Innovation Market Failures and the Design of New Climate Policy Instruments

Sarah Armitage, *Boston University*, United States of America

Noël Bakhtian, *National Academies Board on Science, Technology, and Economic Policy*, United States of America

Adam Jaffe, *Brandeis University, and NBER*, United States of America

Executive Summary

Moving beyond the combination of adoption subsidies, standards, and (albeit limited) attempts at carbon pricing that largely characterized US climate policy over the past decade, recent climate-related legislation has transformed not only the scale of US climate activities but also the policy mechanisms adopted. Newly scaled policy instruments—including demonstration projects, loan guarantees, green banks, and regional technology hubs—are motivated not only by unpriced carbon externalities but also by innovation market failures. This paper maps the economics literature on innovation market failures and other frictions to the stated goals of these policy instruments, with the goal of focusing discussions about how to implement these policies as effectively as possible. The paper also discusses how program evaluation can help to illuminate which market failures are most relevant in a particular context and which policy instruments are most targeted to them.

JEL Codes: O31, O38, Q54, Q55, Q58

Keywords: innovation, climate, market failure, demonstration projects, loan guarantees, green banks, regional technology hubs

I. Introduction

Recent legislation in the United States has provided the opportunity to inject significant federal funding into policy instruments that have not been previously adopted at this scale in US climate policy. Moving beyond the combination of adoption subsidies, standards, and (albeit

Environmental and Energy Policy and the Economy, volume 5, 2024.
 https://doi.org/10.1086/727877

limited) attempts at carbon pricing that largely characterized climate policy over the past decade, the Infrastructure Investment and Jobs Act (IIJA) of 2021, the CHIPS and Science Act (CHIPS) of 2022, and the Inflation Reduction Act (IRA) of 2022 have transformed not only the scale of US climate activities but also the policy mechanisms adopted. These laws have appropriated or authorized significant funding for clean energy demonstration projects ($13.5 billion appropriated under IIJA and $5.8 billion appropriated under IRA), loan guarantees ($11.7 billion in appropriations, $350 billion in lending authority under IRA), green banks ($27 billion appropriated under IRA), and regional technology hubs ($11.5 billion appropriated under IIJA), among other programs.[1]

One common characteristic of these newly scaled policy instruments is that they are motivated not only by the presence of unpriced carbon externalities driving a wedge between private and social costs of emissions but also by innovation market failures. As has been well documented in the economics literature, these innovation market failures exacerbate and interact with the carbon externality in complex ways (Jaffe, Newell, and Stavins 2005). A particular feature of the newly funded policy instruments mentioned above is that they all target the middle of the technology innovation process, after early-stage research and development (R&D) but before widespread deployment. During this middle phase, new technologies are tested at larger scale and integrated into existing infrastructure, and new business and financing models are developed and validated. Without intervention, this phase of the innovation process may proceed too slowly relative to the social optimum, or not at all—as a result of nonappropriable knowledge creation, financial frictions, or coordination failures. (Fig. 1 maps these newly scaled policy instruments and innovation market failures to Technology Readiness Levels, which are defined in table 1.)

Furthermore, key features of these policy instruments are motivated by concerns not traditionally thought of as market failures, such as fostering economic development in disadvantaged regions, creating new jobs in ways that address equity objectives, addressing historically unequal burdens of pollution from fossil fuels, and overcoming institutional inertia. These challenges may interact with innovation market failures in complex ways; for example, new knowledge is created in developing new financing models that allow credit-constrained consumers to adopt a new technology. Moreover, many of these additional policy priorities are particularly relevant for this middle stage of the innovation process but would not necessarily arise during early-stage R&D.

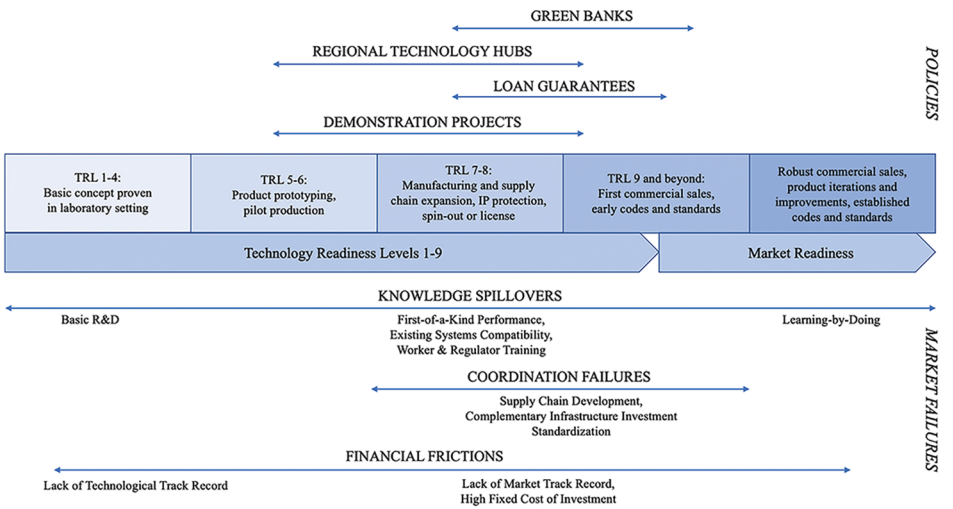

Fig. 1. Technology readiness levels, policy instruments, and innovation market failures. Color version available as an online enhancement.
Note: IP = intellectual property; R&D = research and development.
Source: Adapted from US Department of Energy, Office of Energy Efficiency and Renewable Energy (n.d.).

Table 1
Technology Readiness Levels

Technology Readiness Level	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system completed and qualified through test and demonstration
TRL 9	Actual system proven through successful mission operations

Source: US Government Accountability Office (2020).

In this paper, we seek to map the economics literature on innovation market failures to the stated goals of these newly scaled policy instruments within IIJA, CHIPS, and IRA. We also discuss the equity concerns of these policies in the context of the innovation process. An implicit theory of change behind policies such as demonstration projects or loan guarantees is that resources are not being allocated efficiently or equitably across the economy: there are unfunded projects that should be funded, for one reason or another. Understanding those potential reasons may help to focus discussions about where to allocate program resources and how to make these policies as effective as possible. After reviewing literature on innovation market failures and other policy priorities, we identify specific questions for program design and implementation that may help to inform these discussions.

Several key ideas emerge from this exercise. First, each of these newly scaled policy instruments has the potential to address multiple market failures and other policy concerns inherent in the technology innovation process, including knowledge spillovers, coordination failures, financial frictions, and distributional objectives. Program implementers may wish to apply the market failure framework when collecting input from stakeholders about which barriers are most inhibiting to early technology deployment. Developing hypotheses about which market failures matter most in a given context will allow for tailoring program design accordingly,

which may increase the likelihood of successful program implementation. Furthermore, each of these newly scaled policies is providing funding that—in the absence of innovation market failures—would generally come from private capital markets. Thinking systematically about the ways that these policies are and are not filling similar roles as private capital fosters more effective program design. Where a program is "filling in" for the role played by private capital in other contexts, program implementers can mimic contract structures and other approaches that venture capitalists, commercial banks, and other investors have developed.[2] But to the extent a program is addressing objectives typically ignored by the private sector, such as increasing equity, it may be desirable to deviate intentionally from the practices of private funders, with the nature of those deviations informed by analysis of these distinct goals. Finally, the economics literature has consistently concluded that these are tricky market failures to rectify. And as significant as these new initiatives are, we are still in the early phase of what will be a long-term policy effort to address climate change. Building evaluation and learning into program design will generate new understanding of which of the relevant market failures most inhibit early deployment of climate technologies and which policy instruments address them most effectively.

The paper proceeds as follows. Section II describes the innovation market failures and other priorities that may be targeted with these policy instruments. The section also summarizes the relevant economic literature on these challenges and on policy interventions that have been used in other contexts. Section III describes the four policy instruments in question and their institutional history in US climate policy, linking their stated goals and approaches to the market failures and other priorities described in the previous section. Section IV discusses market failures that are not well addressed through these four policy instruments. Section V concludes and offers directions for future research.

II. Innovation Market Failures and Other Frictions

We begin by discussing the economics literature on three types of market failures of particular relevance to the middle stage of the innovation process—knowledge spillovers, financial frictions, and coordination failures—as well as literature related to the distributional implications of climate innovation. Readers may find it useful to refer to table 2, which provides definitions of key economic terms for a policy audience; these terms are *italicized* throughout the paper.

Table 2
Definition of Key Economics Terms

Concept	Key Terms
Market failures	A "**market failure**" refers to a situation in which the free market does not allocate goods or services efficiently; more technically, the term refers to conditions under which the First Welfare Theorem does not hold, and the equilibrium outcome is not Pareto efficient. In the presence of a market failure, reallocating goods and services could make all actors better off. A "**(Pigouvian) externality**" is one example of a market failure, in which private actors do not fully consider ("**internalize**") the costs or benefits that they impose on others in their decision-making, as those costs or benefits are not fully priced. Greenhouse gas emissions are a well-known example of a negative externality. The "**socially optimal**" level of some good or service is that which maximizes welfare, or total surplus, across all actors.
Knowledge spillovers	"**Appropriability**" refers to whether private actors can capture the value produced through their actions; for example, through increased profits. Value that is instead captured by other actors constitutes a "**positive spillover**."
Financial frictions	"**Asymmetric information**" refers to a situation where one economic actor possesses information that another does not (e.g., about the quality of a new technology); this discrepancy is usually most relevant when the two actors are trying to transact (e.g., to agree on a financial contract). One potential consequence of asymmetric information is "**adverse selection**": project developers or entrepreneurs may have more information about the likelihood of success than investors and may only be willing to pay higher interest rates or post greater collateral for risky projects. Another potential consequence is "**moral hazard**": if investors cannot fully observe the behavior of project developers or entrepreneurs, the latter may have an incentive to engage in risky behavior or divert project funds to maximize their own surplus rather than that of the investor. The "**market for ideas**" refers to the buying and selling of innovations, often before they are developed into a final product. These transactions could take the form of technology licensing, acquisitions of technology companies, or strategic alliances, among other models.
Coordination failures	"**Transaction costs**" may include the costs of identifying counterparties, negotiating terms, enforcing contracts, and so forth. When transaction costs are high, economic actors face greater barriers to realizing economically beneficial transactions. "**Complete contracts**" refer to contracting arrangements in which all parties are able to enumerate their respective rights and responsibilities under any possible state of the world. Such contracts are thought to be impossible to write in practice, leading to incomplete contracts in which one party holds residual control rights. "**Pareto efficiency**" describes a situation in which no actor (e.g., consumer, firm) can be made better off without making another actor worse off. In a Pareto-dominated equilibrium, an alternative equilibrium exists that could make some actors better off without making any worse off.

A. *Knowledge Spillovers*

Perhaps the most well-established motivation for public support of the innovation process is the idea that innovation produces new knowledge, which has characteristics of a public good. Because information is not perfectly *appropriable*, private firms will not fully *internalize* (i.e., profit from) the *positive spillovers* from their innovative activities. Consequently, the private market will underprovide innovation relative to the social optimum (Nelson 1959; Arrow 1962). These knowledge spillovers have long been considered a defining feature of the early stages of the innovation process, especially in basic R&D. New knowledge generated in basic R&D is especially likely to be relevant for many different applications and thus nonappropriable by any individual firm. Ample empirical research, reviewed in Bloom, van Reenen, and Williams (2019), has suggested that the social return to R&D is higher than the private return, implying that firms underinvest in R&D relative to the *socially optimal* level, therefore creating a potential role for public sector support for R&D to correct this market failure.[3] This research has provided theoretical and empirical support for policies that strengthen firms' ability to internalize the full benefits of their R&D activities (such as intellectual property protections) and that increase overall R&D in the economy (such as R&D tax credits and public funding for research).

Economics research has also shown that spillovers can be generated through the development, adoption, and diffusion of new technologies. Learning-by-doing causes the marginal cost of the new technology to decrease with cumulative production as firms learn to produce more efficiently. If some of the knowledge gained through production experience benefits other firms, such positive spillovers could justify deployment subsidies, even in amounts above the externality directly avoided from fossil fuel generation (Gillingham and Stock 2018). Whether learning-by-doing spillovers justify generous deployment subsidies in practice appears to depend on the context. Covert and Sweeney (2022) find that interfirm spillovers have generated substantial cost reductions in the offshore wind industry, whereas Gillingham and Bollinger (2021) find evidence of very small learning spillovers in solar photovoltaic (PV) installations. Beyond learning-by-doing, other potentially relevant forms of knowledge spillovers during widespread technology deployment include learning-by-using, whereby new technology adopters generate information for others about the technology's existence or effectiveness (Jaffe et al. 2005; Gillingham and Bollinger 2021; Bollinger et al. 2022).

Industry observers have also suggested that knowledge spillovers may occur between early R&D and large-scale deployment. For one, the high up-front cost of many clean technologies means that innovative financing arrangements may be critical to deploying new technologies at scale. Likewise, many clean technologies must be integrated with existing systems, which requires training the local workforce to install and service the technology, working with regulators to understand the new technology, or adapting the technology developed at lab and pilot scale to operate with existing infrastructure. These financial, regulatory, and process innovations associated with initial deployment may be subject to the same knowledge spillovers of invention more generally. As an example, after SolarCity's success with offering leases for residential solar installations, which allowed a larger group of customers to avoid high up-front costs and to benefit from tax credits, many other installers adopted this innovative financing model. By 2014, 72% of the residential solar market used this model; SolarCity accounted for half of this total (Gross 2015; Trabish 2015). Of course, the efficient level of public support for these types of innovations depends on the magnitude of spillovers across firms, which in turn depends on the specific context.

