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The valley of death, the technology pork barrel, and public support for large demonstration projects

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ABSTRACT

Moving non-incremental innovations from the pilot scale to full commercial scale raises questions about the need and implementation of public support. Heuristics from the literature put policy makers in a dilemma between addressing a market failure and acknowledging a government failure: incentives for private investments in large scale demonstrations are weak (the valley of death) but the track record of governance in large demonstration projects is poor (the technology pork barrel). These arguments are reassessed in the literature, particularly as to how they apply to supporting demonstration projects for decarbonizing industry. A new data set is built of 511 demonstration projects in nine technology areas and characteristics for each project are coded, including timing, motivations, scale, and the share of public funding. The literature and the results from the case studies have five main implications for policy makers in making decisions about demonstration support. Policy makers should consider: prioritizing learning, iteratively upscaling, engaging the private sector, disseminating knowledge widely, and making demand pull robust.

1. Introduction

A prominent claim in innovation literature, and in practice, is that a technology ‘valley of death’ exists, from which promising technologies fail to emerge due to weak incentives for investment, e.g. due to technical risk, uncertain markets, and the need for large chunky investments. Market failures and innovation system failures lead to underinvestment at this intermediate stage of innovation. While governments might address this problem, a second metaphor holds that a ‘technology pork barrel’ also exists, in which technology support will inevitably fail due to politicians diverting program goals to trade favors and improve reelection prospects. A related notion holds that even beyond these problems with representative democracy, poor access to information implies that ‘governments should not pick winners.’ The strong version of these latter arguments, predominant in some countries today, is that even if market and system failures set up a technology valley of death, it is not worth addressing because government failures are so inherent in democracies that they will undermine efforts to make technologies commercially viable.

That the extent of government failures may exceed market failures has important implications for technologies facing real valley of death problems; they may simply never become widely adopted. This outcome is particularly relevant for technologies needed to address climate change. For example, achieving the ambitious climate change mitigation targets that 196 countries agreed upon in Paris in December 2015 will require near complete decarbonization of developed countries' economies during this century (Rogelj et al., 2015). This transformation will necessarily involve not only sectors such as electricity and transportation, which are already decarbonizing, but also substantial emission reductions in industrial sectors such as steel and cement in which the core production process produces emissions (Woertler et al., 2013; Ahman et al., 2016; Denis-Ryan et al., 2016). While some opportunities remain for picking low hanging fruit, such as emission reductions through energy efficiency improvements, they are not sufficient to achieve the envisaged climate goals (OECD, 2015; Arens and Meister, 2016). Adoption of radical low-carbon innovations in the production process, combined with electrification (IEA, 2011), is crucial to decarbonizing the materials sector (Neuhoff et al., 2015). And because industrial facilities are large to reap scale economies, industrial low-carbon technology needs similar scale to fit into the broader technological system. Large-scale radical innovations with payoffs that depend on uncertain future policies seem especially prone to the valley of death problem. To help improve the prospects of meeting ambitious goals, governments around the world are considering substantial increases in their support for innovation, including demonstration projects. One example is the Mission Innovation initiative, in which 21 governments

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have committed to double their energy R&D investment over the next five years (Karlsson, 2016; Sivaram and Norris, 2016). Further the European Commission has proposed a New Entrants' Reserve (NER) 400 program, which would use the revenue from auctioning 400 million emissions permits to fund projects in the 2020s focused on decarbonizing industry (Borghesi et al., 2016). How this support will be structured, allocated, and coordinated are crucial open questions—ones that need more sophisticated guidance than following heuristics such as removing 'barriers' and avoiding 'picking.' Just letting 'markets decide' ignores the reality of substantial market and system failures, while simply beefing up government funding does not adequately address the perceived poor track record of previous government programs. Further, the potential for high-profile failures heightens the stakes involved in that they may create lasting legacies that affect the political feasibility of future efforts.

The paper thus addresses the broad question of *how public support for low-carbon technology demonstration projects can be structured to be most effective in overcoming the valley of death?* This is done in two ways. First, starting with a simple model of government support for innovation based on technology push and demand pull, the literature is reviewed to more precisely understand the conditions that can produce a technology valley of death. Second, built on this reassessment, important aspects of a large sample of past demonstration projects are characterized. A new data set of 511 demonstration projects is collected, for which the following characteristics are coded: timing, motivations, contributions, scale-up, performance, and markets. Our primary motivation is to contribute to a (hopefully) growing set of studies about technologies that face the challenges of this awkward intermediate stage, between technology push and demand pull. The aim of the paper is to help structure thinking, beyond heuristics, about the policy decisions at stake because the policy outcomes have broad ramifications beyond the sums involved, even if those are substantial (Iyer et al., 2015).

This paper is structured as follows. First, the state of the literature on technology push and demand pull is reviewed, linking the valley of death with the technology pork barrel. Second, specific aspects of large-scale, low-carbon demonstration projects are described and hypotheses around several characteristics are developed, based on the existing literature. Third, these hypotheses are tested with the help of a newly assembled data set of previous large scale demonstration projects. Fourth, a response to our research questions is developed with an empirical assessment of the data set. Fifth, the limitations of the data set are outlined. The paper concludes with a discussion of the implications for policy making.

2. Literature and theory

Informing decisions about public investments in demonstration projects starts with understanding insights from previous research about government involvement in this particularly challenging stage of the innovation process.

2.1. Technology push and demand pull

While more sophisticated theories have emerged, it is difficult to completely discard the nearly century-old notion of the process of innovation as progress along a sequence of stages from scientific research to applied research to commercialization, and diffusion—with various names and fineness in distinctions to describe the stages (Schumpeter, 1947; Abbott and Usher, 1954). Crucial to moving this model from aged caricature to useful depiction of reality are the feedbacks involved in this sequence. Knowledge created in the process is used to inform thinking and decisions in previous stages. For example, experience in production can identify bottlenecks that require new designs to address; consumer use of new technologies can inform how they can be improved. Once feedbacks of knowledge are included in the previously *linear* process it takes on the attributes of a system—with complexity, emergent properties, increasing returns, and stochastic outcomes as defining features.

