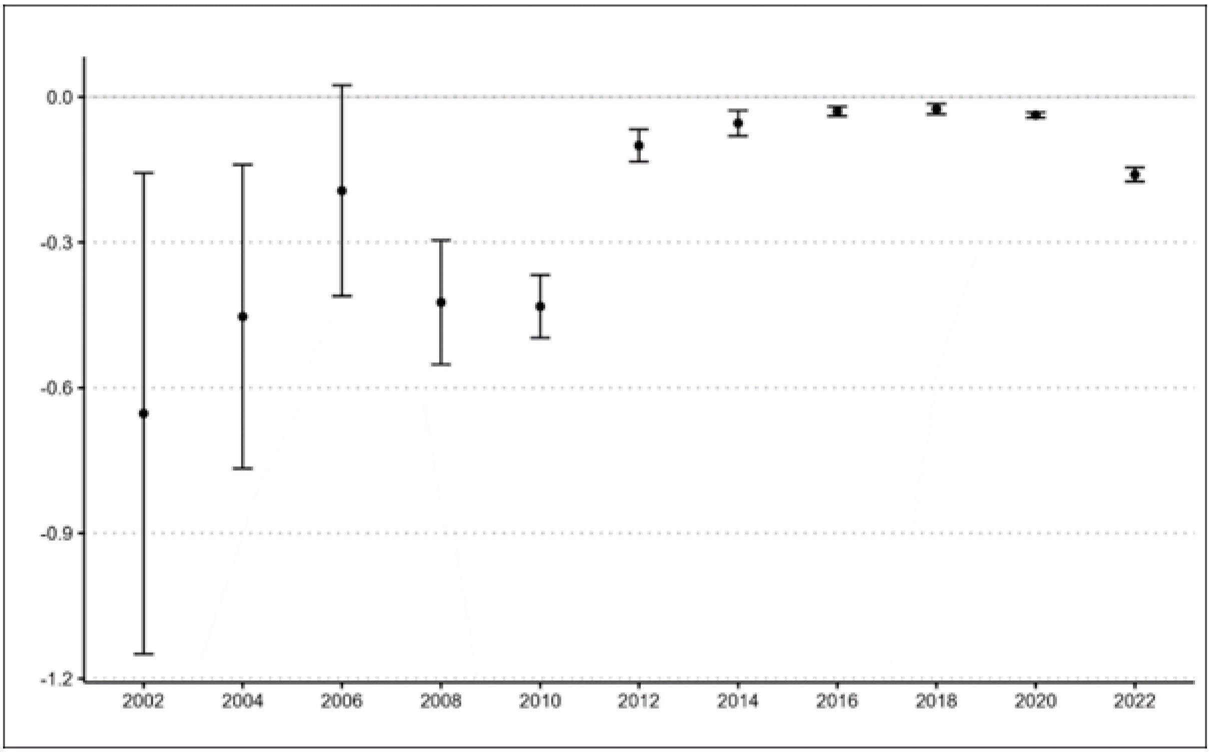

Figure 50: Regression Coefficients and Confidence Intervals for Donation Level Regressions of CF Score on Patents per capita in Donor County.
Note: I regress the contributor CF scores on Patents Per 10k People of the county the donor is in during the relevant year, controlling for state-fixed effects, and the gender of the contributor. I do so for each election cycle.
Data Sources: DIME (Bonica, 2023); Crunchbase; Author's calculations.

This again indicates that even within this group of highly Democrat-oriented donors, more innovative areas are even more Liberal in their policy ideal points as inferred from their campaign donations. clean energy workers have thus grown especially attached to the Democrats. Yet, more innovative areas are systematically more likely to support Democrats and more liberal candidates. This suggests that the divergence in policy preferences across different areas in the United States is also present within the growing clean energy industry.

5.5 Conclusion

Technological innovation and the commercialization of innovative ideas remain highly geographically concentrated in a small number of clusters across the United States. These clusters have been the primary engines of US economic growth in high-technology industries and have spatially concentrated the economic winners of the American Knowledge Economy in a few enclaves. The inhabitants of these enclaves have developed economic and political preferences that sometimes diverge from the rest of the country. In this Chapter, I have investigated to what extent the US clean energy industry has followed a similar development.