B. Financial Frictions

In a world without financial frictions, all investment opportunities where revenues exceed costs (adjusted for risk and the timing of payments) would be able to secure funding. There is a long literature in economics studying deviations from this optimum, both theoretical and empirical. Explanations for frictions in financing positive net present value (NPV) projects are rooted in *asymmetric information* between demanders and suppliers of investment capital and the associated problems of *moral hazard* and *adverse selection*. Financial contracting has developed numerous methods to address these issues, but the solutions generally increase the cost of finance relative to a frictionless world, meaning that some positive NPV projects will not be undertaken.[4] In this section, we review the economic literature on financial frictions affecting innovation and entrepreneurship, focusing on the investment needed for the climate transition. We address three areas in particular: finance for innovation by start-ups, finance for innovation by incumbents, and finance for other forms of entrepreneurship.

Evidence suggests that R&D-intensive start-up firms face particular challenges in securing finance. The entrepreneur typically has more information about the technology than the investor, a situation that is

especially acute in funding new technologies because of how easily innovative ideas may spillover to competitors. This asymmetric information makes it difficult for equity providers to assess the likelihood of a new technology company's eventual success (Hall and Lerner 2010). Furthermore, early-stage technology companies have few assets that could be pledged as collateral in loan contracts, and cash flows may not be sufficiently predictable to enable regular debt repayment (Hall and Lerner 2010). In both debt and equity contracts, it is difficult to contract directly on inputs to the research process (Kerr and Nanda 2015).

Venture capital (VC) has emerged as an effective model for providing equity financing to high-potential technology start-ups, developing certain contractual and governance strategies for overcoming the abovementioned frictions.[5] The VC model uses staged financing to treat funding rounds as a series of real options, where investment sizes increase only as new information is revealed about the technology's probability of success (Gompers 1995; Bergemann and Hege 1998, 2005). In addition, VC funds undertake robust monitoring and oversight of their portfolio companies to address moral-hazard issues in the R&D process (Hellmann 1998; Cornelli and Yosha 2003; Chernenko, Lerner, and Zeng 2020). Although VC investment funds only a small share of new entrants in the US economy—even a small share of patent-generating new entrants—it exerts a disproportionate influence on innovation, including in the climate-technology sector.[6]

Yet in recent years, observers have debated the extent to which the existing VC model is effective for addressing financial frictions facing clean technology companies. Relying on data from 1980 to 2009, Nanda, Younge, and Fleming (2015) argue that several structural factors had limited the role of VC in funding clean technologies, ranging from capital intensity and long timelines, to limited exit opportunities and increased financing risk, to high commodity and policy risk (see also Gaddy et al. 2017). More recently, industry observers have challenged this view, pointing to the recent resurgence of VC interest in climate technologies as well as the changing landscape of early technology funders (Kahn and Naam 2021). The past decade has seen the emergence of specialized climate-focused funds such as Breakthrough Energy Ventures and Energy Impact Partners, new public funding from ARPA-E and philanthropic capital from organizations such as Prime Coalition and the Bezos Earth Fund, and the development of complementary incubators and accelerators such as Activate and Greentown Labs (Prabhakar 2021).

Yet many industry observers continue to point to financial frictions in the middle of the innovation process, as climate technologies seek funding for demonstration plants or first-of-a-kind commercial facilities (Kahn and Jacobs 2022; Khatcherian 2022). Certain structural factors previously identified as barriers to VC funding for early-stage climate technologies may be relevant in understanding financial frictions at this stage.[7] New climate technologies continue to face technology risk (the "learning" phase, in the terminology of Nanda 2020) when implementing full-size demonstration projects, because technologies that succeeded as prototypes may not succeed at this size or when integrated with existing infrastructure. To manage this idiosyncratic risk, portfolio theory suggests that VC investors should fund a portfolio of start-up companies, but the high fixed costs of experimentation at the demonstration phase mean that many investors do not have sufficient resources (Kerr, Nanda, and Rhodes-Kropf 2014; Nanda et al. 2015; Nanda 2020; Jones 2022). The handful of VC firms able to deploy sufficiently large investments to fund these demonstration projects may have more attractive investment opportunities scaling up technologies that have already been derisked.[8] Moreover, the development of specialized climate portfolios or new contractual approaches to address these issues with technology demonstration would still face an undiversifiable risk that the market for these climate technologies will take a long time to develop, will never develop, or will not be very large. This undiversifiable risk makes climate-focused funds inherently riskier than other technology sectors. All these issues suggest that financial frictions may still persist in the middle phase of the technology development process, providing a potential theoretical justification for policy intervention.

Beyond the innovations funded in the VC ecosystem, less R&D-intensive start-ups may also face financial frictions. Economists have debated the extent to which other new entrants and small businesses face "credit rationing," whereby groups of potential borrowers are unable to obtain loans at any interest rate (i.e., any price).[9] The canonical model of Stiglitz and Weiss (1981) suggests that credit rationing may arise due to either adverse selection among borrowers (only the riskiest borrowers are willing to accept high interest rates) or moral hazard (borrowers facing higher interest rates undertake riskier projects to increase payoffs if successful; see also Leland and Pyle 1977). Economists have debated the extent to which financial markets have other tools to mitigate these issues (Bester 1985; Besanko and Thakor 1987; de Meza and Southey 1996) and whether credit rationing is observed in practice, with mixed evidence

(Berger and Udell 1992; Petersen and Rajan 1994, 2002; Beck and Demirguc-Kunt 2006; Kerr and Nanda 2010; Robb and Robinson 2012).

Nonetheless, entrepreneurs in newer sectors, such as those developing new climate-related business models, may be more likely to face challenges in securing funding for positive NPV projects. Several industry observers have commented on the reluctance of lenders to invest in the fixed cost of learning about a new industry and how to structure a new type of loan—say, energy-efficiency retrofits for small businesses—if they are uncertain how quickly that technology or business model will scale (Griffin 2014; Kahn and Shah 2022).

Finally, large incumbent firms are thought to face fewer financial frictions in general, given their longer history of operations, their larger share of "redeployable" assets that can be pledged as collateral, and their access to retained earnings for internal financing (Hall and Lerner 2010). However, incumbent firms' ability to finance innovative projects depends on their ability to access those projects in the first place. Economics research has documented a decline in internal corporate research since the 1980s (e.g., the Bell Labs model), with innovative activity increasingly shifting to universities and start-ups (Arora et al. 2020). Of course, incumbent firms are able to access external innovations through licensing, acquisitions, strategic alliances, or other models, but this *market for ideas* is notably less developed for climate technologies than for sectors such as biotechnology (Gans and Stern 2003; Kerr and Nanda 2015; Akcigit, Celik, and Greenwood 2016).[10] Climate technologies are more technologically differentiated than new pharmaceuticals or other biotechnology innovations, so the market is thinner for a given innovative idea (Nanda and Rothenberg 2011); for example, a new battery chemistry requires a fundamentally different set of skills and machinery to scale compared with methods of low-carbon steel production. Sectors such as biotechnology also benefit from well-defined innovation milestones based on clinical trials, which makes it easier to observe and contract on new ideas without compromising intellectual property (Kerr and Nanda 2015). Last, even if incumbents are able to source external climate innovations, the increasing separation between basic R&D by universities and start-ups and product development by incumbents means that this research may not be well suited for commercial applications at scale (see Arora et al. 2020 for general discussion and Siegmund et al. 2021 for an example from early electrolysis research).

Furthermore, incumbent firms may also face frictions in the type of finance they are able to secure for innovative projects, especially when

trying to apply traditional project finance methods.[11] Firms may prefer to fund a project using off-balance-sheet financing for many reasons, such as the ability to divulge information only about the project rather than about the company as a whole, the ability to avoid contamination risk with the core business, and the ability to enter into horizontal agreements with competitors at the project level (Steffen 2018). Project finance has proved a popular approach to securing funding for renewable energy projects and now is often looked to as a potential solution for other types of climate infrastructure projects (Polzin et al. 2019). Because lenders only have recourse to project-level assets in the case of default, however, they are willing to accept far fewer risks in project financing arrangements (Yescombe 2014). This requisite risk transfer may not be possible for infrastructure projects using newer technologies. For example, given the long time horizons needed to recoup capital costs, lenders may require insurance to cover the risk that offtakers will exit the market, but such insurance products may not yet exist for offtake agreements in green commodity markets.

C. Coordination Failures

A third market failure that might affect this middle phase of the innovation process is known as a "coordination failure," where uncertainty about how other economic actors will behave creates the possibility of multiple equilibria in outcomes (Cooper and John 1988; Cooper 1999). Under a coordination failure, firms or consumers may get stuck in a low-value equilibrium, because there is no mechanism or it is too costly for them to take the multiple coordinated actions that would be necessary to move them to a higher-value equilibrium.

A coordination failure may take several forms. In some cases, everyone could be better off from choosing a particular action, but they instead choose a different action because of their subjective beliefs about what others will do—leaving everyone worse off. To provide a stylized example, assume that car accident fatality rates are the same in a collision between two small cars and between two large cars, but that the fatality rate for a small car in an accident with a large car is higher. Further assume that drivers obtain no additional utility from large cars relative to small cars, but large cars produce more pollution externality. If drivers were able to coordinate on car size, the welfare-maximizing equilibrium would be achieved, where all drivers choose small cars. Yet such coordination may be difficult in practice, given the number of drivers

on the road. Due to uncertainty about what others will do, many drivers will choose large cars to avoid the risk of a small car in an accident with a large car, resulting in a Pareto-dominated equilibrium (see table 3 for an illustration).

In other cases, coordination increases the overall level of surplus in the economy but will make some actors worse off unless transfers are made. In our stylized automobile safety example, imagine that different firms have the technology to produce large cars and small cars, respectively. Then coordinating driver adoption of small cars might increase overall welfare, by reducing the negative environmental externality, but the manufacturers of large cars would be worse off without additional transfers. In the discussion in this section, we focus on the first case—coordination failures with a Pareto-dominated equilibrium—to simplify ideas. Nonetheless, the second type of coordination failure with distributional consequences is also worth studying in the context of the climate transition, as certain firms and consumers will undoubtedly be made worse off by a coordinated effort to shift to low-carbon production.

In the diffusion of climate-mitigation technologies, coordination failures can arise because widespread adoption of a new technology may require near-simultaneous investments in the technology itself, supplier or customer capital, and shared infrastructure.[12] Many of the firms in these different sectors may believe that the necessary investments are only profitable if the needed investments in other sectors are made, and they may believe (correctly) that those investments will not be made because everyone is waiting to be convinced that the climate transition is going to occur.

Indeed, the challenge of coordinating on a low-carbon investment path has parallels to coordination failures in economic development. Beginning with the influential work of Rosenstein-Rodan (1943), economists

Table 3
Hypothetical Coordination Failures in Vehicle Choice

	Driver 1 in Small Car	Driver 1 in Large Car
Driver 2 in small car	Payoff to driver 1 = 5 Payoff to driver 2 = 5 Environmental externality = –1 Total surplus = 9	Payoff to driver 1 = 5 Payoff to driver 2 = 1 Environmental externality = –3 Total surplus = 3
Driver 2 in large car	Payoff to driver 1 = 1 Payoff to driver 2 = 5 Environmental externality = –3 Total surplus = 3	Payoff to driver 1 = 5 Payoff to driver 2 = 5 Environmental externality = –5 Total surplus = 5

have recognized that developing economies may confront a coordination failure whereby simultaneous investment in industrialization by many actors would be privately profitable, but unilateral investment in industrialization is not (see Murphy, Shleifer, and Vishny 1989 for a more recent formulation). This need for simultaneous investment arises because various inputs to production are complementary; the marginal product of one such input depends on the availability of other relevant inputs. For example, as an economy develops, the returns to investing in machinery to produce specialized inputs (e.g., specific grades of steel) will depend on other firms' investments in downstream manufacturing (e.g., automobile production). Likewise, the benefits to a worker from investing in specialized skills to operate this machinery depend on the availability of complementary skill sets among other workers (Rodrik 1996). In a world where *complete contracts* are possible and *transaction costs* are negligible, providers of various inputs to industrial production could collectively coordinate to produce the optimal level of specialized inputs. Yet in many real-world settings, such contracts would be impossible in practice: for example, because input providers are diffuse and transaction costs would be prohibitively high. This combination of increasing returns and imperfect contractability creates the possibility for coordination failures as new markets are developing.[13] Under such an outcome, the economy would be stuck in a low level of economic development due to failure to coordinate these disparate investments, even if doing so could increase the returns to both labor and capital (Collier 2007).