The literature on "technology push" and "demand pull" implies that governments can interact with this system in two ways. In the most succinct terms: technology push policies *reduce the costs* of innovation for private sector actors while demand pull policies *increase the payoffs* to private sector actors for successful innovations (Nemet, 2009). In the technology push approach, the government's goal is to increase the availability of new knowledge while in demand pull the goal is to increase the size of markets for commercialized knowledge. Examples of technology push policies include: public R&D funding, R&D tax credits, subsidizing education, and supporting knowledge networks. Examples of demand pull include: intellectual property rights, pricing externalities, subsidizing demand, government procurement, and technology standards. The innovation literature involves a lengthy debate about this dichotomy including both descriptively about which has been the dominant driver of innovation (Schmookler, 1962; Mowery and Rosenberg, 1979; Godin and Lane, 2013) and normatively about whether governments should focus on creating knowledge or creating markets (Bush, 1945; Veugelers, 2012; Peters et al., 2012). A general consensus has emerged around the following four aspects of innovation. First, technology push and demand pull are both necessary and neither is sufficient; given substantial variation among technologies. Second, technology push is important in early stages and demand pull in later stages. Third, incremental innovations depend on demand pull while radical innovations require technology push. Fourth, successful innovations tend to be those that "couple" a technical opportunity with a market opportunity (Freeman, 1974; Pavitt, 1984; Brian Arthur, 2007; Stefano and Gambardella, 2012).

This framework is particularly useful for assessing demonstration projects as it illustrates what makes support for them challenging. First, demonstration projects fit awkwardly into this framework as they lie *between* the research oriented areas associated with technology push and market oriented stages of demand pull. Second, in the context of low-carbon technologies, demand pull may be weak due to low credibility that policymakers will create future markets making the resulting incentives *fragile*.

2.2. Demonstration projects

Demonstration projects sit at an awkward stage, in the middle of the innovation process; they are well beyond research but not yet commercial products (Kingsley et al., 1996; Mowery, 1998; Spath and Rohracher, 2010; Hendry and Harborne, 2011). As such, it's not even clear whether government funding for demonstrations involves reducing innovation costs or increasing commercial payoffs. To small suppliers of innovation, a billion dollar demonstration project *is* the payoff; to large ones it is part of the cost of bringing an innovation to the market. Ultimately, if one were to choose, the latter description seems more representative.

In an excellent review of what they term "pilot and demonstration" projects, Frishammar et al. (2015) make clear that this term has been used in several different ways and thus suggest the rather general definition of "a tool used to progress knowledge so that an effective organization, design, and management of commercial facilities can be achieved at a lower risk for the stakeholders involved." This definition reveals that demonstrations often involve multiple objectives. Most fundamentally, their goals can diverge between demonstrations 1) as exemplars, proving reliability and performance and 2) as experiments from which to learn. Demonstrations provide opportunities for collaboration, for example among component suppliers, universities, partner firms, and in some cases customers, so that process and interactions can be standardized and improved. These interactions make clear that the challenges involved are not purely technical, encompassing alignment of institutions, rules, standards, codes, and public attitudes. They are

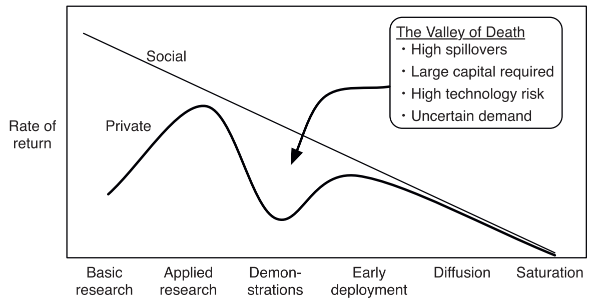

Fig. 1. Innovation stages and the technology valley of death.

also about creating knowledge about technical possibilities, not just creating those possibilities (Weyant, 2011). All of these functions are supportive of a recurring challenge in innovation, scaling up unit size (Wilson, 2012). The scale-up might be needed to achieve some minimum efficient scale, or to fit into a larger technological system.

2.3. Valley of death: 'between' and fragile

The notion of the technology valley of death is that technologies at the demonstration stage face particular challenges that lead to under-investment and ultimately to premature deaths of otherwise promising innovations (Murphy and Edwards, 1998; Watson, 2008; Weyant, 2011). Fig. 1 portrays the valley of death by showing the shift in funding over the course of the innovation lifecycle, from the public to private, is in part due to declining social returns and increasing private ones. At any stage at which social returns exceed private ones, there will be underinvestment unless the public sector plays a role. For example, at early stages the widespread availability of new knowledge as scientific research makes social value high and easy to access for all. At late stages, there are diminishing returns to adoption and firms are able to protect what value remains via brands, patenting, and optimized proprietary production processes.

Why don't firms pay for their own demonstrations? At either end of the innovation sequence, the optimal roles of the public sector and firms are clear: basic research requires public funding; adoption of commercial technologies are best funded by the private sector, including consumers. However, in between, at the demonstration stage, a troublesome combination of factors is typically involved: the potential for knowledge about outcomes to be highly beneficial to companies other than those making an investment; a substantial increase in the scale of investment required; unproven technical reliability; and uncertain market receptiveness. Because knowledge about performance may have high value, but may also be non-excludable, social returns to investment at this stage may far exceed private returns. A lack of investment by both the public and private sector has been a frequent result. The main four reasons for this are described in more detail in the following.

Appropriability Low appropriability is the most widely accepted explanation for why firms will be unwilling to fully fund their own demonstration projects (Teece, 1986; Cohen et al., 2002; Hall and Mairesse, 2009). Appropriability is low when knowledge created as a result of a firm's investment 'spills over' to other firms. Such spillovers might be very tangible e.g. when firms reverse engineer the products of others, or take less tangible forms, e.g. when employees who accumulate tacit knowledge in developing technology, take that knowledge with them when they move to a new firm. Firms might also observe the behavior of other firms directly, for example in the case of a large demonstration project like a large industrial facility, a rival might be able to determine how often the facility operates, and whether the firm builds more of the same design. In all of these example, firms have an incentive to free-ride on the innovation investments of others. The result in aggregate is under-investment in technology development.

Scale The scale required for innovations to become profitable depends on the production process, the sector, whether the innovation involves a process or product, among other factors. Proving reliability at scale is a challenge, particularly for radical innovations which might depend on large demonstration projects for subsequent commercialization (Wilson, 2012; Funk, 2013). For example, upscaling typically identifies new problems that are not apparent at smaller scales (Sahal, 1985). The capital required for a single demonstration project can be in the 100 s of millions of dollars, or even billions. It may even be the case that several demonstration plants will need to be built to sufficiently learn or prove to de-risk the technology and move to commercial production. The required investment may rival the value of the firms themselves making them a potentially unacceptable risk. The under-investment problem due to spillovers is exacerbated if the scales required are large relative to the size of the firms involved.

Radicalness Incentives for private investment in demonstration projects also hinge on the novelty of the innovations. Incremental improvements to existing technologies are more likely to attract financial investment than radical innovations. Radical innovations likely involve more uncertainty over whether they will prove feasible, economical, and reliable (Verhoeven et al., 2016). Radical innovations also have bigger knowledge spillovers than incremental ones, as the latter can often be protected by patents or embedded in unobservable production processes (Hurmelinna-Laukkanen et al., 2008).

