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INNOVATION MARKET FAILURES AND THE DESIGN OF NEW CLIMATE POLICY INSTRUMENTS

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ABSTRACT

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Innovation Market Failures and the Design of New Climate Policy Instruments[*]

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Abstract

Moving beyond the combination of adoption subsidies, standards, and (albeit limited) attempts at carbon pricing that largely characterized U.S. climate policy over the last decade, recent climate-related legislation has transformed not only the scale of U.S. 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 un-priced 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.

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

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

1 Introduction

Recent legislation in the U.S. has provided the opportunity to inject significant federal funding into policy instruments that have not been previously adopted at scale in U.S. climate policy. Moving beyond the combination of adoption subsidies, standards, and (albeit limited) attempts at carbon pricing that largely characterized climate policy over the last decade, the Infrastructure Investment and Jobs Act (IIJA) of 2021, the CHIPS and Science Act of 2022, and the Inflation

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Reduction Act (IRA) of 2022 have transformed not only the scale of U.S. 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 un-priced 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 et al., 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 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 non-appropriable knowledge creation, financial frictions, or coordination failures. (Figure 1 maps these newly scaled policy instruments and innovation market failures to Technology Readiness Levels, which are defined in Table 4.)

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 mid-stage of

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[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.

the innovation process, but would not necessarily arise during early-stage R&D.

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 for 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

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[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 policymakers misjudge the extent of market failures and support projects where private incentives are in fact adequate. But if policymakers judge market failures appropriately, they will be supporting projects in which private actors are not investing, so there would not be crowding out.

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 as to 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 2 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 3 describes the four policy instruments in question and their institutional history in U.S. climate policy, linking their stated goals and approaches to the market failures and other priorities described in the previous section. Section 4 discusses market failures that are not well addressed through these four policy instruments. Section 5 concludes and offers directions for future research.

2 Innovation Market Failures and Other Frictions

We begin by discussing the economics literature on three types of market failures of particular relevance to the mid-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 1, which provides definitions of key economic terms for a policy audience; these terms are *italicized* throughout the paper.

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 which 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.

Table 1: Definition of Key Economics Terms.

2.1 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 under-provide innovation relative to the social optimum (Arrow, 1962; Nelson, 1959). 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 non-appropriable by any individual firm. Ample empirical research, reviewed in Bloom et al. (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 and 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).

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[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 et al., 1993; Griffith et al., 2011). This research has consistently concluded that individual firms do not fully recoup the benefits of their R&D.

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 inter-firm spillovers have generated substantial cost reductions in the offshore wind industry, while Gillingham and Bollinger (2021) find evidence of very small learning spillovers in solar 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 create positive externalities for others by generating information about the technology's existence or effectiveness through their early use (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 upfront 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 Solar City's success with offering leases for residential solar installations, which allowed a larger group of customers to avoid high upfront costs and to benefit from tax credits, many other installers adopted this innovative financing model. By 2014, 72 percent of the residential solar market used this model; Solar City accounted for half of this total (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.

2.2 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 startups, finance for innovation by incumbents, and finance for other forms of entrepreneurship.

Evidence suggests that R&D-intensive startup firms face particular challenges in securing finance. For one, the entrepreneur 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 startups, developing certain contractual and governance strategies for overcoming the abovementioned frictions.[5] For one, 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 re-

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[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 below). 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).

vealed about the technology's probability of success (Gompers, 1995; Bergemann and Hege, 1998, 2005). Additionally, 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 et al., 2020). While VC investment funds only a small share of new entrants in the U.S. 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 et al. (2015) argued that several structural factors had limited the role of venture capital in finding 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, since technologies that succeeded as prototypes may not succeed at this

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[6] In reviewing utility patents granted by the USPTO between 2000 and 2020, Fontana and Nanda (2022) 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 to 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.

size or when integrated with existing infrastructure. To manage this idiosyncratic risk, portfolio theory suggests that VC investors should fund a portfolio of startup companies, but the high fixed costs of experimentation at the demonstration phase mean that many investors do not have sufficient resources (Jones, 2022; Kerr et al., 2014; Nanda et al., 2015; Nanda, 2020). 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 de-risked.[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 venture capital ecosystem, less R&D-intensive startups 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,