Republicans have not invested in climate policy to the same extent that Democrats have. Using Bergquist and Warshaw's (2023) Climate Policy Score, I show that Republican states have produced systematically less stringent climate policy between 1999 - 2020. Drawing on campaign donation data from a sample of clean energy entrepreneurs and another, larger sample of employees within the US clean energy industry, I show that Democrats have benefited politically from their ownership of the climate policy issue.

Democrats have thus clearly benefited from the growth of the clean energy industry. This is more so the case for workers rather than entrepreneurs. Entrepreneurs are big spenders and generally more Liberal than many comparable groups of US entrepreneurs. Still, they are not as staunchly Democratic as workers within this industry. This is especially true in the sense that there remain some high-spending Republican supporters among clean energy entrepreneurs. Further, these entrepreneurs remain highly concentrated in areas of the US that produce substantial amounts of technological innovation related to clean energy. Democrat support is also more pronounced in those areas.

I show that entrepreneur-donors from more innovative areas are systematically more likely to have more Liberal political leanings. The same conclusions can be reached for the larger group of worker-donors within the clean energy industry. The main political dividends for Democrats' action on climate policy have thus come from the most innovative areas in the US. Hence, the clean energy industry shows a similar political pattern to the wider Knowledge Industries in the United States. The heavy focus on developing innovative technology in a small number of innovative agglomerations is stunting the geographically diffused growth of a political constituency pushing for further policy support.

There is a growing trade-off in American innovation policy more generally and in clean energy technology. Federal R&D initiatives rely primarily on a set of highly innovative hubs, often also host most initial commercialization efforts and associated economic growth. While these efforts have been successful in generating considerable technological innovation, this has come at the expense of increased geographical inequality in technology creation.

A growing number of observers have called for active innovation policy aimed at "levelling up" regions in the United States that are currently not competitive in technological innovation and to invest more widely in American innovation and education institutions (see Asquith, 2024; McNutt, 2024). To this end, the Biden administration introduced an "Innovation Engines Award" in early 2024, seeking to boost economic growth and technological innovation in a set of selected areas across the country. The National Science Foundation would coordinate the ten different "Regional Innovation Engine" projects, including a clean energy commercialization project in Louisiana, an R&D project related to climate monitoring and adaptation in Colorado-Wyoming, and an energy storage project in upstate New York (White House, 2024).

These initiatives are insufficient and Congress already significantly reduced appropriations for some of these projects (Hammond, 2021; Mui, 2024). A more comprehensive effort at creating new technology hubs within the US innovation ecosystem would be necessary to reduce the current levels of geographical inequality. Yet, in the short term, the Biden administration's Inflation Reduction Act, as well as some of the provisions in the Chips and Science Act might be more effective in creating a more widely distributed constituency for a growing American clean energy industry.

As this dissertation has shown, American performance in the creation of new inventions in clean energy technology has been strong. Characteristically, American innovation policy has included few provisions aimed at forcing the uptake of these new technologies. Yet, the Inflation Reduction Act is clearly an initiative aimed partly at providing such a policy tool, providing positive inducements for both domestic production and consumer uptake of clean technologies. Additional polices building on this initiative and that are aimed at increasing the diffusion of solar energy, battery technology, and electric vehicles are likely to be more immediately effective at increasing the size of the domestic political constituency necessary to allow for a successful energy transition away from fossil fuels.

This building of a favourable political constituency remains critical despite recent improvements in the energy efficiency of solar energy, better battery technology, and growing uptake of electric vehicles. The analysis of the failed nuclear energy transition in Chapter 1 of this dissertation demonstrated that even promising technologies can experience unforeseen technical issues in their deployment, requiring renewed and ongoing R&D efforts. Moreover, the nuclear case also demonstrates the critical importance of widespread social acceptance for new technologies.[108]

Hence, policy approaches that aim at facilitating the diffusion of clean energy technology through public demonstration projects, education campaigns, and subsidies are critical at this stage. Moreover, public policy investing in education and vocational training related to these new technologies would be beneficial for the creation of a larger domestic industry, also enlarging its political constituency.