Fragile demand pull Incentives to invest in demonstrations may also be weak because expectations about the payoffs are uncertain. This issue is especially problematic for innovations that depend highly on government actions for their payoffs, for example environmental technologies. If future policies are uncertain, investment can be reduced (Nemet et al., 2017). It is quite clear that weak credibility about government commitments to future policies has been a problem in climate policy (Koch et al., 2015). Where payoffs depend on policies, and especially if lags between investment and payoffs are long, weak policy credibility can make demand pull 'fragile' and thus weaken incentives for demonstration investments.

As the above discussion suggests, the interactions among these factors may be especially problematic. Scale and radicalness may simply exacerbate appropriability problems. Large firms may be able to absorb the risk of investing in billion dollar demonstration programs, but if knowledge spillovers exist, the scale of investment may be too much to overcome. Fragile demand pull may be more of government failure than a market failure. This stage of the technology innovation process is particularly amenable to cost sharing between governments, private firms, and industrial consortia. Investment by the public sector is made difficult however by the need to concentrate substantial funds in a small number of projects. This concentration has made investments at the demonstration stage vulnerable to shifting political support and, conversely, prone to regulatory capture that may excessively prolong programs and funding.

2.4. Government failures and the technology pork barrel

As a result, government support of demonstrations involves not only market failure problems but potentially also government failures. The basic argument is that government failures exist that lead to suboptimal implementation of policies to address innovation-related market failures. Several specific mechanisms can result in government failure (Weimer, 2015). Concentrated interest groups in a technology have strong incentives to lobby and thus policy decisions are made with excess weight placed on the costs and benefits of those groups. Because they face elections, representatives have strong incentives to secure and maintain government technology investments in their own districts. This particular mechanism has earned colorful metaphors such as 'log-rolling' and 'pork barrel' politics. Elections may lead representatives to be especially focused on securing funding in the near term, possibly without regard to broader and long term impacts. Problems in bureaucratic supply may also exist. In part because governments do not face competitors, X-inefficiency may lead to programs not performed at least cost. Also, incentives within bureaucracies may create agency problems, which in an innovation context may result in programs implemented above the most efficient least cost method. This is especially problematic in innovation where the private sector is already likely risk averse so that government need to be risk-seeking to avoid crowding out private investment. Their lack of participation in the marketplace may also give governments poor access to information, for example about pricing, competing technologies, and consumer preferences. Finally, decentralized government decision making—in which countries and sub-national governments make independent decisions—inadequate information, poor coordination, and inefficient duplication of programs raise implementation challenges.

This literature establishes the multitude of challenges that new technologies face at a crucial phase in their development, demonstrations. Both market failures and government failures exist. Our premise is that the design of future demonstration programs can benefit from understanding this literature and from understanding what configurations have been tried in the past. Our approach is thus to study the characteristics of previous demonstration projects.

3. Aspects of large-scale, low-carbon demonstration projects

This section focuses on four main aspects of demonstration plants, namely the motivation for building demonstration plants, the timing of upscaling, the role of the public sector, and the role of market conditions. Using claims from the literature about these aspects of demonstration projects, hypotheses for several characteristics of demonstration projects are developed and tested with a new data set in the next section.

3.1. Motivation for demonstration plants

Demonstration projects are undertaken to achieve diverse social goals. These goals create a form of demand pull, but by themselves they do not reveal whether projects might determine that the technology is infeasible, unreliable, too expensive, or too immature for commercial adoption.

More immediately the projects themselves may be undertaken with varied motivations that affect their success. An important distinction is between projects meant to serve as exemplars to encourage commercialization or as experiments from which to learn (Frishammar et al., 2015). Strong arguments emphasize that the real social value is in learning rather than in proving (Reiner, 2016). Still other motivations exist, e.g. given the large public funds being used, they are often used to pursue a social goal itself, such as production, or environmental benefits.

A broad set of literature discusses the benefits of clarifying program objectives (Harborne and Hendry, 2009) and making sure ‘learning’ is a prominent one (Reiner, 2016). Demonstrations are best seen as experiments (Lefevre, 1984), part of a process of continuous experimentation (Hellsmark, 2010) where risk and failure are crucial to learning (Anadon et al., 2016). Making mistakes should not just improve chances of hits, but should be used to learn from what did not work (Grubler and Wilson, 2014). Consequently, appropriate metrics for project selection or continuation are maximizing learning or minimizing cost per learning, rather than in terms of performance or cost per performance, which was a problem in NER300, a previous carbon capture and storage (CCS) demonstration solicitation (Lupion and Herzog, 2013).

In the empirical analysis of this paper, the main motivations of demonstration projects will be analyzed and it will be tested whether the objective of learning is prioritized over others.

3.2. Upscaling

Given learning as a prime objective, the programs of the past make clear that there are benefits to sequential iteration to enhance learning. Iteration enables learning and technology improvement (Wright, 1936; Sheshinski, 1967). Sequential construction of projects allows for opportunities from learning by doing; knowledge generated in producing one demonstration can be used to inform subsequent plants. Iteration enables successful learning by allowing for responses to failure (Frishammar et al., 2015) and thus enhancing the ability to assume and manage risk. Further iteration allows for a progression of technical to organizational to market learning (Bossink, 2015).

Increasing the scale of plants is a central function of the demonstration phase (Rai et al., 2010; Herzog, 2011; Zhou et al., 2015; Frishammar et al., 2015). Upscaling however involves overcoming obstacles (Rosenberg and Steinmueller, 2013) and consequently takes considerable time, going through a ‘formative phase’ of experimentation (Wilson, 2012). More bluntly it is clear that building to full commercial size immediately is asking for trouble, as we've seen in wind (Garud and Karnoe, 2003) and to some extent in CCS (Lupion and Herzog, 2013). As previous work has shown, a sequence of technical, organizational and market demo is needed (Bossink, 2015).

Using the new data set of this paper, it will be evaluated how the previous experience in upscaling looked like and whether this differs across technologies.

3.3. The role of the public sector

Typically, some form of public funding is essential for demonstrations (Foxon, 2010). The presence of knowledge spillovers mean public funding is needed (Foxon, 2010), in addition to private participation (Macey and Brown, 1990). Nonetheless, experiential learning, in which knowledge is created by participants, implies that the private sector must play an active role in developing new technologies and demonstration plants (Hendry et al., 2010). However, part of the technology pork barrel argument is that the firms see securing government funding as their primary objective and consequently have little incentive to implement projects effectively (Cohen and Noll, 1991).