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[8] On the one hand, Ewens and Farre-Mensa (2020) document a substantial increase in funding for VC-backed startups, due to investment from pension funds, mutual funds, hedge funds, and other non-traditional investors. This increase in funding has enabled startups to raise larger funding rounds and to stay private for longer. Nonetheless, the associated increases in venture capital funding have been highly concentrated in a small number of VC firms: Lerner and Nanda (2020) document that 5 percent of VC firms investing in U.S. startups raised over half of the total venture capital funding over 2014 to 2018. Furthermore, direct investments in startups from non-traditional investors have prioritized liquidity, investing in later funding rounds and in larger companies, obtaining stronger redemption and IPO-related rights, 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.

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 (Kahn and Shah, 2022; Griffin, 2014).

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 startups (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; Akcigit et al., 2016; Kerr and Nanda, 2015).[10] For one, 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); a new battery chemistry requires a fundamentally different set of skills and machinery to scale compared to 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). Lastly, even if incumbents are able to source external climate innovations, the increasing separation between basic R&D by universities and startups 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 that they are

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

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 exit the market, but such insurance products may not yet exist for offtake agreements in green commodity markets.

2.3 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

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[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.

	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

Table 2: Coordination Failures in Vehicle Choice

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 2 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 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 and/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

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[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 invest in low-carbon production. More broadly, coordination failures are a useful lens through which to study new technology markets at the early stages of commercial deployment.

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 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 et al. (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 depends on the availability of complementary skillsets 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

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[13] Many papers have considered the existence of coordination failures in national and regional economic development. A non-exhaustive list includes: Azariadis and Drazen (1990); Krugman (1991); Matsuyama (1991); Adserà and Ray (1998).

[14] The buildout 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

startups 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 in transitioning climate technologies from labs to full-scale commercialization. Furthermore, many high-emitting sectors depend on extensive infrastructure and supply chains which must evolve alongside low-carbon technologies. Consider the decarbonization of maritime shipping: if maritime shipping transitions 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, especially popular in the 1990s, 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 policymakers should instead focus on “a set of mechanisms that recognizes errors and revises policies accordingly.”

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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.

[15] In a U.S. 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)).

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 upfront investments in capacity. 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 gas-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.

2.4 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 policymakers 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 policymakers drawing connections between job losses in "fossil fuel communities" and the historical loss of manufacturing employment due to globalization (Boushey,

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

2021; Curtis and Marinescu, 2022; Curtis et al., 2024). Beyond the labor market, there are many ways in which emissions are correlated with demographic vulnerability (Metcalf, 2022), and a long history of racism and other forms of discrimination mean 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 one, there are often more jobs created in the production (e.g., manufacturing) of new technologies as compared to earlier R&D (Glaeser and Hausman, 2019), so 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 et al. (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, 2019; 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 U.S. 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 et al., 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

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[17] More broadly, the Biden administration's Justice40 initiative sets a goal that 40 percent 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`.

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, 2019). 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 et al., 2021; Ewens, 2022). Other research has suggested that minority-owned small businesses face greater barriers to raising upfront and ongoing capital (Henderson et al., 2015; Fairlie et al., 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 co-benefits 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 upfront 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 et al., 2009; Broady et al., 2021). Those who are not able to pay outright or to finance these upfront costs may be left with a disproportionate share of the burden of managing the wind-down of legacy

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[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.

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)).

3 Newly Scaled Policy Instruments

In this next 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 3 and Figure 1). We also offer questions for policy design and evaluation that may help to disentangle which market failures matter most in a given context and which policy mechanisms are most effective (summarized in Table 5).

3.1 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] 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 U.S. 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. Regional hydrogen hubs are the single largest investment area (discussed in a subsequent section). Other demonstration programs funded under the IIJA include $2.5 billion for advanced nuclear reactors, $2.5 billion for

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[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.

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 et al., 2018). Demonstration projects may also provide valuable information about whether a project is unlikely to be commercially successful (Kotchen and Costello, 2018). While 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 3): 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 venture capital 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] While prototypes help to achieve certain technological milestones, they do not fully resolve the type of technology risk that occurs at full-size implementation. Certainly venture capital investors have made investments

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[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).