There are many analogous examples of imperfectly contractable complementary inputs in markets for new climate technologies.[14] As noted in the previous section, the migration of research to start-ups and universities, away from established firms with basic manufacturing capabilities and other complementary assets in place, means that there may be more opportunities for coordination failures to arise when climate technologies make the transition from labs to full-scale commercialization. Furthermore, many high-emitting sectors depend on extensive infrastructure and supply chains that must evolve alongside low-carbon technologies. Consider the decarbonization of maritime shipping: if maritime shipping makes the transition from diesel to a new type of fuel, say ammonia or methanol, this change will require not only scaling up the production of these new fuels but also contemporaneously redesigning ship engines and potentially ship layouts, building infrastructure to transport the new fuels to ports, building new refueling infrastructure at the ports themselves, training workers in handling the new fuels, developing

new safety regulations for the use of these fuels, training workers in the maintenance of new engines and infrastructure, and so forth (Cameron and Turner 2021). Of course, these complementary inputs have developed for existing carbon-intensive methods of shipping, but this process has taken decades, even centuries in some cases. Given the urgency of climate change, this slow process of development may well be a Pareto-dominated equilibrium, where coordination to produce a faster transition could be welfare enhancing.

Yet it is often a formidable challenge to address coordination failures through policy. In economic development, suspected coordination failures led to policy prescriptions for a "big push" in public support for industrialization, to increase the profitability of each firm's individual investments. These policies, first influential in the 1950s, proved quite controversial (Matsuyama 1998).[15] Policies to address coordination failures are challenging to assess empirically because of the underlying discontinuities and increasing returns to scale, and there is a limited evidence base about which policy instruments have proved effective. Furthermore, it may even be difficult to identify specific interventions that have a reasonable chance of effectiveness, given the nature of the multiple equilibrium problem (Cooper 2005). Rodrik (2014) argues that missteps are inevitable, and policy makers should instead focus on "a set of mechanisms that recognizes errors and revises policies accordingly."

As a final point about coordination failures, it is worth commenting briefly on the distinction between coordination failures and Pigouvian externalities, as they are conceptually distinct but potentially easy to conflate in a climate context (de Mesquita 2016). With coordination failures, a short-term intervention may be sufficient to move to a new, self-sustaining equilibrium by changing agents' beliefs about others' behavior and thereby increasing the expected payoff from investing in complementary inputs. These beliefs may then prove self-reinforcing even after the policy has ended, especially if agents have made up-front investments in capacity (Rodrik 2004). By contrast, policies that cause agents to internalize the cost or benefits of Pigouvian externalities—most notably, by pricing the externalities directly—will induce efficient behavior only for as long as they are in force. From this perspective, the climate transition may more closely resemble a coordination problem in some sectors and a pure externality problem in others. For example, in the switch from gasoline-powered to electric light-duty vehicles, it is possible that only temporary policy interventions will be needed to help automakers descend the learning curve in electric vehicle production,

accelerate the build-out of charging infrastructure, increase consumer confidence in the new products, and induce the entry of complementary services such as dealers and mechanics trained in electric drivetrains. On the other hand, industries that rely on carbon capture for decarbonization will likely always depend on externality-correcting policies even after technologies have reached maturity. Industrial production with the additional energy costs of carbon capture is likely to be more expensive than the equivalent process without carbon capture devices running, unless a significant market develops for captured CO_2.

D. Distributional Concerns

In addition to these innovation market failures, key features of the newly scaled policy instruments are motivated by other policy priorities. Shifting to low-carbon methods of production will create winners and losers, and policy makers and other stakeholders are increasingly aware of and attentive to the distributional impacts of the energy transition.[16] Labor-market impacts have received particular focus, with policy makers drawing connections between job losses in "fossil fuel communities" and the historical loss of manufacturing employment due to globalization (Boushey 2021; Curtis and Marinescu 2022; Curtis, O'Kane, and Park 2024). Beyond the labor market, there are many ways in which emissions are correlated with demographic vulnerability (Metcalf 2023), and a long history of racism and other forms of discrimination means that some demographic groups have greater access to resources to manage the costs of climate transition. For these reasons, several of the newly scaled innovation policy instruments discussed in this paper—as well as many other recently implemented climate policies—explicitly promote redistribution as part of the climate transition.[17] These distributive goals interact in nuanced ways with the innovation market failures discussed in this paper.

Several of these newly scaled policy instruments incorporate distributional considerations by targeting a subset of program budgets to places with certain characteristics. An important theme that emerges from the literature on place-based innovation policies is that location-specific benefits often differ across R&D, production, and consumption of new technologies. For example, if more jobs are created in the production (e.g., manufacturing) of new technologies as compared with earlier R&D (Glaeser and Hausman 2020), then place-based policies targeting production might more effectively address the risk of widespread job

loss in locations where the employment base directly depends on fossil fuel–based energy or industrial production. Greenstone, Hornbeck, and Moretti (2010) document substantial gains in local productivity from the arrival of a "million dollar plant"; by contrast, efforts to stimulate economically distressed regions by providing incentives for new innovation clusters have met limited success (Lerner 2009; Glaeser and Hausman 2020; Kerr and Robert-Nicoud 2020). Nonetheless, the literature on place-based policies also poses a key question: rather than targeting places, why not develop policies to support the individuals affected by the climate transition directly? One reason why place-based policies may be important is the recent decline in US labor mobility, suggesting that affected individuals may not easily move to new employment; Ganong and Shoag (2017) document a corresponding plateau in income convergence at the state level. Evidence also suggests that the welfare benefits to a robust employment base exceed the monetary value of wages (Deaton and Case 2017; Autor, Dorn, and Hanson 2019).

How program implementers balance the dual objectives of maximizing aggregate emissions reductions and ensuring an equitable distribution of benefits and costs associated with the climate transition also depends on the characteristics of the technology in question. On the one hand, to the extent that R&D productivity depends on the training of the local workforce and the proximity to relevant labs and other institutions, the locations most conducive to productive innovation may not match economically distressed areas in greatest need of support (Glaeser and Hausman 2020). On the other hand, achieving widespread adoption of distributed climate technologies—which require large numbers of adopters to have a meaningful impact on emissions—may require developing business and financing models suited for local contexts. For example, business models for energy efficiency or building electrification may depend on the characteristics of local buildings, state and local regulations, and community access to credit.[18] Public support may be useful in ensuring that this place-based tailoring of climate innovation is inclusive of low-income and minority communities, given the considerable evidence that minority racial and ethnic groups are underrepresented in the innovation sector even relative to similar occupations (Gompers and Wang 2017; Cook, Gerson, and Kuan 2021; Ewens 2022). Other research has suggested that minority-owned small businesses face greater barriers to raising up-front and ongoing capital (Henderson et al. 2015; Fairlie, Robb, and Robinson 2022), so targeted support for entrepreneurship in minority communities may be particularly effective.

Similar considerations apply for the consumption of new climate technologies. In some cases, the benefits will be spatially diffuse regardless of where new technologies are developed, manufactured, or installed, given nationally and internationally integrated product markets and the global nature of climate change. In other cases, technologies may create cobenefits for adopters—such as improved indoor air quality from building electrification—so ensuring that consumption occurs in a wide variety of places is an important equity issue. Credit constraints are one example of a barrier that may prevent disadvantaged communities from realizing these benefits. Communities with greater access to credit will be more easily able to adopt low-carbon technologies with high up-front costs such as renewables, energy-efficient appliances, energy storage, building electrification, and so forth (Schleich 2019; Berkouwer and Dean 2022). Yet low-income and minority communities have lower access to credit in general and pay higher interest rates for access (Adams, Einav, and Levin 2009; Broady, McComas, and Ouazad 2021). Those who are not able to pay outright or to finance these up-front costs may be left with a disproportionate share of the burden of managing the wind-down of legacy infrastructure (Davis and Hausman 2022). Without deliberate efforts to increase access to credit for climate technologies—or other redistributive policies—the energy transition will be inherently unequal in its allocation of benefits and costs (see Borenstein and Davis 2016; for an exception, see Davis 2024).

III. Newly Scaled Policy Instruments

In this section, we discuss the institutional history of the newly scaled policy instruments and connect their stated goals to the literature on innovation market failures and distributional concerns (summarized in table 4 and fig. 1). We also offer questions for policy design and evaluation that may help disentangle which market failures matter most in a given context and which policy mechanisms are most effective (summarized in table 5).

A. Demonstration Projects

"Demonstration projects" typically refer to the first full-size manufacturing facilities, energy generating plants, or other capital-intensive infrastructure constructed to assess whether new technologies can operate successfully at scale and when integrated with existing systems.[19]

Table 4
Overview of How Policy Instruments May Address Goals

	Policy Instruments			
Market Failure or Policy Goal	Demonstration Projects	Loan Guarantees	Green Banks	Regional Technology Hubs
Knowledge spillovers	Share knowledge of systems integration and technology testing at scale	Share knowledge of financial innovation for new technologies and commercial track record	Share knowledge of financial innovation for new business models and commercial track record	Share knowledge of systems integration and supply chain
Coordination failures			Standardize contracts	Coordinate customers, suppliers, specialized infrastructure, other inputs
Financial frictions	Incur high fixed costs for technology derisking	Mitigate credit rationing; signals technical quality	Mitigate credit rationing	
Distributional concerns		Target uneven financial frictions	Can target uneven financial frictions; adapt distributed climate technologies for local markets	Create jobs; boost underserved locales

Select technology areas have previously received federal funding for demonstration projects, such as carbon capture and energy storage under the American Recovery and Reinvestment Act of 2009. Certain states, most notably New York and California, have also been active in funding a range of energy demonstration projects. Rozansky and Hart (2020) identify three waves of demonstration projects in the energy sector, precipitated by three crises: the energy crises in the 1970s and early 1980s and the Great Recession of 2008. Lester and Hart (2015) also note that the US Department of Defense has a successful track record of demonstration projects for advanced weapons systems.

Most recently, the IIJA appropriated $21.5 billion for energy demonstration projects and created a new Office of Clean Energy Demonstrations within the Department of Energy (DOE). Regional hydrogen hubs are the single largest investment area (discussed in a subsequent section).

Table 5
Key Questions for Program Design and Evaluation

Demonstration Projects	Loan Guarantees	Green Banks	Regional Technology Hubs
Would demonstration projects in this sector be underprovided if start-ups were well capitalized or incumbents were working in this area?	What are the largest fixed costs from underwriting a new technology? What information reduces this cost for future private lenders?	What are the largest fixed costs from underwriting a new business model? What information reduces this cost for future private lenders?	Would this industry be privately profitable to enter if complementary inputs and infrastructure were available, or would additional subsidies still be needed?
Which fixed costs of project development can be reduced through learning from demonstration projects?	Ignoring the fixed costs of underwriting, would commercial lenders be willing to finance this project at any interest rate?	Ignoring the fixed costs of underwriting, would commercial lenders be willing to finance this project at any interest rate?	Which fixed costs of industry development can be reduced through learning from regional demonstration projects?
What are the remaining uncertainties about whether a technology can be commercially successful at scale? What information from demonstration projects would reduce that uncertainty?	Do private lenders view support from LPO as a positive signal? What are the trade-offs between the quality of signal and the burden of the application process?	Does this business model require contract standardization to scale?	What are the remaining uncertainties about whether a supply chain can be commercially successful at scale? What information from regional demonstration projects would reduce that uncertainty?
How can program implementers share key information publicly without undermining the incentives of private developers to participate?	How do private lenders view more years of operational data from one project (higher T) versus operational data from more projects (higher N)?	Is this distributed climate technology part of a least-cost portfolio of decarbonization solutions?	Are potential agglomeration economies specific to new technologies or cumulative with previous technologies?
In what ways is public funding for demonstration projects like venture capital and in what ways not?	In what ways are public loan guarantees like commercial debt and in what ways not?	How does the deployment of a distributed climate technology depend on local regulations, demographics, or infrastructure?	
		In what ways are green banks like commercial debt providers and in what ways not?	

Note: LPO = Loan Programs Office, US Department of Energy.

Other demonstration programs funded under the IIJA include $2.5 billion for advanced nuclear reactors, $2.5 billion for carbon capture, $6.3 billion for industrial emissions (which includes additional funding from IRA), $5 billion for power-grid modernization and resilience, and $500 million for long-duration energy storage. Demonstration project funding is also embedded in other parts of recent legislation; for example, CHIPS created a program for R&D, demonstration, and commercial applications of low-emissions steel manufacturing.

New knowledge creation—and by extension, the possibility for knowledge spillovers—plays an especially important role at the demonstration stage. To build a full-size facility that is integrated with existing infrastructure, firms must train workers to build and operate the equipment, work with regulators to permit the new facility and apply existing safety and environmental standards in a new context, resolve issues with the technology that were not apparent at the prototype stage, and so on (Hart 2018; Nemet, Zipperer, and Kraus 2018). Demonstration projects may also provide valuable information about whether a project is unlikely to be commercially successful (Kotchen and Costello 2018). Although some of this new knowledge will benefit the firm incurring these fixed costs, some will undoubtedly benefit competitors. The existence of a trained workforce or regulators familiar with new production methods should reduce barriers to entry for future competitors, as an example. Of course, there are certain types of uncertainty that would not be resolved through demonstration projects, such as uncertainty around commodity prices, customer demand, or the policy environment. Useful questions for program planning and evaluation are outlined in table 4: What types of uncertainty matter most to potential private lenders of early commercial projects? What information from demonstration project outcomes would reduce that uncertainty? How can program implementers share key information publicly without undermining the incentives of private developers to participate?