An important development in the past decades has been much more careful consideration of risk and reward for participants (Baer et al., 1976; Dosi et al., 2006; Markusson et al., 2011; Scarpellini et al., 2012; Russell et al., 2012). Crucially, involvement of firms provides opportunities for experiential learning (Baer et al., 1976; Hendry et al., 2010; Schreuer et al., 2010; Russell et al., 2012) and can stimulate networks of cooperating firms (Bossink, 2015). Moreover, success of the projects often depends on the private sector assuming a large share of both funding and management (Lefevre, 1984; Macey and Brown, 1990).

The empirical analysis of this paper will evaluate how big the share of public funding is and whether this differs according to technologies. Furthermore, it will be explored whether the involvement of the public sector is related to specific project characteristics.

3.4. The role of market conditions

The ultimate (but not immediate) goal of supporting demonstrations is to facilitate widespread adoption, and thus demand and markets are of course key (Kingsley et al., 1996). Especially in climate change and thus low-carbon technology areas, policies and their credibility are a central determinant of market conditions (Taylor et al., 2003; Zhou et al., 2015; Rai et al., 2010; Finon, 2012; Nemet et al., 2014). Previous literature has emphasized the need to connect demonstration projects to adopters and the markets in which they will ultimately compete (Kingsley et al., 1996; Sun et al., 2014). This importance is bolstered by demand pull arguments about the importance of demand for innovation (Stefano and Gambardella, 2012).

The example of the EU's NER300 program shows how important

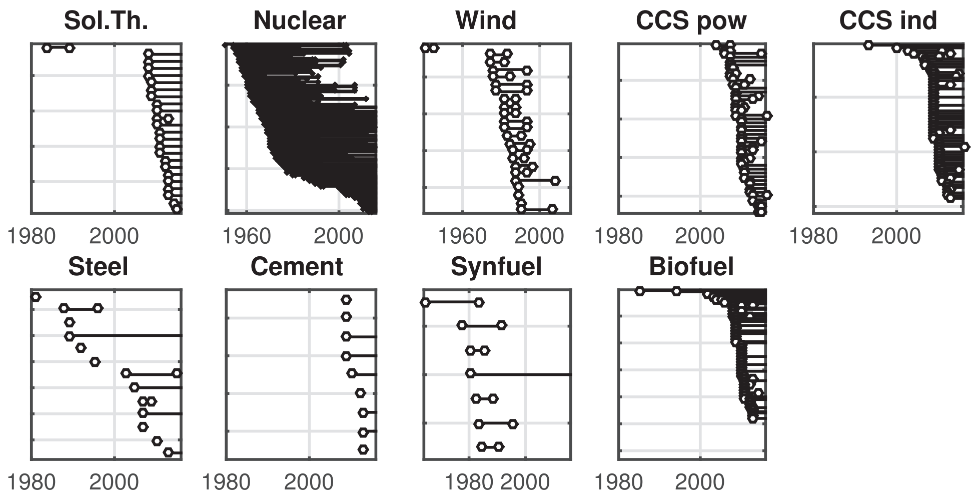

Fig. 2. Timing of demonstration projects included in analysis.

market conditions are for the development of new demonstration projects. Lupion and Herzog (2013) attribute the failure of the NER300 program to stimulate the construction of any CCS projects to four factors: competition with renewables, project complexity, low carbon prices, and a combination of fiscal austerity and weak climate policy around the global financial crisis. Note that three of the four problems involved future demand, not the funding structure itself. Demonstrations need markets that pay off innovation investments not just under a steadily increasing Hotelling-style market, but under a broad range of market conditions.

Supplementing the dataset with additional data on prices of competing technologies, the analysis of this paper will investigate the empirical evidence for demonstration projects and their surrounding market conditions.

4. Dataset and selection of case studies

On the basis of a unique dataset collected for this study, the empirical relevance of the four aspects of large scale demonstration projects which were discussed in the previous section, namely the motivation of projects, the upscaling phase, as well as the role of the public sector and of the market are investigated. More than 500 case studies in low-carbon technology areas over the past several decades are examined, coding each demonstration project on the factors described in more detail in the next section.

4.1. Dataset and methodology

The focus in the collection of case studies lies on demonstration projects of low-carbon technologies in the following three sectors: electricity, industry, and liquid fuels. In total, 511 cases are examined in nine low-carbon technology areas. Technologies are selected that are analogous to large demonstration plants in low-carbon industry due to similarities in scale, complexity, markets, and integration into a broader technological system:

> Electricity: 1) solar thermal electricity, 2) nuclear power, 3) wind power, 4) carbon capture and storage (CCS) for power plants;
> Industry: 5) CCS for industry, 6) steel, 7) cement; and
> Liquid fuels: 8) synthetic fuels, and 9) cellulosic biofuels.

Each case involves a well-documented government effort to demonstrate the technology, e.g. wind power (Gipe, 1995), CCS (Herzog, 2016), and synthetic fuels (Anadon and Nemet, 2014).

Demonstration projects in each of these technologies are identified by using the general definition of demonstrations by Frishammar et al. (2015). These are projects for which: 1) there is an element of novelty, e.g. a first-of-a-kind, or nth-of-a-kind, 2) development is advanced enough that scale and maturity are beyond the laboratory and prototype stage, e.g. operating in a real environment, but 3) not yet commercially available, e.g. for sale to a third party.

Every database entry and coding of a demonstration project case in the dataset can be identified by a unique ID (see Supporting Information on more details about data collection). Additional identifiers that are coded for each case include the full project name, sector and technology area. The time period for each demonstration project is coded according to the project begin and end dates, as well as the year a project became operational. Budget data is coded in standardized US Dollars of the year 2015 as well as original budget currency for each demonstration project. Data is mainly collected from online databases in each technology sector.[1] Additionally, the dataset is built on information from other academic publications and data of individual project homepages and various websites. The case study protocol (see Supporting Information) presents a detailed overview of these different data sources. The resulting dataset spans start dates from 1940–2015 (see Fig. 2).

4.2. Coding characteristics of case studies

Given that all projects are part of a portfolio, no attempt is made to classify each as a success or failure. Rather a data set of characteristics of each project is assembled and the focus lies on evaluating four areas which the literature has pointed to as important attributes of government support for innovation at the demonstration stage.