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 startups 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 startups in the later "scale-up" phase, when technological risk and uncertainties about product-market fit have largely been resolved, rather than to capital-intensive startups 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.

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[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.

3.2 Loan Guarantees

Originally authorized under the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007, the Department of Energy'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 and the Nissan Leaf and infamous funding for Solyndra.[22] Less well known is that DOE's Loan Programs Office supported the first five utility-scale solar plants larger than 100 MW, after which private financing for utility-scale solar projects increased significantly (Levin, 2017). Studies have found loan guarantees to be effective in other contexts (Shi et al., 2016), though rigorous evidence on the impact of DOE's loan programs is still limited (Bhandary et al., 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 Loan Programs Office guarantees repayment of loan principal and interest – either from the U.S. Treasury's Federal Financing Bank or from commercial lenders – for up to 80 percent 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 Loan Programs Office 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

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[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 six projects using a particular innovative energy technology, if regional variation significantly affects technology deployment; previously, DOE was limited to only two 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 upfront payments required for applications to be considered.

at the demonstration stage, projects supported by DOE's Loan Programs Office 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 to 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 to 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 to reduce the fixed costs of underwriting future loan contracts or reduce 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 Loan Programs Office 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]

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[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

Program implementers may again 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 Loan Programs Office as a positive signal, and are they willing to adjust their behavior accordingly? Are there tradeoffs between the quality of the signal and the fixed costs that applicants must incur to obtain support from the Loan Programs Office? How would commercial lenders weight one or two years of operational data from several projects funded by the Loan Programs Office relative to five or six years of operational data from a single project?

3.3 Green Banks[26]

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. In the U.S., approximately 20 green banks have emerged at the state

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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 U.S. to date, in contrast to the large-scale climate infrastructure and manufacturing facilities supported by DOE's Loan Programs Office. 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 Loan Programs Office beginning to focus on distributed energy technologies.

and local level, the largest of which are the New York and Connecticut Green Banks.[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 et al., 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) and/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 U.S. 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," while $12 billion is available for any community.[31]

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[27] EPA identifies 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 and American Green Bank Consortium" (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 bank(s).

[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."

The exact structure of funding for these projects is still unclear at the time of writing; in its most recent announcement, EPA noted that it anticipates making between two and 15 grants to eligible institutions, one of which may operate at a national scale.[32,33] Observers have suggested that EPA may fund existing green banks and/or help to create new ones at the national, regional, state, or local level (Turner, 2023).

Green banks in the U.S. 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 last 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 last decade is green bank funding for energy efficiency retrofits in small businesses: dry cleaners, houses of worship, daycares, retirement communities, among others.[34] New business and financing models were needed to enable energy efficiency retrofits with high upfront 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 to 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

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[32] For EPA's announcement of initial program design, see: `https://www.epa.gov/newsreleases/epa-announces-initial-program-design-greenhouse-gas-reduction-fund`.

[33] 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."

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

community solar projects (Green Bank Network, 2022).[35]

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 upfront 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 deployment. 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

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[35] 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.

role with funding from a green bank to defray the upfront cost.[36]

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; Fairlie et al., 2022; Howell et al., 2021). 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; while the former would not create equity-efficiency tradeoffs, the latter are valuable primarily because they help to make the climate transition more inclusive.

3.4 Regional Technology Hubs

Finally, recent federal legislation has appropriated funds for several large-scale regional technology hubs. IIJA provides \$8 billion for six to ten regional hydrogen hubs and \$3.5 billion for four regional direct air capture (DAC) hubs.[37] The idea of bringing together diverse actors in a specific location to solve a particular technological challenge has an established history at the Department of Energy. Under the Obama administration, the Department of Energy 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).[38] Beyond the Department of Energy, other parts of the federal

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[36] One startup 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).

[37] Beyond these large programs in IIJA, the CHIPS Act authorized \$10 billion for the Regional Technology and Innovation Hubs Program, to be 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 U.S. global competitiveness and expanding access to jobs in the innovation sector.