Demonstration projects have proved difficult to fund using traditional VC or project-finance approaches, leading many industry observers to suggest that financial frictions have also contributed to inadequate resources for this stage of the innovation process.[20] Although prototypes help to achieve certain technological milestones, they do not fully resolve the type of technology risk that occurs at full-size implementation. Certainly VC investors have made investments of comparable amounts to what would be needed for capital-intensive demonstration projects in recent years, as the supply of VC funding has grown considerably and as

start-ups are raising more and larger funding rounds (Ewens and Farre-Mensa 2020). Yet as noted in our discussion of financial frictions above, many of the largest VC investments have gone to start-ups in the later "scale-up" phase, when technological risk and uncertainties about product-market fit have largely been resolved, rather than to capital-intensive start-ups in the earlier "learning" phase (Nanda 2020). Though hard to test empirically given the relatively small sample size of projects, it seems plausible that public support for demonstration projects will allow technologies with high fixed costs of experimentation to have an opportunity to be commercially successful. One implication might also be that publicly funded demonstration projects for technologies with lower costs of experimentation would be less impactful, all else equal.

A central challenge, then, is distinguishing between candidate projects that would struggle to obtain private funding because of market failures and those that cannot secure funding because they are simply bad projects. One path forward for program implementers might be to think systematically about the ways in which they are or are not similar to providers of private finance—venture capitalists being perhaps the closest fit in the case of demonstration projects. Then program implementers could strive to mimic the solutions that venture capitalists have adopted for overcoming asymmetric information problems to the extent that they are filling similar roles, and think critically about how to alter standard VC practices to the extent that they are not. For example, demonstration projects might still benefit from staged financing, as these projects are inherently risky and information is revealed over time about the likelihood of success.[21] On the other hand, new knowledge creation is an important part of undertaking demonstration projects, implying that the definition of success is not the level of private returns that a VC would expect but other metrics developed by program implementers that would include learning spillovers within these nascent industries.

B. Loan Guarantees

Originally authorized under the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, the DOE's loan programs provide direct loans and loan guarantees to innovative energy projects, advanced vehicle manufacturing, and energy projects on tribal lands. These programs were first active under the Obama administration, funding their first 30 projects between 2009 and 2011, including funding for the Tesla Model S, the Nissan Leaf, and Solyndra.[22] Less well known

is that DOE's Loan Programs Office (LPO) supported the first five utility-scale solar plants larger than 100 megawatts, after which private financing for utility-scale solar projects increased significantly (McCall 2016). Studies have found loan guarantees to be effective in other contexts (Shi, Liu, and Yao 2016), though rigorous evidence on the impact of DOE's loan programs is still limited (Bhandary, Gallagher, and Zhang 2021).

The IRA significantly increased total lending authority (by approximately $350 billion) and available credit subsidy (by $11.7 billion in appropriations) for loan programs. Beyond increasing funding for existing programs, the IRA and IIJA also created two new loan programs (for energy infrastructure upgrading and CO_2 transport, respectively).[23] Under these new and newly scaled programs, the LPO guarantees repayment of loan principal and interest—either from the US Treasury's Federal Financing Bank or from commercial lenders—for up to 80% of the costs of approved projects. In contrast to demonstration projects, DOE's loan programs fund projects where there is a reasonable expectation of repayment, which means they are not interested in funding projects that still face residual technology risk. The LPO now describes its role as a "bridge to bankability," focusing on projects that are "mature from a technology standpoint but not mature from an access to capital standpoint" (DeHoratiis 2022).

Following the derisking of construction, engineering, and other technical implementation details at the demonstration stage, projects supported by the LPO may generate additional knowledge spillovers from financial innovation. Commercial lenders may be unwilling to incur the fixed costs of learning how to underwrite new types of loans if the new knowledge created has characteristics of a public good (Kahn and Shah 2022). Loan programs may create two types of knowledge in this scenario. First, by derisking projects and enabling them to proceed, they may help create a track record for new types of projects in the marketplace, creating public knowledge that new business and financing models are commercially viable.[24] Second, they may publicly share technical information about financial contracts employed in the early projects that they helped support, lowering the fixed costs for commercial lenders to enter the new market in the future (St. John 2021).

DOE's loan programs may also overcome financial frictions, by enabling entrepreneurs or project developers to obtain financing for first-of-a-kind or other early deployment projects. As noted above, banks may choose not to lend to risky but positive expected NPV projects if the interest

rate required to compensate for risk induces sufficiently undesirable behavior or adverse selection among borrowers. By guaranteeing loan repayment, DOE may allow projects to be undertaken without a strong selection or behavioral response. Then, new knowledge created through these early projects may help reduce the fixed costs of underwriting future loan contracts or the riskiness of future lending in this area, enabling similar projects to secure private financing without a DOE guarantee later on. Beyond the track record of the first-of-a-kind project itself, successful vetting by DOE's scientific and engineering staff may also provide a positive signal for technological viability (Leland and Pyle 1977; Kahn and Shah 2022). Finally, even if subsequent deployments of a new climate technology might be eventually funded in the private market, once sufficient time has passed to gather years of data from the first-of-a-kind plant, additional support from the LPO for the second, third, or fourth project might accelerate this process (Kahn and Shah 2022). Given the ongoing atmospheric accumulation of greenhouse gas pollutants, compressing this process may be socially beneficial.[25]

Program implementers again may find it useful to think systematically about the ways in which DOE's loan programs are and are not acting like commercial lenders, to adopt practices that are common in the private lending market in the areas where they are similar, and to modify standard practices in the areas where they are not. For example, if program implementers are most focused on lowering the fixed costs of entering a new market, then they may wish to adopt standard commercial debt contracts once the hurdle of the underwriting process has been surmounted. By contrast, if program implementers are more focused on overcoming credit rationing in a new technology area, then they may instead wish to deviate from standard lending practices.

Of course, many of these potential channels of program impact are empirical questions that might be addressed through program evaluation or other information-gathering processes by program implementation staff. Relevant questions include: What are the greatest fixed costs of underwriting a new technology or business model, and what information can DOE provide from its loan programs that most substantially reduces this cost? If fixed costs of underwriting were accounted for, would commercial lenders be willing to finance these projects at any interest rate? Do commercial lenders view support from the LPO as a positive signal, and are they willing to adjust their behavior accordingly? Are there trade-offs between the quality of the signal and the fixed costs that applicants must incur to obtain support from the LPO? How would

commercial lenders weight 1 or 2 years of operational data from several projects funded by the LPO relative to 5 or 6 years of operational data from a single project?

C. Green Banks

Contrary to its name, a "green bank" is not a deposit institution but rather a type of financial institution that uses public or quasi-public seed funding to provide debt capital to projects that align with its mandate.[26] In the United States, approximately 20 green banks have emerged at the state and local level; the New York and Connecticut green banks have been particularly significant.[27] These institutions have supported clean energy, energy efficiency, and other climate-related projects that the private sector would be otherwise unwilling to fund, using a variety of financial instruments. Funding amounts have typically ranged from $5 million to $50 million, though the scale of funding has also varied across different state and local green banks depending on their overall capitalization (Kehoe, Lee, and Radulovic 2021). In contrast to a direct subsidy program, green banks often seek to leverage public funding at the project level (by coinvesting with private funders, guaranteeing loans from private funders, or using other instruments to bring in private funding) or portfolio level (by receiving outside capital to increase the size of its balance sheet beyond the initial seed (Coalition for Green Capital 2019).[28] The president of the New York Green Bank has suggested that priority areas for green banks in coming years include vehicle-charging infrastructure, energy storage, and building decarbonization (Kessler 2022).

Discussions about establishing a national green bank in the United States have occurred for more than a decade, with the creation of a Clean Energy Deployment Administration included in the version of the Waxman-Markey Bill that passed in the House of Representatives in 2009.[29] Nonetheless, the IRA represents the first time that Congress has appropriated significant funding for this concept. As part of the General Assistance and Low-Income and Disadvantaged Communities Grant Program, the IRA appropriates $20 billion for projects that "reduce or avoid greenhouse gas emissions or other forms of air pollution in partnership with, and by leveraging investment from, the private sector; or assist communities in the efforts of those communities to reduce or avoid greenhouse gas emissions and other forms of pollution."[30] Of the $20 billion total, $8 billion is appropriated specifically for projects in "disadvantaged communities," and $12 billion is available for any community.[31]

The exact structure of funding for these projects is still unclear at the time of this writing; in its most recent announcement, the Environmental Protection Agency (EPA) noted that it anticipates making between 2 and 15 grants to eligible institutions, 1 of which may operate at a national scale.[32] Observers have suggested that EPA may fund existing green banks or help create new ones at the national, regional, state, or local level (Turner 2023).

Green banks in the United States have typically focused on supporting new business and financing models for already commercial climate technologies. For example, community solar projects are a well-known funding area for green banks over the past decade. Developed after the market for rooftop solar PV had emerged in the 2000s, community solar represented a new model of solar deployment in which renters, households with lower incomes or poorer credit scores, and others whose homes were not physically suited to rooftop solar panels could participate in distributed solar generation (Kessler 2022). Another example from the past decade is green-bank funding for energy efficiency retrofits in small businesses: dry cleaners, houses of worship, daycares, and retirement communities, among others.[33] New business and financing models were needed to enable energy efficiency retrofits with high up-front costs relative to the revenues of these small businesses and to develop financial contracts that were suitable for the small businesses' cash-flow patterns.

Just as commercial lenders may not initially understand how to structure loans for new types of large-scale climate infrastructure, they also may not initially understand how to structure loans for new methods of deploying distributed climate solutions. As in our above discussion about DOE's loan programs, insofar as new knowledge about how to structure these loans has characteristics of a public good, private lenders may underinvest in this learning. Green banks may help reduce fixed costs of issuing loans in new areas and create public knowledge about the viability of new business and financing models. With community solar projects, for example, representatives of the New York Green Bank have described their efforts to "flatten the learning curve for other lenders" by developing, successfully using, and publicly documenting scalable and replicable loan terms for community solar projects (Green Bank Network 2022).[34]

Furthermore, community-level climate projects may face additional financial frictions due to credit rationing. Motivated by this possibility, governments have long offered credit enhancements to small businesses,

with a mixed record (Cowling 2010). Perhaps more compelling than general credit enhancements for small businesses is support for particularly risky phases of project development in nascent industries (Khatcherian 2022). As an example, the New York Green Bank has provided "interconnection bridge loans" to early community solar developers, allowing them to pay certain interconnection fees that were incurred before offtake agreements were signed and project finance became available (Green Bank Network 2018; New York Green Bank 2022). As an industry matures, these up-front fees may be instead paid out of retained earnings, avoiding costly external finance; alternatively, regulations may be updated to reflect the characteristics of new technologies and business models.

Beyond these initial investments in one-off projects, a coordinating force may also be needed to help distributed climate solutions reach widespread adoption. For small-scale deployments of climate technology, the transaction costs associated with customizing loan terms for each project are likely to be prohibitively high. One solution is converging on a standardized contract structure and terms, as financial markets have done successfully for residential mortgages or even rooftop solar installations. Standardization not only lowers transaction costs but also allows loans to be bundled together to attract much larger institutional capital providers (Griffin 2014; Kaufman 2018). For example, energy efficiency retrofits at a range of small and medium-sized businesses might be bundled together so that they no longer need to be treated as stand-alone projects despite differences in the underlying business. But standardization also requires agreeing on a standard, creating an opportunity for a green bank to help overcome coordinating frictions across disparate players in the market (Green Bank Network 2022). In many cases, the green bank might play that coordinating role directly; standardization would be an appropriate focus for a regional or national green bank (Green Bank Network 2022). Alternatively, the private sector may fill this coordinating role, with funding from a green bank to defray the up-front cost.[35]

Each of these potential market failures interacts with equity issues in the context of green banks. Many of the financial frictions identified above may be most acute in low-income or minority communities with more limited access to traditional forms of credit, providing stronger rationale for credit enhancements in low-income or minority communities (Miller and Soo 2020; Howell et al. 2021; Fairlie et al. 2022). Furthermore, place-based policies may be especially warranted to support business and financial innovation that enables climate technology to be deployed

in communities that might not otherwise have access. Distributed climate solutions—which will only have a substantial impact on aggregate emissions if they are adopted by many different demographic groups—may unite the goals of achieving decarbonization at scale and ensuring equitable participation in the climate transition. A useful exercise for program implementers is distinguishing between distributed solutions that are part of a least-cost portfolio of decarbonization approaches and those that have higher abatement costs; although the former would not create equity-efficiency trade-offs, the latter are valuable primarily because they help to make the climate transition more inclusive.

D. Regional Technology Hubs

Finally, recent federal legislation has appropriated funds for several large-scale regional technology hubs. IIJA provides $8 billion for 6 to 10 regional hydrogen hubs and $3.5 billion for 4 regional direct air capture (DAC) hubs.[36] The idea of bringing together diverse actors in a specific location to solve a particular technological challenge has an established history at the DOE. Under the Obama administration, the DOE funded several Energy Innovation Hubs, themselves inspired by bioenergy research centers from the George W. Bush administration, which sought to bring together basic and applied research to solve specific practical challenges (Cho 2021).[37] Beyond the DOE, other parts of the federal government have sought to combine local or regional economic development with a specific agency mission (reviewed in Chatterji, Glaeser, and Kerr 2014). As with the other policy instruments discussed in this paper, the regional technology hubs funded in IIJA develop an existing concept at much larger scale than hitherto attempted in the energy sector.