1. Motivation: Each project is coded on the stated motivations including: production, creating knowledge, scale-up, proving technology, and other motivation. The category 'other motivation' i.a. includes environmental protection, job creation, and energy independence.
2. Timing and upscaling: The timing of each project is coded by the

[1] Data on solar thermal electricity is collected from the database by the National Renewable Energy Laboratory (NREL). NREL compiled data on concentrating solar power (SCP) projects in collaboration with Solar Power and Chemical Energy Systems (SolarPACES). Gipe (1995) is the main data source for wind power. Data on carbon capture for power plants is mainly collected from the MIT Carbon Capture and Sequestration Technologies (CC and ST) Program. The MIT CC and ST Program also provides data on carbon capture projects for the industry. The Global CCS Institute provides data for carbon capture plants as well as demonstration plants in the cement and steel sectors. The data for synthetic fuels cases is taken from Anadon and Nemet (2014). Demonstration project data in the sector of cellulosic biofuels is provided by the online database of Task 39 IEA Bioenergy 2020.

year the project was begun, when it became operational, and when it ended. Furthermore, the scale of production for each project is coded, using equivalent units within each technology area.
3. Role of public sector: For each project where information on the public involvement was available, the total project cost and the public and private sector shares of those costs are calculated.
4. Role of markets: Each demonstration project is connected to market indicators (prices) over time at the technology level. This allows comparing decisions to initiate, operate, and cancelled projects with market expectations at the time.

4.3. Methodology

The data collected from the demonstration projects is used to inform the hypotheses developed in the previous section. The qualitative analysis is based on descriptive statistics of the data set as well as it explores the time dimension of the data set. Correlations of project characteristics are presented, as well as characteristics are set into context of market developments.

5. Results of empirical analysis

Based on coding these demonstration projects, results on project motivations, timing and scale-up, private sector contributions, and connections to markets are reported.

5.1. Motivation

Table 1 shows the motivations expressed by each project for which information was available. The motivations are arranged in terms of timing of impact: the most near-term focused objective is to produce a product while the most long-term would be to learn, which serves a broader goal (such as production) in the longer term. The three main motivational drivers in the category ‘others' were environmental protection, job creation, and energy independence.

In aggregate, the four categories are at quite similar levels. However, the technology specific mixes are quite distinct. Steel, cement, and synthetic fuels have prioritized learning in more than half of the projects. Scale up has been important for wind, cement, and synfuels; proving technology for power plant CCS, steel, and cement. More than half of projects in power plant CCS, cement, and synfuels see production as a motivation. Note that some projects stated more than one motivation so that they sum to more than 100%. Fig. A.11 in A.1 shows trends over time in the occurrence of each motivation. There is no distinct shift notable, although a broader mix of motivations (and thus lower shares for all) toward the end of the time period can be noticed.

This question was approached with the prior hypothesis that projects tend to overemphasize production as an objective, at the expense of learning. The results however do not provide support, the shares of motivations are quite similar, at least across all projects. Solar thermal electricity, biofuels, and wind power have been least focused on learning as a motivation. This result fits with the prominence of demand pull policy instruments for these technologies, as well as below-median levels of public investment, which are discussed next (Fig. 5). One possible explanation is some selection in terms of which cases provided information on motivations; for 60% of the cases information on motivation is available. A second possibility is related to the option of multiple responses. In a secondary analysis the responses are weighted inversely by the number of objectives provided, e.g. each motivation weighted by 1/4 if four motivations were provided. This results in similar outcomes with the additions that production is important for wind power and proving technology is important for industrial CCS.

Table 1
Stated motivations in demonstration projects (>1 response possible per project).

Technology	Production	Proving	Scale up	Learning	Other	N
1) Sol. Th. Elec.	29%	33%	21%	17%	29%	24
3) Wind Power	43%	26%	78%	13%	0%	23
4) CCC Power	52%	64%	45%	50%	25%	44
5) CCC Industry	29%	40%	31%	34%	19%	62
6) Steel	46%	62%	38%	54%	15%	13
7) Cement	56%	89%	67%	89%	33%	9
8) Syn. fuels	56%	56%	56%	56%	44%	7
9) Cell. biofuels	6%	12%	6%	13%	2%	126
All Sectors	27%	34%	28%	29%	14%	308

5.2. Timing and upscaling

As shown in Fig. 2, the projects span a 75 year period. Having coded the project start, completion, and cancellation dates (see A.2 Table A.21), the following findings emerge: Average time from beginning of a project to coming on-line was 1.9 years for all projects, highest in CCS power plants and synfuels. In contrast to prominent literature on commercial plants, nuclear demonstrations were only slightly above the average (2.5 years), although it also had the most variation. For all projects, 36% were cancelled, with the highest cancellation rate in nuclear power plants. For nuclear, lifetimes of <30 years are considered as cancellations rather than end of life shutdowns since many reactors operate after 50 years. For projects that were cancelled, the average time on-line before project cancellation was 11.4 years. Of the projects that were ultimately cancelled, 27% were cancelled before they ever came on-line. For the projects that were cancelled after they came on-line, average time to complete construction was 5.3 years, more than double the mean construction time.

Looking at the size of projects within a technology area over time, it is clear that upscaling is a central outcome. In every case, one can see a trend to larger projects over time (Fig. 3). These nine technology areas are in part selected based on the technologies needing to function at large scale to be commercially viable. Yet, there is no case in which demonstrations were built at a commercial scale at the beginning. It is known that the process of upscaling takes years and involves iterative improvement (Wilson, 2012), and that is certainly the case with these projects. For a closer look, consider the example of nuclear fission power plants, for which there is comprehensive data for over 65 years available (Fig. 4). It took 15 years to go from the first demonstrations to commercial scale plants; and that is for the technology that has been deployed more rapidly than any other. One sees a similar pattern in wind turbines. In that case, it was quite clear in the early 1970s that wind turbines would need to be built at MW scale to be economically competitive (Vargo, 1974). As a result, the U.S. and Germany developed several demonstrations with a capacity of over 1 MW using technology from the aerospace industry (Gipe, 1995). Yet, these approaches failed compared to the Danish approach which was to gradually upscale their turbines, so that it took over 20 years to reach 1 MW scale. The Danish approach of gradual upscaling with iterative improvement led them to dominate the wind power industry (Garud and Karnoe, 2003).