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[108] Incidentally, soft costs related to clean energy are one of the most critical hurdles to deployment today. Issues of siting and social acceptance of large-scale solar and wind projects loom large (Ko, Dolsak, and Prakash, 2023).

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Chapter A: Appendix

A.1 Chapter 2

List of Keywords related to Clean Energy and Climate Change: climate change, renewable energy, clean energy, solar energy, energy alternative, alternative energy, solar power, solar panel, hydroelectric, hydropower, electric vehicle, geothermal, wind power, photovoltaic, clean electricity, reduce energy use, biofuel, bioenergy, bio energy, ocean energy, offshore wind, solar heat, fuel cell, co2, gas emission, energy storage, global warm.

List of National Security Keywords: department of defense, pentagon, our national security, energy security, national safety, army, navy, military.

A.2 Chapter 4

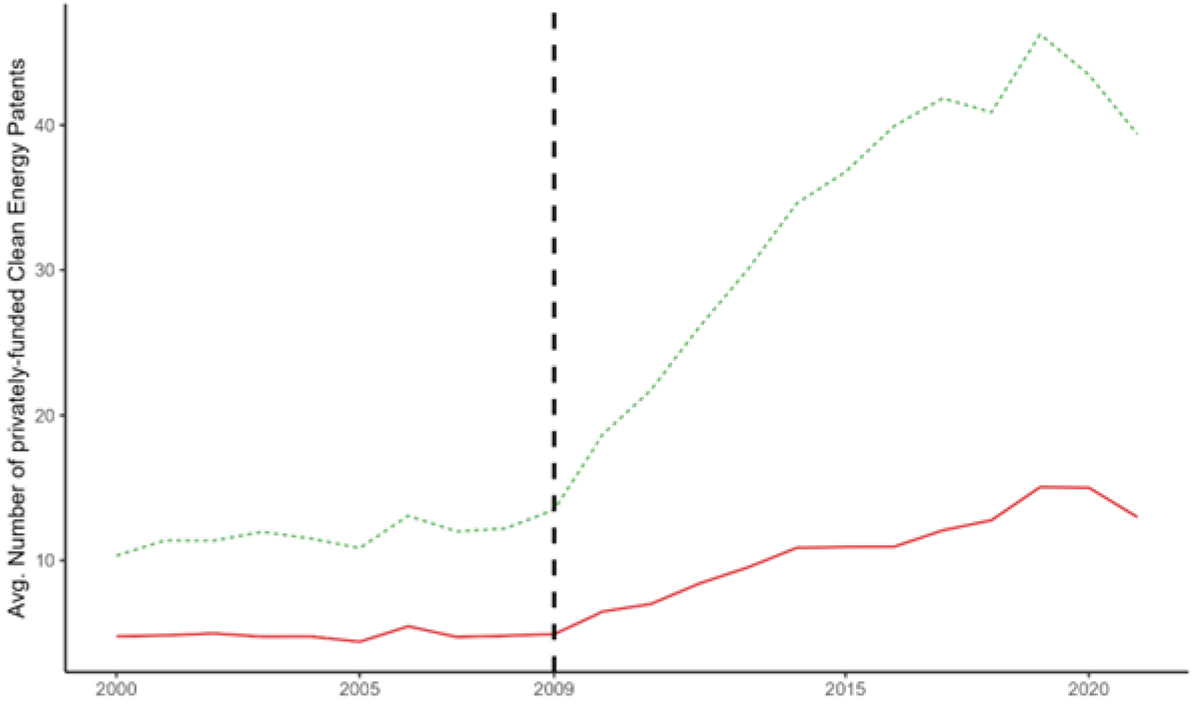

Figure 51: Treated Counties and matched counties average annual Y02 patents.
Notes: I calculate the average number of Y02 patents between counties eventually treated matched with one comparable county each on pre-trends. Treated counties in green (dashed line), control counties in red (straight line).
Data Source: USPTO, ARPA-E Website, Author's calculations.