Both the regional hydrogen and DAC hubs are conceptually close to demonstration projects in terms of the knowledge spillovers that they may create. Indeed, the regional hydrogen hubs represent the largest single investment area overseen by DOE's Office of Clean Energy Demonstrations. Both the hydrogen and DAC programs prioritize funding a diversity of technologies (feedstocks for hydrogen production and methods of carbon capture, respectively), end uses (for hydrogen and captured CO_2), and geographic regions; demonstration of these technologies and end uses may generate knowledge about performance at scale and when integrated with existing infrastructure, as discussed above. Unlike stand-alone demonstration projects, however, the hubs are also explicitly

focused on technology development in particular regions, which raises questions about potential knowledge spillovers in geographic space. The economics literature on knowledge spillovers suggests that such benefits are highly localized for individual firms (decaying within a few miles) but that overlapping interaction zones may create larger knowledge clusters at the city or county level (Kerr and Kominers 2015; Lychagin et al. 2016; Hausman 2022). Understanding these historical patterns may prove useful for program implementers when working with large multistate applicants (Bioret, Zhu, and Krupnick 2023).

The coordination failures that these regional technology hubs may address are even more likely to have an explicitly spatial dimension. Relative to demonstration projects, the hydrogen and DAC hubs face the same challenges of coordinating activities among producers, consumers, and a wide array of intermediate inputs, including enabling regulations, physical infrastructure, an appropriately trained workforce, upstream and downstream suppliers, and so forth. The magnitude of the positive externalities that these actors create for each other is likely to be larger when they are located closer together, thereby lowering transport costs from one to the other—a form of "agglomeration effects." Indeed, economists have suggested that agglomerative forces are likely to matter more for newer industries, as clusters of activity allow firms to share the fixed costs of common inputs (Carlino and Kerr 2015).[38] Given the specialized infrastructure needed for transporting CO_2 and H_2 and the increased risk of leakage the further they are transported, these industries may be particularly conducive to spatial concentration across the value chain, even relative to other nascent climate technologies (Nemet 2023). Finally, the highly regulated nature of these industries and the infrastructure that they require (e.g., pipelines) suggest another type of spatial externality: ease of coordinating the relevant permits and regulations, which are often promulgated at a state and local level.

Beyond the initial demonstration of a regional ecosystem for these new technologies, an additional goal is to seed self-sustaining industries. Economists have been largely pessimistic about the ability of policy makers to create new technology clusters at the local or regional level (Lerner 2009; Chatterji et al. 2014; Kerr and Robert-Nicoud 2020). There is, however, a conceptual distinction between proverbial efforts to "create the next Silicon Valley" and an effort to develop a specific new technology that focuses on building specialized infrastructure and production facilities in a specific location. Nonetheless, it is still useful to pay

attention to the pitfalls that have befallen earlier attempts to create localized technology clusters.

One theme that emerges repeatedly in this literature is the importance of the right mix of firms for sustained innovation. On the one hand, large incumbent firms can serve as "anchor firms" that strengthen the innovation ecosystem and seed spin-off entrepreneurship (Agrawal and Cockburn 2003; Feldman 2005; Figueiredo, Guimarães, and Woodward 2009; Glaeser and Kerr 2009). On the other hand, too much support for large incumbent firms can crowd out new entrants and stifle more radical innovation (Agrawal, Cockburn, and Rosell 2010; Chatterji et al. 2014).[39] Therefore, diversity in firm size within a given industry location is important, combining anchor firms with a supportive environment for new entrants (Markusen 1996; Agrawal et al. 2014; Klepper 2010, 2016). How to achieve this balance in practice is tricky and not well understood, and likely depends on the characteristics of the technology in question. For example, electrolyzers for producing "green hydrogen" are modular technologies, whereas existing methods for producing "blue hydrogen" from fossil fuels with carbon capture are not; therefore, the efficient distribution of larger versus smaller firms may differ across different hydrogen hubs (see Carlino and Kerr 2015 for discussion of modularity and lab size).

Finally, we note that these regional technology hubs have an explicit focus on the distributional consequences of the climate transition. The enabling legislation instructs DOE to locate the DAC hubs "to the maximum extent practicable" in regions with existing or recently retired "carbon-intensive fuel production or industrial capacity," prioritizing projects that are "likely to create opportunities for skilled training and long-term employment to the greatest number of residents of the region." In addition, the legislation instructs DOE to locate two of the four DAC hubs in "economically distressed communities" with "high levels of coal, oil, or natural gas resources." For hydrogen hubs, DOE is also instructed to prioritize applications that are likely to provide skilled training and long-term employment to residents.

The opportunity for agglomeration effects in the development of the nascent hydrogen and DAC industries—leading to more and faster development in a specific location—creates a potential policy synergy between innovation and equity goals. If agglomeration economies are specific to the new technologies, rather than cumulative with previous technologies, then at this early stage of technology deployment, it might be possible to create agglomeration benefits in many different places. By

launching these nascent industries in disadvantaged places, or places that will be disadvantaged by the transition away from fossil fuels, policy makers may mitigate regional inequities and take advantage of agglomeration benefits going forward. That said, concerns about equity are multidimensional, and providing employment or other economic benefits does not address the concerns of environmental justice groups about air pollution or hazardous waste associated with these industries.

IV. Unaddressed Market Failures

An explicit goal of many of these policies is to support clean technologies temporarily, as they find a foothold in the market, but then to allow the private sector to realize large-scale deployment. Even if these policy instruments are necessary to enable widespread commercialization, they may not be sufficient. As we have emphasized in this paper, there may be innovation market failures—especially in this middle part of the innovation process, during initial technology deployment—that are effectively targeted through these policy instruments. In some cases, these policy instruments may help to shift an industry to a new equilibrium, as financial innovations are developed and diffused, standards are adopted, and dispersed market actors shift their subjective beliefs about each other's actions. Technologies developed in the United States may also create international spillovers, especially in developing economies.[40] However, these policy instruments may not address all of the innovation market failures that slow the initial deployment of climate technology. For example, none of these policy instruments directly addresses the underdeveloped "market for ideas" in many climate-technology areas, although these policies may ameliorate this issue indirectly by helping incumbents secure external financing for demonstration or first-of-a-kind projects, thereby making acquisitions or alliances more attractive. These policy instruments also do not address broader organizational and institutional reasons why it may be difficult to develop and commercialize technology aimed at solving very long-term problems, such as managerial myopia (Stein 1989) and other forms of short-termism (Budish, Roin, and Williams 2015).

Most crucially, none of the policy instruments discussed in this paper addresses the carbon externality directly. It is important not to confuse a lack of demand for clean technologies due to unpriced externalities with, for example, a lack of financing (van den Heuvel and Popp 2022). In many cases, the recent injection of federal funding into these policy

instruments creates greater urgency to address underlying demand for clean technologies.

Indeed, an implicit assumption in the theory of change underlying these newly scaled policy instruments is that climate change is such a significant problem that this underlying demand for carbon reduction will emerge in the medium term, one way or another. Certainly some firms (and ultimately consumers) have signaled a willingness to pay a "green premium" for low-carbon inputs in the near term, which may prove critical during this period of early deployment. Yet voluntary adoption is inherently small relative to the magnitude of the overall externality and cannot provide the necessary scale in the medium term. In other cases, the federal government will provide direct subsidies that overlap with these innovation-focused policies, helping to unlock additional sources of demand. For example, federal tax credits for carbon removal ("45Q" tax credits, funded in IRA) should help bolster the market for DAC in tandem with funding for regional DAC hubs.[41] Yet these tax credits will eventually expire, and the market for carbon capture will ultimately depend on a stable price signal reflecting the negative externalities from emitting CO_2. Some noncarbon technologies will eventually become sufficiently cost-effective that they can compete with carbon-intensive technologies even without any price on carbon or green premium. But most climate-mitigation technologies will not be cost-effective without further policies such as a carbon price to induce demand for carbon reduction in the medium to long term. If those direct mitigation-inducing policies do not develop, the newly scaled technology policy instruments will fail as both technology and climate policies, as they will have built bridges to nowhere.

V. Conclusion

This paper maps the economics literature about innovation market failures to the stated goals of policy instruments newly scaled under recent climate-related legislation. Understanding the range of potential underlying market failures may help to focus discussions about how to implement these policies as effectively as possible. Because each of these newly scaled policy instruments has the potential to address several different innovation market failures, applying the market-failures framework to stakeholder input about the most important barriers may help program implementers to tailor program design accordingly. For example, green banks may prioritize different projects or contract structures if trying to

reduce the fixed costs of underwriting new business models versus trying to avoid credit rationing due to high perceived risk. More generally, the market-failure framework can help program implementers think systematically about the ways they can learn from and appropriately imitate the tools and practices of private funders, and the ways they should deviate from private capital providers to address policy concerns that private funders do not share.

Of course, although the existence of market failures or redistributive goals is necessary for effective policy intervention, they are by no means sufficient to ensure that policy is able to achieve its goals. In some cases, government is well suited to easing frictions that the private sector is unable to address. In other cases, the market failures in question are extremely tricky to eliminate. Much of the economics literature reviewed in this paper provides a sobering reminder that these innovation market failures often fall into the latter category. Given this challenge, experimentation and continuous evaluation are key components of program implementation. Climate change is simultaneously very urgent and very long term as a policy priority. The "shocks" of recent climate legislation create opportunities to learn systematically about which market failures are most inhibiting and which instruments address them most effectively (Aldy 2022). This learning does not happen automatically but requires evaluation to be built into program design at every stage of the process.

Endnotes

Author email addresses: Armitage (armitage@bu.edu), Jaffe (adam.jaffe@motu.org.nz), Bakhtian (nmb@alumni.stanford.edu). The authors would like to thank Michael Kearney, Josh Lerner, Ramana Nanda, and Tom Kalil for helpful conversations and the editors Matthew Kotchen and Catherine Wolfram for valuable feedback. For acknowledgments, sources of research support, and disclosure of the authors' material financial relationships, if any, please see https://www.nber.org/books-and-chapters/environmental-and-energy-policy-and-economy-volume-5/innovation-market-failures-and-design-new-climate-policy-instruments.

1. Under the American Recovery and Reinvestment Act of 2009, the Department of Energy's Loan Programs Office provided $16.1 billion in loans for innovative energy projects, as well as $8.4 billion in loans for advanced vehicle manufacturing under the Energy Independence and Security Act of 2007; IRA has scaled these programs even further. Also note that some sources refer to $21.5 billion in appropriations for demonstration projects under IIJA; this amount combines the $13.5 billion for demonstration projects listed above and $8 billion for regional hydrogen hubs, which we have instead categorized under regional technology hubs.

2. Note that government capital "filling in" for private capital is not the same as the concern about government capital "crowding out" private capital. Crowding out refers to a situation where private actors reduce their investment as a result of the government

investment, so that total investment is not increased by the full amount of government spending. This could happen if policy makers misjudge the extent of market failures and support projects where private incentives are in fact adequate. But if policy makers judge market failures appropriately, they will be supporting projects in which private actors are not investing, so there would not be crowding out.

3. For one, empirical research using patent citations has traced spillovers across patenting firms, mediated by factors such as geographic or technological distance (Jaffe 1986; Trajtenberg 1990; Jaffe, Trajtenberg, and Henderson 1993; Griffith, Lee, and van Reenen 2011). This research has consistently concluded that individual firms do not fully recoup the benefits of their R&D.

4. It is not necessarily the case that these costs are higher for climate-mitigation technologies than for other investments (though some have argued that they are, as discussed in the main text). Instead, government might choose to intervene to overcome these barriers for climate-mitigation technologies but not for other technologies because of the interactions with unpriced carbon externalities.

5. So influential has the VC model been in unlocking funding for innovation that Kenneth Arrow famously claimed, "Venture capital has done much more, I think, to improve efficiency than anything" (Arrow 1995).

6. In reviewing utility patents granted by the US Patent and Trademark Office between 2000 and 2020, Dalla Fontana and Nanda (2023) find that VC-backed patents are a small share of overall "Net Zero" patents, but that the potentially more innovative subset of "Deep Tech" patents constitute a larger share of VC-backed firms' overall patenting, compared with the share of Deep Tech patents within the patenting of other young firms or mature firms. This finding is consistent with other work on VC-backed patenting across multiple sectors, which also finds that VC-backed patents are higher quality and more economically important than the average patent (Howell et al. 2020).

7. Without implicating him in any errors, the authors are grateful to Ramana Nanda for a helpful conversation about these issues.

8. On the one hand, Ewens and Farre-Mensa (2020) document a substantial increase in funding for VC-backed start-ups, due to investment from pension funds, mutual funds, hedge funds, and other nontraditional investors. This increase in funding has enabled start-ups to raise larger funding rounds and to stay private for longer. Nonetheless, the associated increases in VC funding have been highly concentrated in a small number of VC firms. Lerner and Nanda (2020) document that about 5% of VC firms investing in US start-ups raised half of the total VC funding over 2014–18. Furthermore, direct investments in start-ups from nontraditional investors have prioritized liquidity, investing in later funding rounds and in larger companies, obtaining stronger rights related to share redemption and initial public offerings, and ceding more traditional control rights (Chernenko et al. 2020).