5.3. Public contribution

In Fig. 5 the public share of expenditures for each project for which data was available is shown. Across all projects, there is a median public contribution of 64%, with a 25–75th percentile range of 29–80%. Every technology area shows a wide dispersion in public contribution, with many including both completely publicly and completely privately funded projects. Notably the data shows substantially higher public sector participation in industrial CCS projects compared to power-sector CCS; the 25–75 ranges do not overlap. It should be noted that some firms may be in a regulated environment that allows

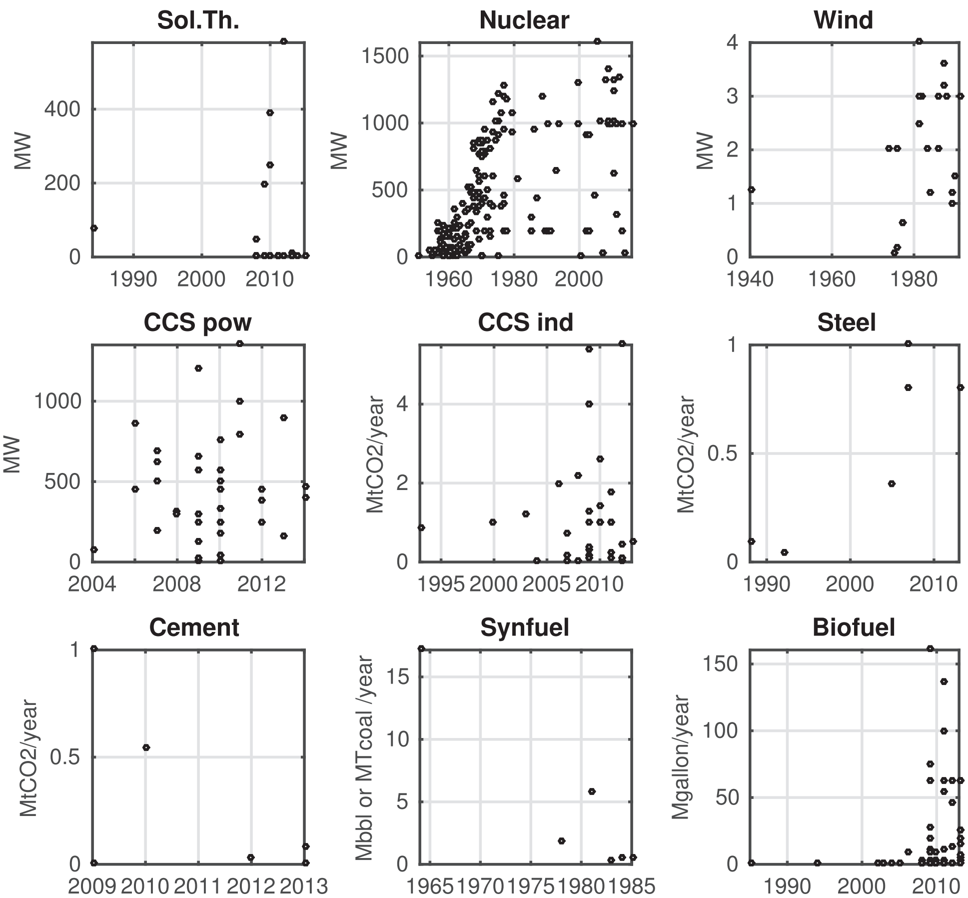

Fig. 3. Scale of demonstration projects by project start year.

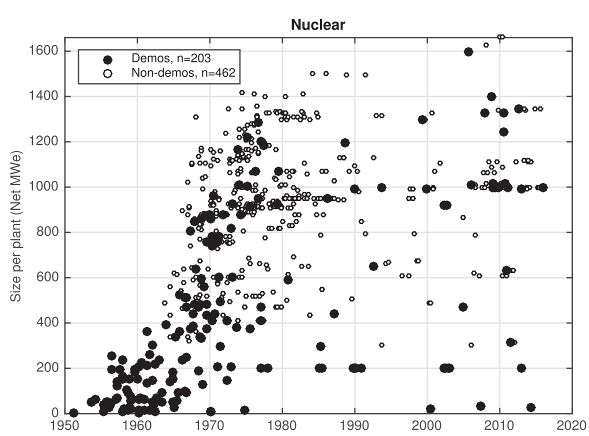

Fig. 4. Nuclear power plants: scale of demonstration projects compared to commercial plants (non-demos). Demonstrations defined as: 1) first of a kind reactor type by supplier, 2) built at <50% of minimum commercial scale (500 MW), or 3) operating for <25% of 60 year life.

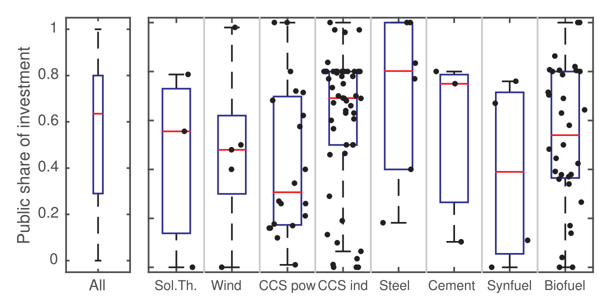

Fig. 5. Contributions of public sector to demonstration projects included in analysis. Boxes represent 25–75th percentile ranges, with the horizontal line within the box being the median, and dashed vertical lines indicate full range.

them to pass on all or some of their share to ratepayers (Averch and Johnson, 1962). However, even in the power sector in a single country there is inconsistent treatment of cost recovery in these projects so no attempt is made to code them in this way.

To explore some of the possible factors affecting this wide dispersion, Fig. 6 shows bivariate comparisons of public share with: start year, sequence, budget, and market prices in which the technologies would ultimately compete. Note that this figure does not include data on nuclear projects where data on the public share was unavailable. Linear fits show only weak relationships, e.g. there appears to be a trend toward higher public share. Notably there are very little indications of a relationship between project size (in terms of budget) or in terms of prices. To further assess these possible relationships, a fractional logit model is used to estimate the determinants of the public sector share of funding (see A.3). No significant results are found, although the budget coefficient is negative and slightly significant at the ten percent level in two out of seven estimations. There is however only full data for about 100 observations, and we are careful to include 8 technology dummies in every estimation, so there is some risk of a type II error. Nonetheless it is somewhat surprising to see no effect of public share given the large range of project budgets included and the notion that scale affects incentives. These results are included in A.3.

5.4. Markets and expectations

To assess the markets in which these demonstration projects were

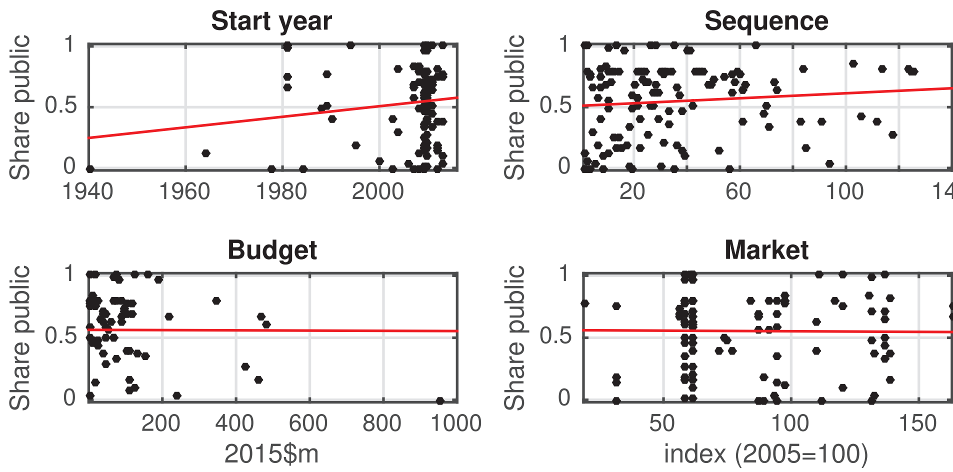

Fig. 6. Contributions of private sector to demonstration projects included in analysis. Horizontal axes show: year project began, nth plant for each technology, total project budget, and price index for relevant market.