Alternative Specification for DiD:

I instead use not-yet treated counties as the control group. I present the dynamic effect plot here:

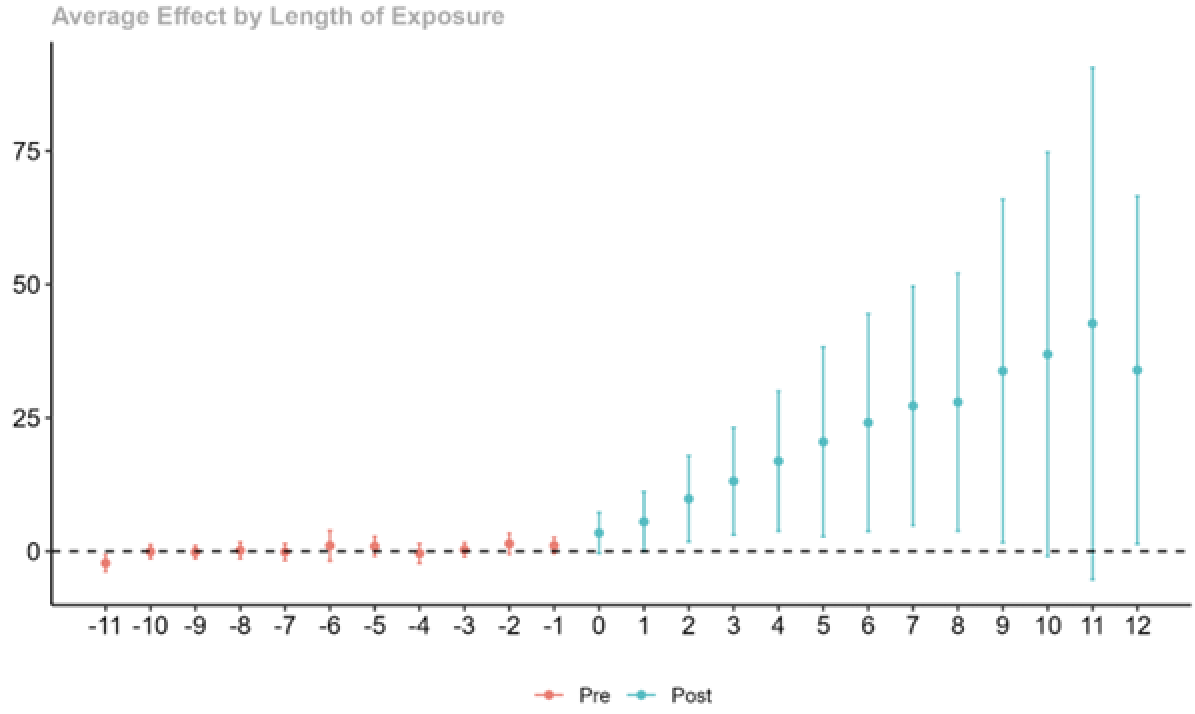

Figure 52: Staggered DID – Average Effect by length of Exposure to treatment. Alternative Specification.

Notes: Control group consists of not-yet-treated counties. This graph shows the average effect size, the average treatment effects at different lengths of exposure.