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

government have sought to combine local or regional economic development with a specific agency mission (reviewed in Chatterji et al. (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 multi-state applicants (Bioret et al.).

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 between 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. 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).[39] Existing research also supports the idea that agglomerative forces between customers

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[39] "Agglomeration effects" refer to the benefits of clustering economic actors together in geographic space, by

and suppliers decay less quickly with distance than do knowledge spillovers (Kerr and Kominers, 2015). 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 policymakers 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 spinoff entrepreneurship (Agrawal and Cockburn, 2003; Feldman, 2005; Glaeser and Kerr, 2009; Figueiredo et al., 2009). On the other hand, too much support for large incumbent firms can crowd out new entrants and stifle more radical innovation (Agrawal et al., 2010; Chatterji et al., 2014).[40] 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 while existing methods for producing 'blue hydrogen' from fossil fuels with carbon

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reducing the transportation costs of ideas (knowledge spillovers), people (workforce), and goods (customer-supplier linkages).

[40] 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 UK. 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."

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).

Lastly, 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." Additionally, 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 direct air capture 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, policymakers may mitigate regional inequities while taking advantage of agglomeration benefits going forward. That said, concerns about equity are multi-dimensional 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.

4 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 U.S. may also create positive international spillovers, especially in developing economies.[41] 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 to 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 et al., 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 to bolster the market for direct air capture in tandem with funding for regional

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[41] 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 of the U.S.

DAC hubs.[42] 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 non-carbon 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.

5 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. As 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 and/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 to think systematically about the ways in which they can learn from and appropriately imitate the tools and practices of private funders, and the ways in which they should deviate from private capital providers in order to address policy concerns that private funders do not share.

Of course, while 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

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[42] 45Q and 45V tax credits also play a similar role with regional hydrogen hubs.

Market Failure or Policy Goal	**Policy Instruments**			
	Demonstration Projects	**Loan Guarantees**	**Green Banks**	**Regional Technology Hubs**
Knowledge Spillovers	Knowledge of systems integration and technology testing at scale	Knowledge of financial innovation for new technologies & commercial track record	Knowledge of financial innovation for new business models & commercial track record	Knowledge of systems integration and supply chain
Coordination Failures			Contracts standardized	Customers, suppliers, specialized infrastructure, other inputs coordinated
Financial Frictions	High fixed costs for technology derisking incurred	Mitigates credit rationing; signals technical quality	Mitigates credit rationing	
Distributional Concerns		Can target uneven financial frictions	Can target uneven financial frictions; distributed climate technologies adapted for local markets	Jobs created; under-served locales boosted

Table 3: Overview of How Policy Instruments May Address Goals.

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.

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 characteristics 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

Table 4: Technology Readiness Levels. Source: U.S. Government Accountability Office (2020).

Demonstration Projects	**Loan Guarantees**	**Green Banks**	**Regional Technology Hubs**
Would demonstration projects in this sector be underprovided if startups were well capitalized or incumbents were working in this area? Which fixed costs of project development can be reduced through learning from 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? How can program implementers share key information publicly without undermining the incentives of private developers to participate? In what ways is public funding for demonstration projects like venture capital and in what ways not?	What are the largest fixed costs from underwriting a new technology? What information reduces this cost for future private lenders? Ignoring the fixed costs of underwriting, would commercial lenders be willing to finance this project at any interest rate? Do private lenders view support from LPO as a positive signal? What are the tradeoffs between the quality of signal and the burden of the application process? How do private lenders view more years of operational data from one project (higher T) versus operational data from more projects (higher N)? In what ways are public loan guarantees like commercial debt and in what ways not?	What are the largest fixed costs from underwriting a new business model? What information reduces this cost for future private lenders? Ignoring the fixed costs of underwriting, would commercial lenders be willing to finance this project at any interest rate? Does this business model require contract standardization to scale? Is this distributed climate technology part of a least-cost portfolio of decarbonization solutions? 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?	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 industry development can be reduced through learning from regional demonstration projects? 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? Are potential agglomeration economies specific to new technologies or cumulative with previous technologies?