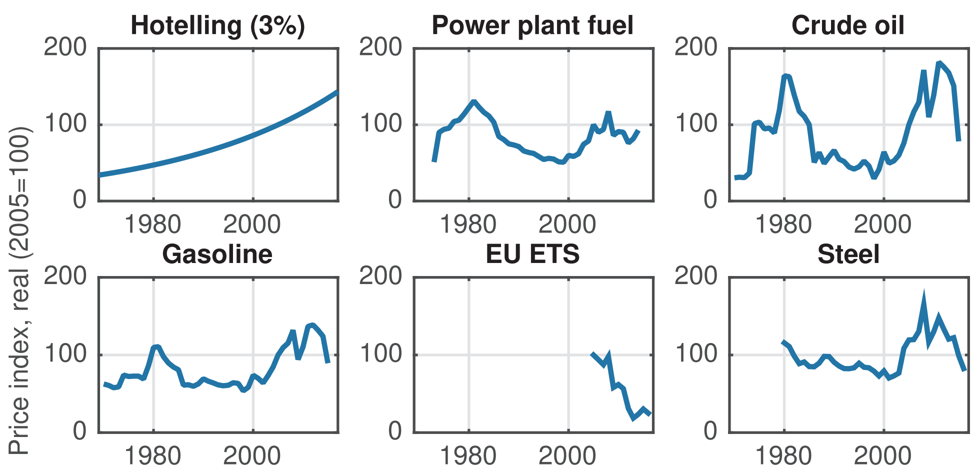

Fig. 7. Price indices for markets relevant to each technology.

ultimately to compete, price indices are created for each of the markets in which each of these 9 technologies competes (Fig. 7). Prices are in real dollars and indexed so that 2005 = 100. In addition, a Hotelling curve is added using a typical social discount rate of 3% to give a sense of the general expectation of a long term price path for a non-renewable resource (Hotelling, 1931). A Hotelling price path predicts that prices of an exhaustible resource (e.g. oil, atmospheric storage of CO_2) rise at a constant pure rate of time preference for the time of project duration. It is important to consider that Hotelling is not merely an academic construct, it shapes expectations about future prices in a variety of contexts. This descriptive comparison supports what is clear from the literature (Krautkraemer, 1998; Zaklan et al., 2011), that price paths following Hotelling are the exceptions rather than the rule - it is more likely to see shocks and boom–bust cycles, as the prices related to each demonstration project in Fig. 7 show.

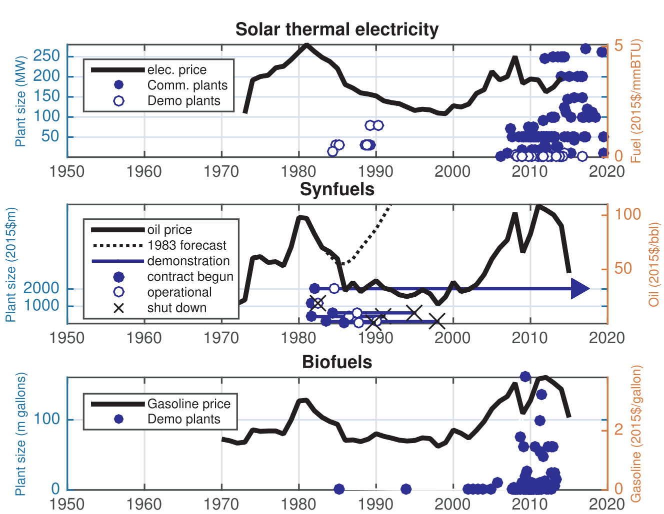

Fig. 8. Markets for demonstration projects: solar thermal electric, synthetic fuels, and cellulosic biofuels.

Looking at market prices in the context of previous demonstrations shows a recurring outcome; demonstration project often come on-line just as markets for them are heading in the wrong direction. The projects were planned when prices and expectations rose, and only came on-line when prices crashed. The lags between project initiation and on-line make them vulnerable to volatile markets. This is clearly seen in synfuels (Fig. 8), in which projects came on-line just as the market was disappearing. Similar outcomes are observed in solar thermal electricity and cellulosic biofuels. In the synfuels case, only one project survived; this more than any other outcome led to the notion of the technology pork barrel. It was not that technology did not perform according to projections, but the unexpected drop of global oil prices that eliminated the commercial viability of the projects. This outcome created the impression of a failure of the innovation policy.

CCS projects show a similar pattern; projects have come on-line just as the EU ETS price has crashed (Fig. 9). Taking a more future oriented perspective, expectations of future carbon prices in 2030 (Usher and Strachan, 2013) are plotted. Expectations of prices seem higher than

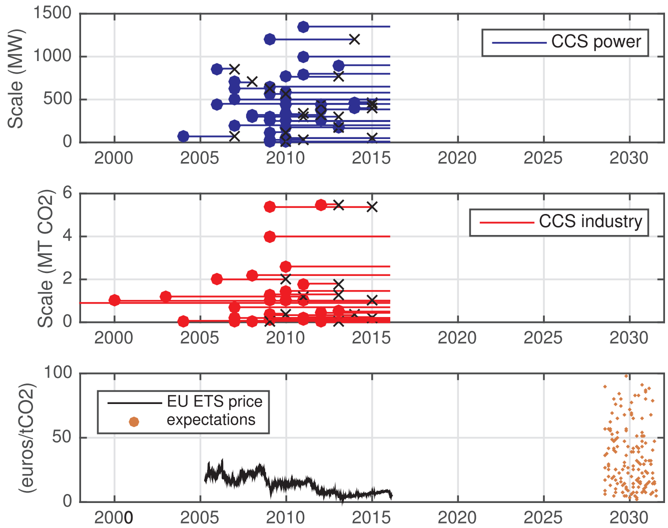

Fig. 9. Markets for demonstration projects in CCS.