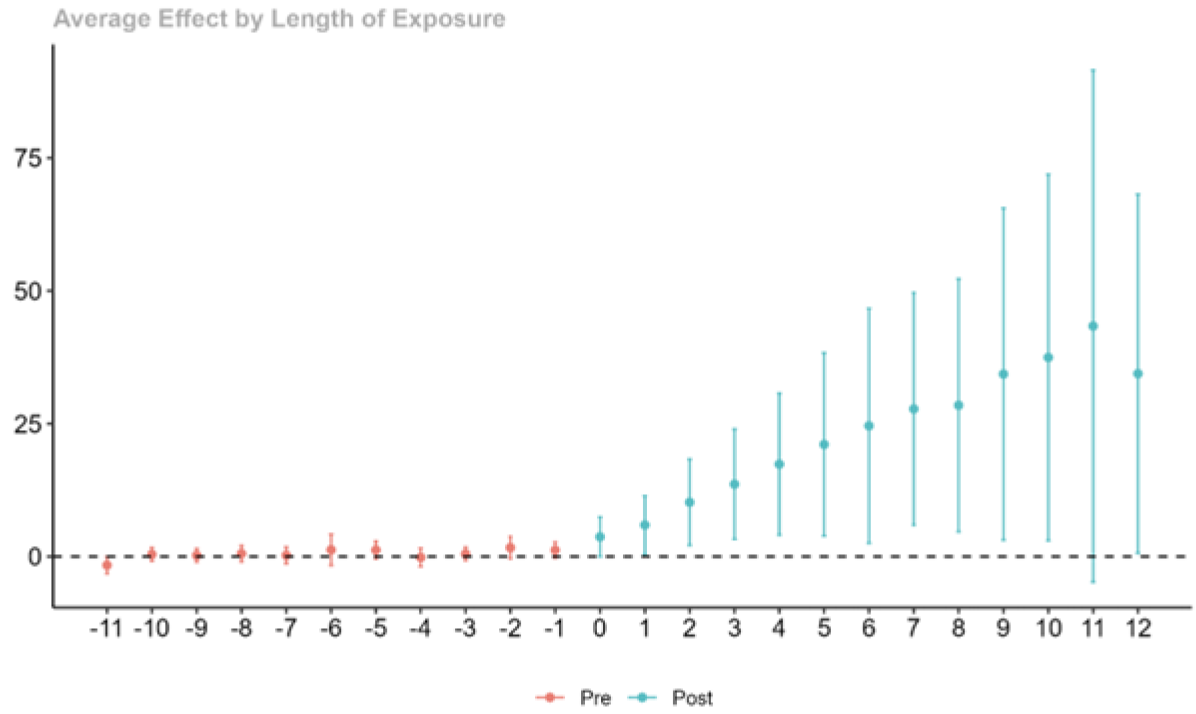

Figure 53: Staggered DID – Average Effect by length of Exposure to treatment. Alternative Specification.
Notes: Control group consists of two matches per treated county, matched on private Y02 patents prior to 2008, population size, and State (I restrict matches to being from the same state). The matching algorithm used is nearest neighbor matching.

A.3 Chapter 5

Here, I compare Common-Factor ideology scores of 36,666 Clean Energy Workers to 145,804 oil and gas OCC worker donors.