9. Stiglitz and Weiss (1981) also include under the definition of credit rationing circumstances where some observationally identical potential borrowers are able to obtain loans and others are not, and those who are denied are unable to obtain loans even at higher interest rates.

10. Nanda et al. (2015) also note the critical role of incumbents such as Cisco, Lucent, HP, and Juniper Networks in acquiring start-ups in the information technology and networking industry.

11. Project finance is an external financing arrangement that relies on project-level assets and projected cash flows rather than the balance sheets of the project developer.

12. In the climate-economics literature, coordination failures have largely been considered in the context of international agreements. That is, if countries collectively agreed to curb their emissions, global surplus would increase; yet countries fail to coordinate because they cannot credibly contract with each other on emissions reductions (e.g., Barrett and Dannenberg 2012). One exception is Mielke and Steudle (2018), which examines coordination failures in decisions about whether to invest in low-carbon production. More broadly, coordination failures are a useful lens through which to study new technology markets in the early stages of commercial deployment.

13. Many papers have considered the existence of coordination failures in national and regional economic development. A nonexhaustive list includes Azariadis and Drazen

(1990), Krugman (1991), Matsuyama (1991), and Adserà and Ray (1998). For a helpful review, see de Mesquita 2016.

14. The build-out of electric vehicle (EV) charging infrastructure is one example that has received significant attention in the economics literature. Yet there are two distinct challenges here that are often conflated. First is the network externality associated with the charging infrastructure itself; even if charging stations were owned by a vertically integrated monopolist automaker, the industry would still face increasing returns to scale associated with charging-station investment in specific geographies. The second challenge is one of complementary investments, sometimes referred to as the "chicken and egg" problem, as it may be difficult for diverse automakers to coordinate with diverse charging-station providers on investments in new EVs and new charging stations, respectively. Many nascent climate technologies encounter this latter problem, even where there is not an explicit spatial network. For discussion of coordination problems in electric vehicle deployment and in the climate transition more broadly, see Boushey (2023).

15. In a US context, Kline and Moretti (2013) document the Tennessee Valley Authority's effectiveness in inducing long-run manufacturing productivity through a "big push" of investment. By contrast, Carlino and Kerr (2015) reflect on the "very questionable record of targeted government interventions to create ecosystems for innovation" (see also Kerr and Robert-Nicoud 2020).

16. We note that there are other dimensions of a just and equitable transition besides distributional issues, but we focus on distributive justice here because it is particularly suited to the tools of economics.

17. More broadly, the Biden administration's Justice40 initiative sets a goal that 40% of benefits from certain federal investments, including climate-related investments, flow to disadvantaged communities. Many provisions of recent legislation are consistent with this goal. See https://www.whitehouse.gov/environmentaljustice/justice40.

18. The local share of homeowners versus renters is another relevant characteristic. See Davis (2012) for evidence on lower adoption rates of efficient appliances among renters, even controlling for energy prices, weather, income, and other demographic characteristics.

19. Khatcherian (2022) provides a useful distinction between "demonstration projects," which are unlikely to be profitable, and "first-of-a-kind" projects, which are intended to be profitable, noting that definitions sometimes vary within the industry.

20. In this regard, climate technologies are not necessarily different from other capital-intensive technology areas that require significant time and resources to derisk. For example, in the early years of semiconductor manufacturing, the federal government funded "pilot transistor production lines"; early semiconductor manufacturing was also helped by defense procurement contracts awarded to new entrants with little track record (Fabrizio and Mowery 2007).

21. This idea echoes Rodrik (2014), who notes that one opposition argument to industrial policy is that government does not have the necessary information to "pick winners." Rodrik counters that this argument is largely irrelevant, as industrial policy should not be viewed as a one-time decision but rather a continuous process of recognizing errors and updating as the market develops.

22. The Recovery Act made it easier to fund projects, hence why the first projects were funded during these years.

23. See https://www.energy.gov/lpo/inflation-reduction-act-2022 and https://www.energy.gov/lpo/carbon-dioxide-transportation-infrastructure. Beyond increases in lending authority and credit subsidy, recent legislation has also changed other details of DOE's loan programs. In 2020, Congress allowed DOE to issue loan guarantees for up to 6 projects using a particular innovative energy technology, if regional variation significantly affects technology deployment; previously, DOE was limited to only 2 loan guarantees for a given innovative technology. IIJA also expanded the scope of the advanced vehicle manufacturing loan program to include medium- and heavy-duty vehicles, maritime vessels, aviation, and other transportation, in addition to light-duty vehicles; the innovative clean-energy loan guarantees program also expanded to include projects related to critical minerals. Other changes have streamlined the application process and reduced the up-front payments required for applications to be considered.

24. Beyond new knowledge created among commercial lenders and other market participants, the process of negotiating and contracting on loan terms will also likely result in new knowledge for entrepreneurs or other project developers who have not previously raised debt for this specific technology. If lenders are not unbounded in the rates (i.e., prices) that they are able to charge, due to concerns about adverse selection or moral hazard, then they may not be able to extract this additional surplus from borrowers.

25. An analogy might be the development of COVID-19 vaccines under the federal government's Operation Warp Speed. Given the urgency of the public health crisis, government intervention was able to collapse various stages of the innovation process to happen simultaneously rather than sequentially, as well as simultaneously scale up the supply chain for complementary products to reduce bottlenecks in production. For additional discussion, see https://www.npr.org/transcripts/1053003777 and https://crsreports.congress.gov/product/pdf/IN/IN11560.

26. This section focuses on community-level projects supported by green banks in the United States to date, in contrast to the large-scale climate infrastructure and manufacturing facilities supported by the LPO. However, the distinction between these types of programs may be increasingly blurred under recent legislation, with the opportunity to establish a green bank–like entity at the national level and with the LPO beginning to focus on distributed energy technologies.

27. EPA identified 21 green banks at the state and local level as of 2021; see https://www.epa.gov/statelocalenergy/green-banks.

28. The increasing focus on portfolio-level leverage represents an evolution of the green-bank concept in the United States. Early efforts focused largely on achieving maximum project-level leverage. For further discussion, see Coalition for Green Capital (2018).

29. For additional legislative history, see https://bipartisanpolicy.org/download/?file=/wp-content/uploads/2020/06/Looking-Forward-with-a-Clean-Energy-Deployment-Administration.pdf.

30. Note that the text of the IRA—or EPA's recent notice of initial program design—does not actually use the phrase "green bank." However, the definition of an eligible funding recipient in the legislation closely adheres to accepted definitions of a green bank, and commentators have typically referred to this provision of the IRA as funding for green banks.

31. Closely related is the IRA funding for the Zero Emissions Technologies Grant Program, which allocates $7 billion for projects that "enable low-income and disadvantaged communities to deploy or benefit from zero-emission technologies."

32. For EPA's announcement of initial program design, see https://www.epa.gov/newsreleases/epa-announces-initial-program-design-greenhouse-gas-reduction-fund. An eligible recipient is defined in the IRA as "a nonprofit organization that (A) is designed to provide capital, leverage private capital and provide other forms of financial assistance for the rapid deployment of low- and zero-emission products, technologies, and services; (B) does not take deposits other than deposits from repayments and other revenue received from financial assistance using the grant funds; (C) is funded by public or charitable contributions; and (D) invests in or finances projects alone or in conjunction with other investors."

33. For these examples of commercial energy-efficiency retrofits supported by state and local green banks, see Green Bank Network (2022).

34. It is also worth noting that one reason commercial lenders were unwilling to participate in early community solar projects in New York, according to a representative of the New York Green Bank, was the confusion around complex regulations for how distributed energy resources would be compensated in the state. The New York Green Bank was able to work with their state regulatory colleagues to develop loan terms that were compatible with the new rules. A far more efficient approach might have been for the state to develop simpler rules in the first place.

35. One start-up founder described how funding from the New York Green Bank allowed his company to develop a proof-of-concept credit pool for standardized energy-efficiency retrofits; subsequently, the company was able to fund an even larger credit pool using commercial debt (Green Bank Network 2022).

36. Beyond these large programs in IIJA, CHIPS authorized $10 billion for the Regional Technology and Innovation Hubs Program, administered by the Department of Commerce. These Tech Hubs cover several different technology areas, some of which are relevant for climate technologies, including advanced energy technology, storage, and energy efficiency. The program seeks to strengthen regional technological capabilities in these priority areas, with the goal of improving US global competitiveness and expanding access to jobs in the innovation sector.

37. The Energy Innovation Hubs were funded at $25 million over 5 years, with the possibility of renewal. They were recently wound down, having achieved mixed success (Cho 2021).

38. "Agglomeration effects" refer to the benefits of clustering economic actors together in geographic space by reducing the transportation costs of ideas (knowledge spillovers), people (workforce), and goods (customer-supplier linkages). Existing research also supports the idea that agglomerative forces between customers and suppliers decay less quickly with distance than do knowledge spillovers (Kerr and Kominers 2015).

39. In some contexts, larger firms may be less likely to alter their behavior in response to government policy. Criscuolo et al. (2019) study the causal effects of an industrial policy supporting distressed regions in the United Kingdom. They find that investment subsidies have a positive impact on employment only for smaller firms, which they suggest may result from larger firms' better ability to "game the system."

40. Of course, recent climate-related legislation may also result in negative international spillovers, as domestic content requirements may redirect activity away from established supply chains outside the United States.

41. 45Q and 45V tax credits also play a similar role with regional hydrogen hubs.

References

Adams, W., L. Einav, and J. Levin. 2009. "Liquidity Constraints and Imperfect Information in Subprime Lending." *American Economic Review* 99 (1): 49–84.

Adserà, A., and D. Ray. 1998. "History and Coordination Failure." *Journal of Economic Growth* 3 (3): 267–76.

Agrawal, A., and I. Cockburn. 2003. "The Anchor Tenant Hypothesis: Exploring the Role of Large, Local, R&D Intensive Firms in Regional Innovation Systems." *International Journal of Industrial Organization* 21 (9): 1227–53.

Agrawal, A., I. Cockburn, A. Galasso, and A. Oettl. 2014. "Why Are Some Regions More Innovative Than Others? The Role of Small Firms in the Presence of Large Labs." *Journal of Urban Economics* 81 (5): 149–65.

Agrawal, A., I. Cockburn, and C. Rosell. 2010. "Not Invented Here? Innovation in Company Towns." *Journal of Urban Economics* 67 (1): 78–89.

Akcigit, U., M. A. Celik, and J. Greenwood. 2016. "Buy, Keep, or Sell: Economic Growth and the Market for Ideas." *Econometrica* 84 (3): 943–84.

Aldy, J. 2022. "Learning How to Build Back Better through Clean Energy Policy Evaluation." Working Paper no. RWP22-010 (August), Resources for the Future, Washington, DC.

Arora, A., S. Belenzon, A. Patacconi, and J. Suh. 2020. "The Changing Structure of American Innovation: Some Cautionary Remarks for Economic Growth." *Innovation Policy and the Economy* 20:39–93.

Arrow, K. 1962. "Economic Welfare and the Allocation of Resources for Invention." In *The Rate and Direction of Inventive Activity*, ed. R. Nelson, 609–26. Princeton, NJ: Princeton University Press.

Arrow, K. 1995. Interview with Kenneth Arrow. Federal Reserve Bank of Minneapolis, December 1, 1995. https://www.minneapolisfed.org/article/1995/interview-with-kenneth-arrow.