Table 5: Key Questions for Program Design and Evaluation.

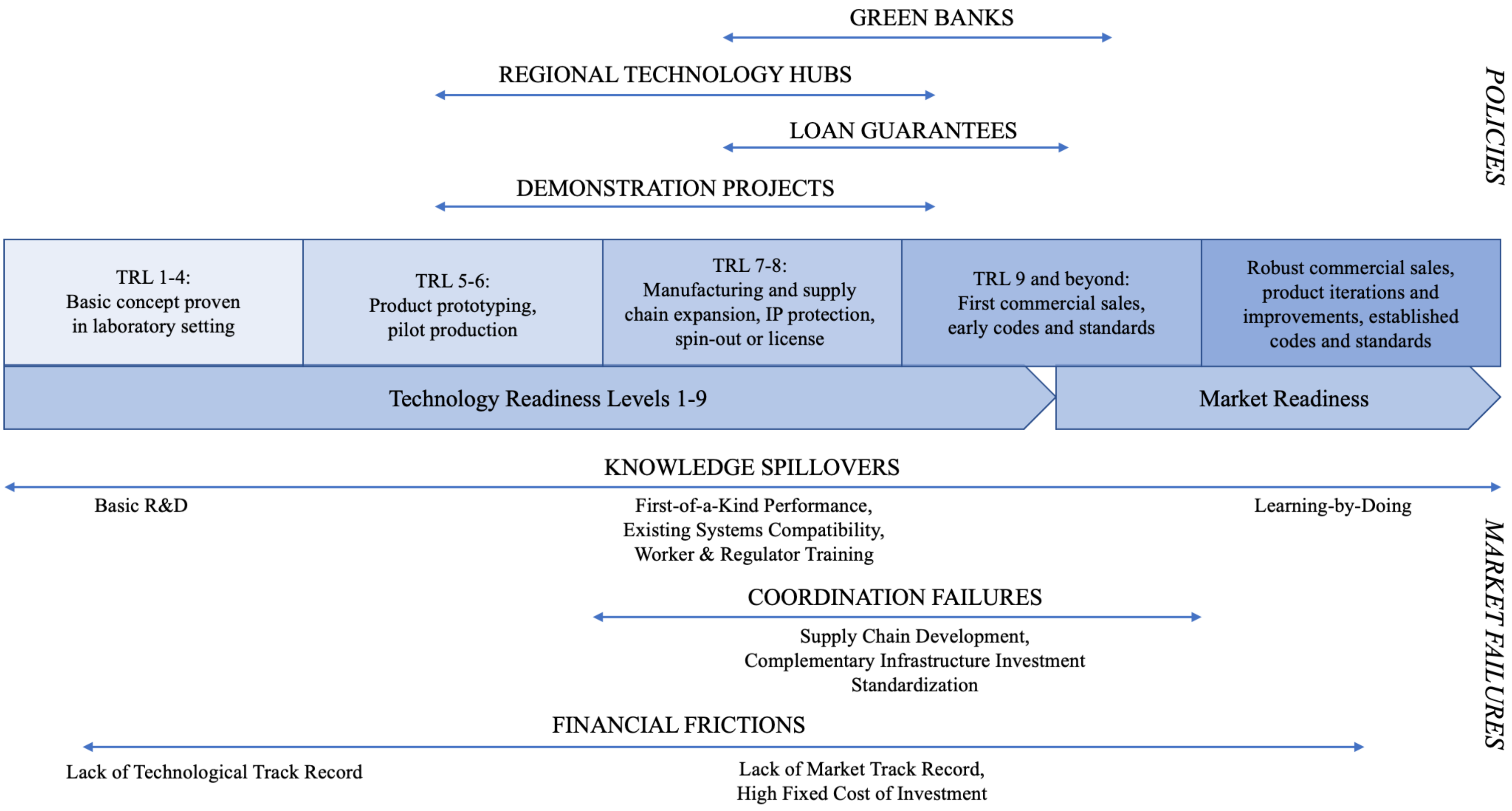

Figure 1: Technology Readiness Levels, Policy Instruments, and Innovation Market Failures. Adapted from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

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