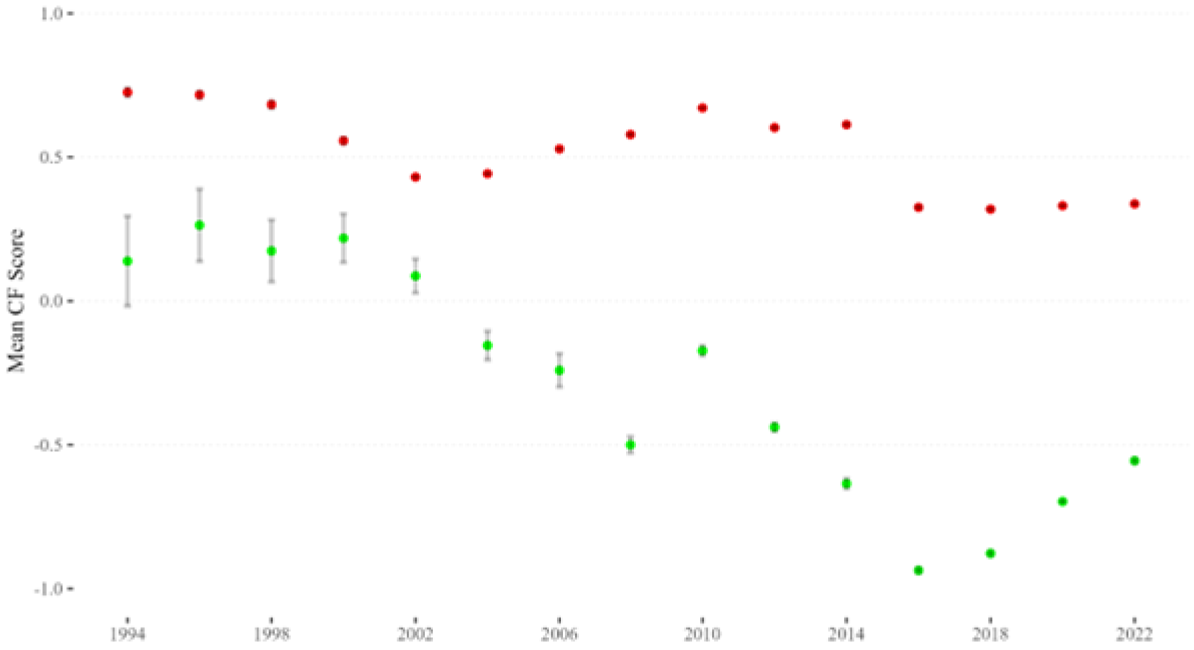

Figure 54: Common-factor ideology scores of CE employees (Green and Oil Gas industry employees between 1994 – 2022 election cycles.

Notes: I calculate average CF scores for each group and election cycle. Additionally, I provide 95% confidence intervals based on the standard deviation of the CF score for each group-cycle. The CF score ranges from -2 to +2, measuring the distance in political ideal points.
Data source: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Figure 55 below shows the average Common-Factor Ideology scores of Clean Energy Worker-Donors from counties with either zero Clean Energy patents between 2010-2020, the 25th percentile of Clean Energy Patents, 25th – 50th percentile, 50th – 75th percentile, and above the 75th percentile.