Autor, D., D. Dorn, and G. Hanson. 2019. "When Work Disappears: Manufacturing Decline and the Falling Marriage Market Value of Young Men." *American Economic Review: Insights* 1 (2): 161–78.
Azariadis, C., and A. Drazen. 1990. "Threshold Externalities in Economic Development." *Quarterly Journal of Economics* 105 (2): 501–26.
Barrett, S., and A. Dannenberg. 2012. "Climate Negotiations under Scientific Uncertainty." *Proceedings of the National Academy of Sciences of the United States of America* 109 (43): 17372–76.
Beck, T., and A. Demirguc-Kunt. 2006. "Small and Medium-Size Enterprises: Access to Finance as a Growth Constraint." *Journal of Banking and Finance* 30 (11): 2931–43.
Bergemann, D., and U. Hege. 1998. "Venture Capital Financing, Moral Hazard, and Learning." *Journal of Banking and Finance* 22 (6): 703–35.
———. 2005. "The Financing of Innovation: Learning and Stopping." *RAND Journal of Economics* 36 (4): 719–52.
Berger, A. N., and G. F. Udell. 1992. "Some Evidence on the Empirical Significance of Credit Rationing." *Journal of Political Economy* 100 (5): 1047–77.
Berkouwer, S. B., and J. T. Dean. 2022. "Credit, Attention, and Externalities in the Adoption of Energy Efficient Technologies by Low-Income Households." *American Economic Review* 112 (10): 3291–330.
Besanko, D., and A. V. Thakor. 1987. "Collateral and Rationing: Sorting Equilibria in Monopolistic and Competitive Credit Markets." *International Economic Review* 28 (3): 671–89.
Bester, H. 1985. "Screening vs. Rationing in Credit Markets with Imperfect Information." *American Economic Review* 75 (4): 850–55.
Bhandary, R. R., K. S. Gallagher, and F. Zhang. 2021. "Climate Finance Policy in Practice: A Review of the Evidence." *Climate Policy* 21 (4): 529–45.
Bioret, L., Y. Zhu, and A. Krupnick. 2023. "Hydrogen Hubs: Get to Know the Encouraged Applicants." *Resources*, February 7. https://www.resources.org/common-resources/hydrogen-hubs-get-to-know-the-encouraged-applicants.
Bloom, N., J. van Reenen, and H. Williams. 2019. "A Toolkit of Policies to Promote Innovation." *Journal of Economic Perspectives* 33 (3): 163–84.
Bollinger, B., K. Gillingham, A. J. Kirkpatrick, and S. Sexton. 2022. "Visibility and Peer Influence in Durable Good Adoption." *Marketing Science* 41 (3): 453–76.
Borenstein, S., and L. W. Davis. 2016. "The Distributional Effects of US Clean Energy Tax Credits." *Tax Policy and the Economy* 30 (1): 191–234.
Boushey, H. 2021. Speech delivered to NBER Environmental and Energy Policy and the Economy Conference, Washington, DC, May 20. https://www.whitehouse.gov/wp-content/uploads/2021/05/Heather-Boushey-NBER-Climate-remarks-May-20-2021.pdf.
Boushey, H. 2023. "The Modern American Industrial Strategy: Building a Clean Energy Economy from the Bottom Up and Middle Out." Speech delivered at the University of California Berkeley, March 22, 2023. https://news.berkeley.edu/2023/06/16/berkeley-talks-transcript-heather-boushey.
Broady, K., M. McComas, and A. Ouazad. 2021. "An Analysis of Financial Institutions in Black-Majority Communities: Black Borrowers and Depositors Face Considerable Challenges in Accessing Banking Services." Report (November), Brookings Institution, Washington, DC.
Budish, E., B. N. Roin, and H. Williams. 2015. "Do Firms Underinvest in Long-Term Research? Evidence from Cancer Clinical Trials." *American Economic Review* 105 (7): 2044–85.

Cameron, A., and A. Turner. 2021. "Lord Adair Turner Talks about What Has to Happen in the 2020s for Net Zero to Be Achievable." Decarb Connect, December. https://share.transistor.fm/s/dd87fa6f.
Carlino, G., and W. R. Kerr. 2015. "Agglomeration and Innovation." In *Handbook of Regional and Urban Economics*, Vol. 5, ed. G. Duranton, J. V. Henderson, and W. C. Strange, 349–404. Amsterdam: Elsevier.
Chatterji, A., E. Glaeser, and W. Kerr. 2014. "Clusters of Entrepreneurship and Innovation." *Innovation Policy and the Economy* 14:129–66.
Chernenko, S., J. Lerner, and Y. Zeng. 2020. "Mutual Funds as Venture Capitalists? Evidence from Unicorns." *Review of Financial Studies* 34 (5): 2362–410.
Cho, A. 2021. "Department of Energy's 'Mini–Manhattan Projects' for Key Energy Problems Wind Down." *Science*, August 11. https://www.science.org/content/article/department-energy-s-mini-manhattan-projects-key-energy-problems-wind-down.
Coalition for Green Capital. 2018. "Green Banks in the United States: 2018 Annual Industry Report." Report (May), Coalition for Green Capital and American Green Bank Consortium. https://greenbanknetwork.org/wp-content/uploads/2019/07/GreenBanksintheUS-2018AnnualIndustryReport.pdf.
Coalition for Green Capital. 2019. "Mobilizing $1 Trillion towards Climate Action: An Analysis of the National Climate Bank." Report (September). https://greenbanknetwork.org/wp-content/uploads/2019/09/US-National-Climate-Bank-1T-investment-white-paper.pdf.
Collier, P. 2007. *The Bottom Billion: Why Are the Poorest Countries Failing and What Can Be Done about It*. Oxford: Oxford University Press.
Cook, L. D., J. Gerson, and J. Kuan. 2021. "Closing the Innovation Gap in Pink and Black." Working Paper no. 29354, NBER, Cambridge, MA.
Cooper, R. 1999. *Coordination Games*. Cambridge: Cambridge University Press.
———. 2005. "Economic Policy in the Presence of Coordination Problems." *Revue d'Économie Politique* 115 (4): 379–90.
Cooper, R., and A. John. 1988. "Coordinating Coordination Failures in Keynesian Models." *Quarterly Journal of Economics* 103 (3): 441–63.
Cornelli, F., and O. Yosha. 2003. "Stage Financing and the Role of Convertible Securities." *Review of Economic Studies* 70 (1): 1–32.
Covert, T., and R. Sweeney. 2022. "Winds of Change: Estimating Learning by Doing without Cost or Input Data." Working paper (March). https://api.semanticscholar.org/CorpusID:247974350.
Cowling, M. 2010. "The Role of Loan Guarantee Schemes in Alleviating Credit Rationing in the UK." *Journal of Financial Stability* 6 (1): 36–44.
Criscuolo, C., R. Martin, H. G. Overman, and J. van Reenen. 2019. "Some Causal Effects of an Industrial Policy." *American Economic Review* 109 (1): 48–85.
Curtis, E. M., and I. Marinescu. 2022. "Green Energy Jobs in the US: What Are They and Where Are They?" Working Paper no. 30332, NBER, Cambridge, MA.
Curtis, E. M., L. O'Kane, and R. J. Park. 2024. "Workers and the Green-Energy Transition: Evidence from 300 Million Job Transitions." *Environmental and Energy Policy and the Economy* 5:127–161.
Dalla Fontana, S., and R. Nanda. 2023. "Innovating to Net Zero: Can Venture Capital and Start-Ups Play a Meaningful Role?" *Entrepreneurship and Innovation Policy and the Economy* 2:79–105.
Davis, L. W. 2024. "The Economic Determinants of Heat Pump Adoption." *Environmental and Energy Policy and the Economy* 5:162–199.
Davis, L. W. 2012. "Evaluating the Slow Adoption of Energy Efficient Investments: Are Renters Less Likely to Have Energy Efficient Appliances?" In

The Design and Implementation of US Climate Policy, ed. Don Fullerton and Catherine D. Wolfram, 301–32. Chicago: University of Chicago Press.
Davis, L. W., and C. Hausman. 2022. "Who Will Pay for Legacy Utility Costs?" *Journal of the Association of Environmental and Resource Economists* 9 (6): 1047–85.
Deaton, A., and A. Case. 2017. "Mortality and Morbidity in the 21st Century." *Brookings Papers on Economic Activity* Spring:397–476.
DeHoratiis, G. 2022. "Building a Bridge to Bankability for CCUS." Presentation, US Department of Energy, Loan Programs Office, August. https://netl.doe.gov/sites/default/files/netl-file/22CM_GS_DeHoratiis.pdf.
de Mesquita, E. B. 2016. "Coordination Problems." In *Political Economy for Public Policy*, ed. E. B. de Mesquita. Princeton, NJ: Princeton University Press.
de Meza, D., and C. Southey. 1996. "The Borrower's Curse: Optimism, Finance and Entrepreneurship." *Economic Journal* 106 (435): 375–86.
Ewens, M. 2022. "Race and Gender in Entrepreneurial Finance." Working Paper no. 30444, NBER, Cambridge, MA.
Ewens, M., and J. Farre-Mensa. 2020. "The Deregulation of the Private Equity Markets and the Decline in IPOs." *Review of Financial Studies* 33 (12): 5463–509.
Fabrizio, K. R., and D. C. Mowery. 2007. "The Federal Role in Financing Major Innovations: Information Technology during the Postwar Period." In *Financing Innovation in the United States, 1870 to the Present*, ed. N. R. Lamoureaux and K. L. Sokoloff. Cambridge, MA: MIT Press.
Fairlie, R., A. Robb, and D. T. Robinson. 2022. "Black and White: Access to Capital among Minority-Owned Start-Ups." *Management Science* 68 (4): 2377–400.
Feldman, M. 2005. *The Locational Dynamics of the U.S. Biotech Industry: Knowledge Externalities and the Anchor Hypothesis*. Heidelberg: Physica.
Figueiredo, O., P. Guimarães, and D. Woodward. 2009. "Localization Economies and Establishment Size: Was Marshall Right after All?" *Journal of Economic Geography* 9 (6): 853–68.
Gaddy, B. E., V. Sivaram, T. B. Jones, and L. Wayman. 2017. "Venture Capital and Cleantech: The Wrong Model for Energy Innovation." *Energy Policy* 102:385–95.
Ganong, P., and D. Shoag. 2017. "Why Has Regional Income Convergence in the U.S. Declined?" *Journal of Urban Economics* 102:76–90.
Gans, J. S., and S. Stern. 2003. "The Product Market and the Market for 'Ideas': Commercialization Strategies for Technology Entrepreneurs." *Research Policy* 32 (2): 333–50.
Gillingham, K., and B. Bollinger. 2021. "Social Learning and Solar Photovoltaic Adoption." *Management Science* 67 (11): 7091–112.
Gillingham, K., and J. H. Stock. 2018. "The Cost of Reducing Greenhouse Gas Emissions." *Journal of Economic Perspectives* 32 (4): 53–72.
Glaeser, E. L., and N. Hausman. 2020. "The Spatial Mismatch between Innovation and Joblessness." *Innovation Policy and the Economy* 20:233–99.
Glaeser, E. L., and W. R. Kerr. 2009. "Local Industrial Conditions and Entrepreneurship: How Much of the Spatial Distribution Can We Explain?" *Journal of Economics and Management Strategy* 18 (3): 623–63.
Gompers, P. A. 1995. "Optimal Investment, Monitoring, and the Staging of Venture Capital." *Journal of Finance* 50 (5): 1461–89.
Gompers, P. A., and S. Q. Wang. 2017. "Diversity in Innovation." Working Paper no. 17-067 (January), Harvard Business School, Cambridge, MA.
Green Bank Network. 2018. "Community Solar in New York State." Remarks by Jason Moore and Max Heering, New York Green Bank, and Max Joel,

NY-SUN Program Manager, NYSERDA, April 25. https://greenbanknetwork.org/portfolio/community_solar_ny_green_bank.
Green Bank Network. 2022. "Green Banking at Scale: Green Banks at the City, State, and National Level." Remarks by Gregory Randolf, Managing Director at New York Green Bank; Marcelo Rouco, Founder, Chairman, and Chief Executive Officer at Ecosave, Inc.; Sarah Davidson, Director at New York Green Bank; Jeffrey Diehl, Executive Director and Chief Executive Officer at Rhode Island Infrastructure Bank; Eli Hopson, CEO at DC Green Bank; and Bert Hunter, Executive Vice President and Chief Investment Officer at Connecticut Green Bank, September 20. https://greenbanknetwork.org/portfolio/green-banking-at-scale.
Greenstone, M., R. Hornbeck, and E. Moretti. 2010. "Identifying Agglomeration Spillovers: Evidence from Winners and Losers of Large Plant Openings." *Journal of Political Economy* 118 (3): 536–98.
Griffin, A. 2014. "Future of Environmental Finance." Remarks by Alfred Griffin, President of the New York Green Bank, at the Future of Environmental Finance Forum, Environmental Finance Center, University of North Carolina Chapel Hill, May. https://greenbanknetwork.org/portfolio/ny-green-bank-president-on-the-future-of-environmental-finance.
Griffith, R., S. Lee, and J. van Reenen. 2011. "Is Distance Dying at Last? Falling Home Bias in Fixed-Effects Models of Patent Citations." *Quantitative Economics* 2 (2): 211–49.
Gross, D. 2015. "The Miracle of SolarCity." *Slate*, July 31, 2015. https://slate.com/business/2015/07/solarcity-the-company-didnt-invent-the-solar-panel-but-it-invented-something-even-more-important.html.
Hall, B. H., and J. Lerner. 2010. "The Financing of R&D and Innovation." In *Handbook of The Economics of Innovation*, Vol. 1, ed. B. H. Hall and N. Rosenberg, 609–39. Amsterdam: North-Holland.
Hart, D. 2018. "Beyond the Technology Pork Barrel? An Assessment of the Obama Administration's Energy Demonstration Projects." *Energy Policy* 119:367–76.
Hausman, N. 2022. "University Innovation and Local Economic Growth." *Review of Economics and Statistics* 104 (4): 718–35.
Hellmann, T. 1998. "The Allocation of Control Rights in Venture Capital Contracts." *RAND Journal of Economics* 29 (1): 57–76.
Henderson, L., C. Herring, H. D. Horton, and M. Thomas. 2015. "Credit Where Credit Is Due? Race, Gender, and Discrimination in the Credit Scores of Business Startups." *Review of Black Political Economy* 42 (4): 459–79.
Howell, S. T., T. Kuchler, D. Snitkof, J. Stroebel, and J. Wong. 2021. "Lender Automation and Racial Disparities in Credit Access." Working Paper no. 29364, NBER, Cambridge, MA.
Howell, S. T., J. Lerner, R. Nanda, and R. R. Townsend. 2020. "How Resilient Is Venture-Backed Innovation? Evidence from Four Decades of U.S. Patenting." NBER Working Paper Series. Working Paper no. 27150 (May), NBER, Cambridge, MA.
Jaffe, A. B. 1986. "Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits, and Market Value." *American Economic Review* 76 (5): 984–1001.
Jaffe, A. B., R. G. Newell, and R. N. Stavins. 2005. "A Tale of Two Market Failures: Technology and Environmental Policy." *Ecological Economics* 54 (2–3): 164–74.
Jaffe, A. B., M. Trajtenberg, and R. Henderson. 1993. "Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations." *Quarterly Journal of Economics* 108 (3): 577–98.