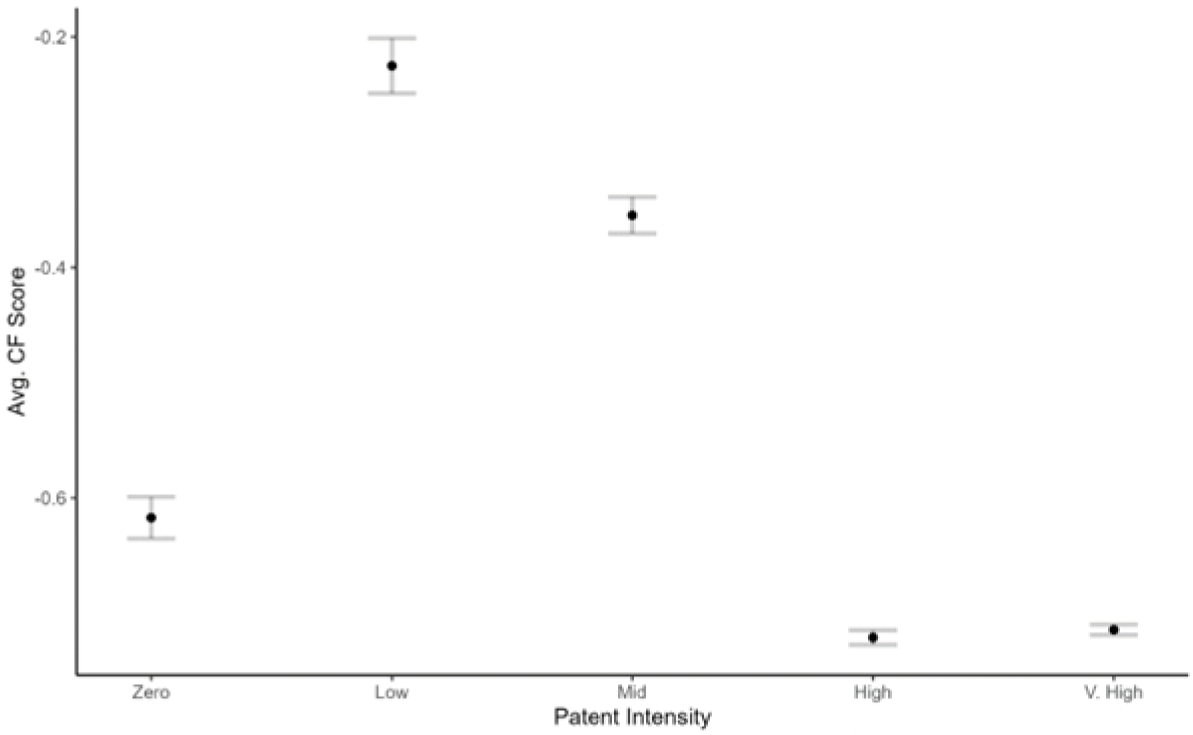

Figure 55: More innovative Counties display more Liberal Donation patterns.
Notes: I divide donations into their counties of origin and group them by the Clean Energy patent intensity of the counties. I then calculate average Common-Factor ideology scores for each group of counties.
Data source: DIME (Bonica, 2023); Crunchbase; Author's calculations.

Figure 56below shows the number of donations and the total spend for counties with either zero Clean Energy Patents between 2010-2020, the 25th percentile of Clean Energy Patents, 25th – 50th percentile, 50th – 75th percentile, and above the 75th percentile.

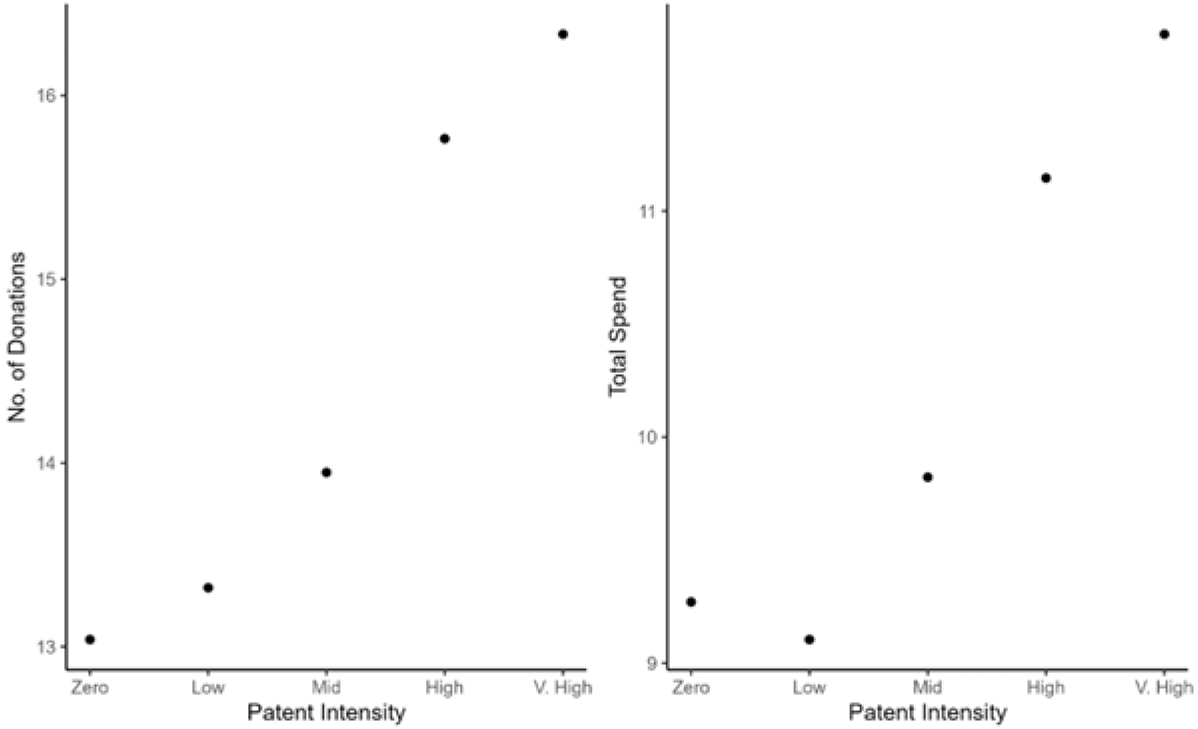

Figure 56: Clean Energy Worker-donors are more likely to donate in innovation clusters and donate larger amounts.

Notes: This graph is based on all election cycles after 2010 combined. Both y-axes are logged. Data source: DIME (Bonica, 2023); Crunchbase; Author's calculations.