Jones, B. F. 2022. "Where Innovation Happens, and Where It Does Not." In *The Role of Innovation and Entrepreneurship in Economic Growth*, ed. Michael J. Andrews, Aaron K. Chatterji, Josh Lerner, and Scott Stern, 577–602. Chicago: University of Chicago Press.

Kahn, S., and S. Jacobs. 2022. "Helping Early-Stage Climatetech Startups Survive the Valley of Death." *Catalyst*, July 14. https://www.canarymedia.com/podcasts/catalyst-with-shayle-kann/crossing-the-valley-of-death.

Kahn, S., and R. Naam. 2021. "Can Deeptech Venture Capital Solve Climate Change?" *Catalyst*, November 11. https://www.canarymedia.com/podcasts/catalyst-with-shayle-kann/deep-tech-venture-climate-capital-catalyst-shayle-kann-podcast.

Kahn, S., and J. Shah. 2022. "Inside the Department of Energy's Loan Deal to Back Hydrogen." *Catalyst*, January 10. https://www.canarymedia.com/podcasts/catalyst-with-shayle-kann/inside-the-department-of-energys-loan-deal-to-back-hydrogen.

Kaufman, R. 2018. "Can Green Banks Scale Clean Energy?" Yale Insights: Management in Practice, November. https://insights.som.yale.edu/insights/can-green-banks-scale-clean-energy.

Kehoe, J., M. Lee, and V. Radulovic. 2021. "Catalyzing Investment with a National Climate Bank: Lessons from Subnational Green Banks." C2ES Report (June), Center for Climate and Energy Solutions, Arlington, VA. https://www.c2es.org/wp-content/uploads/2021/06/catalyzing-investment-with-a-national-climate-bank.pdf.

Kerr, W. R., and S. D. Kominers. 2015. "Agglomerative Forces and Cluster Shapes." *Review of Economics and Statistics* 97 (4): 877–99.

Kerr, W. R., and R. Nanda. 2010. "Banking Deregulations, Financing Constraints, and Firm Entry Size." *Journal of the European Economic Association* 8 (2/3): 582–93.

———. 2015. "Financing Innovation." *Annual Review of Financial Economics* 7 (1): 445–62.

Kerr, W. R., R. Nanda, and M. Rhodes-Kropf. 2014. "Entrepreneurship as Experimentation." *Journal of Economic Perspectives* 28 (3): 25–48.

Kerr, W. R., and F. Robert-Nicoud. 2020. "Tech Clusters." *Journal of Economic Perspectives* 34 (3): 50–76. https://www.aeaweb.org/articles?id=10.1257/jep.34.3.50.

Kessler, A. 2022. "Green Banks and Financing the Energy Transition." Pivotal 180 in Conversation, October. https://pivotal180.com/green-banks-and-financing-the-energy-transition.

Khatcherian, K. 2022. "Barriers to the Timely Deployment of Climate Infrastructure." Technical report (April), Prime Coalition, Cambridge, MA. https://static1.squarespace.com/static/60903dcf05bc23197b2b993b/t/6269c7a70847634d26c0d81b/1651099594061/2022+Climate+Infrastructure+Full+Report_final.

Klepper, S. 2010. "The Origin and Growth of Industry Clusters: The Making of Silicon Valley and Detroit." *Journal of Urban Economics* 67 (1): 15–32.

———. 2016. *Experimental Capitalism: The Nanoeconomics of American High-Tech Industries*. Princeton, NJ: Princeton University Press.

Kline, P., and E. Moretti. 2013. "Local Economic Development, Agglomeration Economies, and the Big Push: 100 Years of Evidence from the Tennessee Valley Authority." *Quarterly Journal of Economics* 129 (1): 275–331.

Kotchen, M. J., and C. Costello. 2018. "Maximizing the Impact of Climate Finance: Funding Projects or Pilot Projects?" *Journal of Environmental Economics and Management* 92:270–81.

Krugman, P. 1991. "History versus Expectations." *Quarterly Journal of Economics* 106 (2): 651–67.
Leland, H. E., and D. H. Pyle. 1977. "Informational Asymmetries, Financial Structure, and Financial Intermediation." *Journal of Finance* 32 (2): 371–87.
Lerner, J. 2009. *Boulevard of Broken Dreams: Why Public Efforts to Boost Entrepreneurship and Venture Capital Have Failed—and What to Do about It*. Princeton, NJ: Princeton University Press.
Lerner, J., and R. Nanda. 2020. "Venture Capital's Role in Financing Innovation: What We Know and How Much We Still Need to Learn." *Journal of Economic Perspectives* 34 (3): 237–61.
Lester, R. K., and D. M. Hart. 2015. "Closing the Energy-Demonstration Gap." *Issues in Science and Technology* 31 (2): 48–54.
Lychagin, S., J. Pinkse, M. E. Slade, and J. van Reenen. 2016. "Spillovers in Space: Does Geography Matter?" *Journal Of Industrial Economics* 64 (2): 295–335.
Markusen, A. 1996. "Sticky Places in Slippery Space: A Typology of Industrial Districts." *Economic Geography* 72 (3): 293–313.
Matsuyama, K. 1991. "Increasing Returns, Industrialization, and Indeterminacy of Equilibrium." *Quarterly Journal of Economics* 106 (2): 617–50.
———. 1998. "Economic Development as Coordination Problems." In *The Role of Government in East Asian Economic Development: Comparative Institutional Analysis*, ed. M. Aoki, H.-K. Kim, and M. Okuno-Fujiwara. Oxford: Oxford University Press.
McCall, M. 2016. "Update: How DOE Loan Guarantees Helped Launch the Utility-Scale PV Solar Market." US DOE, Loan Programs Office, February 11, 2016. https://www.energy.gov/lpo/articles/update-how-doe-loan-guarantees-helped-launch-utility-scale-pv-solar-market.
Metcalf, G. E. 2023. "The Distributional Impacts of a VMT-Gas Tax Swap." *Environmental and Energy Policy and the Economy* 4:4–42.
Mielke, J., and G. A. Steudle. 2018. "Green Investment and Coordination Failure: An Investors' Perspective." *Ecological Economics* 150:88–95.
Miller, S., and C. K. Soo. 2020. "Do Neighborhoods Affect the Credit Market Decisions of Low-Income Borrowers? Evidence from the Moving to Opportunity Experiment." *Review of Financial Studies* 34 (2): 827–63.
Murphy, K. M., A. Shleifer, and R. W. Vishny. 1989. "Industrialization and the Big Push." *Journal of Political Economy* 97 (5): 1003–26.
Nanda, R. 2020. "Financing 'Tough Tech' Innovation." In *Global Innovation Index 2020: Who Will Finance Innovation?* ed. S. Dutta, B. Lanvin, and S. Wunsch-Vincent, 113–19. Ithaca, NY: Cornell University Press.
Nanda, R., and J. Rothenberg. 2011. "A Quiet Revolution in Clean Energy Finance." *Harvard Business Review*, October 26. https://hbr.org/2011/10/quiet-revolution-clean-energy-finance.
Nanda, R., K. Younge, and L. Fleming. 2015. "Innovation and Entrepreneurship in Renewable Energy." In *The Changing Frontier: Rethinking Science and Innovation Policy*, ed. A. B. Jaffe and B. F. Jones, 199–232. Chicago: University of Chicago Press.
Nelson, R. R. 1959. "The Simple Economics of Basic Scientific Research." *Journal of Political Economy* 49:297–306.
Nemet, G. 2023. "Opportunities and Risks of Scaling Up Carbon Dioxide Removal." *Resources Radio*, February 28. https://www.resources.org/resources-radio/opportunities-and-risks-of-scaling-up-carbon-dioxide-removal-with-gregory-nemet.

Nemet, G. F., V. Zipperer, and M. Kraus. 2018. "The Valley of Death, the Technology Pork Barrel, and Public Support for Large Demonstration Projects." *Energy Policy* 119:154–67.
New York Green Bank. 2022. "Annual Plan 2022–23." Report. https://greenbank.ny.gov/-/media/Project/Greenbank/Files/AnnualPlan_2022-FINAL.pdf.
Petersen, M. A., and R. G. Rajan. 1994. "The Benefits of Lending Relationships: Evidence from Small Business Data." *Journal of Finance* 49 (1): 3–37.
———. 2002. "Does Distance Still Matter? The Information Revolution in Small Business Lending." *Journal of Finance* 57 (6): 2533–70.
Polzin, F., F. Egli, B. Steffen, and T. S. Schmidt. 2019. "How Do Policies Mobilize Private Finance for Renewable Energy? A Systematic Review with an Investor Perspective." *Applied Energy* 236:1249–68.
Prabhakar, A. 2021. "Philanthropy's Role in Addressing Climate Change." Columbia Energy Exchange, December 30. https://www.energypolicy.columbia.edu/philanthropys-role-addressing-climate-change.
Robb, A. M., and D. T. Robinson. 2012. "The Capital Structure Decisions of New Firms." *Review of Financial Studies* 27 (1): 153–79.
Rodrik, D. 1996. "Coordination Failures and Government Policy: A Model with Applications to East Asia and Eastern Europe." *Journal of International Economics* 40 (1): 1–22.
Rodrik, D. 2004. "Industrial Policy for the Twenty-First Century." Working paper, Harvard Kennedy School, Cambridge, MA.
———. 2014. "Green Industrial Policy." *Oxford Review of Economic Policy* 30 (3): 469–91.
Rosenstein-Rodan, P. N. 1943. "Problems of Industrialisation of Eastern and South-Eastern Europe." *Economic Journal* 53 (210/211): 202–11.
Rozansky, R., and D. M. Hart. 2020. "More and Better: Building and Managing a Federal Energy Demonstration Project Portfolio." Report (May), Information Technology and Innovation Foundation, Washington, DC. https://itif.org/publications/2020/05/18/more-and-better-building-and-managing-federal-energy-demonstration-project.
Schleich, J. 2019. "Energy Efficient Technology Adoption in Low-Income Households in the European Union—What Is the Evidence?" *Energy Policy* 125:196–206.
Shi, X., X. Liu, and L. Yao. 2016. "Assessment of Instruments in Facilitating Investment in Off-Grid Renewable Energy Projects." *Energy Policy* 95:437–46.
Siegmund, D., S. Metz, V. Peinecke, T. E. Warner, C. Cremers, A. Grevé, T. Smolinka, D. Segets, and U.-P. Apfel. 2021. "Crossing the Valley of Death: From Fundamental to Applied Research in Electrolysis." *Journal of the American Chemical Society Au* 1 (5): 527–35.
Steffen, B. 2018. "The Importance of Project Finance for Renewable Energy Projects." *Energy Economics* 69:280–94.
Stein, J. C. 1989. "Efficient Capital Markets, Inefficient Firms: A Model of Myopic Corporate Behavior." *Quarterly Journal of Economics* 104 (4): 655–69.
Stiglitz, J. E., and A. Weiss. 1981. "Credit Rationing in Markets with Imperfect Information." *American Economic Review* 71 (3): 393–410.
St. John, J. 2021. "Jigar Shah's Big Idea for Getting Rooftop Solar and Smart Appliances to Low-Income Americans." Canary Media, November 23. https://www.canarymedia.com/articles/policy-regulation/jigar-shahs-big-idea-for-getting-rooftop-solar-and-smart-appliances-to-low-income-americans.

Trabish, H. K. 2015. "Why Solar Financing Is Moving from Leases to Loans." Utility Dive, August 17. https://www.utilitydive.com/news/why-solar-financing-is-moving-from-leases-to-loans/403678.

Trajtenberg, M. 1990. "A Penny for Your Quotes: Patent Citations and the Value of Innovations." *RAND Journal of Economics* 21 (1): 172–87.

Turner, A. 2023. "New Details about the Inflation Reduction Act's Greenhouse Gas Reduction Fund and Takeaways for Cities." Climate Law: A Sabin Center Blog, February 16. https://blogs.law.columbia.edu/climatechange/2023/02/16/new-details-about-the-inflation-reduction-acts-greenhouse-gas-reduction-fund-takeaways-for-cities.

US Department of Energy, Office of Energy Efficiency and Renewable Energy. n.d. "Technology-to-Market." https://www.energy.gov/eere/buildings/technology-market.

US Government Accountability Office. 2020. "Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects." Report no. GAO-20-48G (January). https://www.gao.gov/assets/gao-20-48g.pdf.

van den Heuvel, M., and D. Popp. 2022. "The Role of Venture Capital and Governments in Clean Energy: Lessons from the First Cleantech Bubble." Working Paper no. 29919, NBER, Cambridge, MA.

Yescombe, Y. R. 2014. *Principles of Project Finance*. 2nd ed. Oxford: Elsevier.