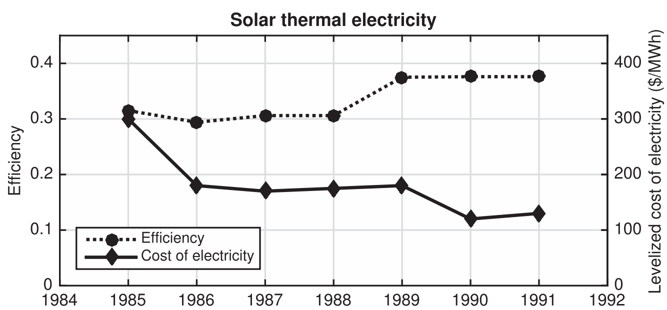

Fig. 10. Performance of solar thermal electricity demonstration projects.

current prices, but the wide dispersion of expected prices imply considerable uncertainty, even as to whether prices will be higher or lower than today's. It seems possible that CCS markets could look similar to those of synfuels and others, such that projects coming on-line may need to survive multiple years selling into a low price regime before prices rise. The persistent pattern of unstable energy markets suggests that demonstration programs need a plan for robustness, so that projects have a chance to proceed to commercial adoption under a range of market outcomes, not just optimistic ones.

6. Discussion and limitations

The dataset collected for this analysis relies on publicly available information. Evidently, this limits the scope of data collection and thus the analysis, especially with respect to performance, knowledge dissemination, and broader project contexts.

A project focus on learning means that management of knowledge is central; how it is produced but also how it is codified, stored, and transmitted (Grubler and Nemet, 2014). Dissemination is even more important given the global public good aspect (atmospheric greenhouse gas storage capacity) of the problems to be addressed. Performance review of demonstrations helps (Frishammar et al., 2015), including especially reporting of results (Gallagher et al., 2006).

We were unsuccessful in obtaining performance data and details about knowledge dissemination for anything close to a representative sample of the projects which were coded. However, as an exception, results from the first solar thermal electricity plants in California in the 1980s (Fig. 10) are shown. These results show impressive cost reductions over sequential plants, including scale-up. Perhaps even more relevant to this paper is that this improvement was only observable due to a 50:50 cost shared post-demonstration assessment by the private firm who developed the plants and the U.S. Department of Energy (Nemet, 2014). Performance was assessed systematically over time and made publicly available (Lotker, 1991). From the projects that were reviewed in this paper, this post-project assessment represents the gold standard for knowledge codification and dissemination for demonstration plants.

Another factor which was not feasible to code in a comprehensive manner was the broader context of demonstration projects. The strong effects of scale economies for the technologies under consideration imply a need for diversity support (Markusson et al., 2012) to avoid lock in (Shackley and Thompson, 2012). Given multiple pathways available for large scale low carbon technologies, premature focus can be risky (Nemet et al., 2013). This creates a need to support variety while evolutionary mechanisms impose selection pressure (Kemp et al., 1998). However, this analysis cannot provide insights on these broader project contexts.

7. Conclusion

Looking at a broad set of previous demonstration projects provides insights for how to make the most out of future government support for demonstrations. Our review of past demonstration projects reveals five main conclusions which are important policy design elements to include as several countries consider how to support innovation for large scale decarbonization.

First, there is still scope to prioritize learning as a motivation for such projects. Our review of past projects identified a wide range of motivations. Only 60% of the projects for which motivation information was obtained, stated something related to learning as an explicit objective. To enhance the social returns of these government investments, all of them should consider learning as part of their objectives at the very least. They thus should be monitored and reported on to facilitate learning. Milestone payments provide help in this direction as they raise the importance of defining meaningful milestones. Basing milestones e.g. on knowledge created, could offer a promising direction for the design of public innovation funds to ensure the importance of knowledge creation.

Second, iterative scale up is important for the development of new technologies. Our data show achieving full commercial scale takes considerable time. For example, one can clearly see two decades of demonstrations and upscaling in nuclear. That may be an extreme example given the complexity of that technology. Still, it points to the need for sequencing and iterative learning, and perhaps most importantly, some urgency in initiating projects. Policy makers need to learn from failures and successes of the past in order to design a demonstration strategy that itself can both generate new knowledge and learn from that which is created.

Third, the role of the public sector is independent of projects characteristics. A very heterogenous mix of public-private financial contributions was found in the data set. The share of public contribution in the overall budget of demonstration projects seems to be unrelated to other project characteristics like technology, scale, motivation, or market environment. Experiential learning, in which knowledge is created by participants, mean that the private sector must play an active role. Managing public-private relations in innovation funding is nontrivial, including not only funding and risk, but also knowledge.

Fourth, knowledge dissemination is essential in contributing to overall learning objectives. A focus on learning means that management of knowledge is central; how it is produced but also how it is codified, stored, and transmitted. Performance review of demonstrations helps, including especially reporting of results. Policymakers must carefully weigh the benefits of knowledge dissemination against private claims of proprietary access to knowledge created. The benefits of widespread access to knowledge created is not something to give up easily in negotiations to secure private funding.

Fifth, a robust demand pull policy environment helps sustain the ongoing viability of projects once initial capital investment has been made. Pairing our dataset of demonstration projects with market conditions, it is striking how many demonstration programs competed in markets that involved negative shocks around the time that projects came on-line—this is observable in synfuels, biofuels, solar thermal electricity, and CCS. The time lag from project initiation to time on-line, an average of 1.9 years in our sample, is thus crucial in times of changing market conditions. Our data suggests that relying on a Hotelling path for future payoffs is a risky bet and that it is more likely to see booms and busts of relevant prices over the duration of projects. This large uncertainty about the price development of competing technologies creates the need for a robust demand pull policy in addition to public financial support of demonstration projects. Features of robust demand pull include for example niche markets (Kemp et al., 1998), hedging across jurisdictions (Nemet, 2010), and flexible production (Sanchez and Kammen, 2016). Last but not least, government price guarantees have played an important role as was seen in the case of synfuels, solar thermal electricity, and on a smaller scale, photovoltaics.

There are however additional factors which should be considered when setting up a demonstration strategy and we touch on three aspects providing direction for further research. First, policy makers are ultimately concerned about two questions: 1) *How big a demonstration plant should we build?* and 2) *How many demonstration plants do we need?* Our take on the first question is that iterative upscaling implies that the budget should increase over time. The median cost of all projects in our data set is $64 m. Other work indicates that each demonstration costs $1b (Reiner, 2016) while others have designed strategies in which a similar amount is divided into 5 to 6 grants of $200 m each (IEA, 2011). The second is an even bigger open question (Reiner, 2015). Some have suggested that 5–10 projects are needed (Herzog, 2011), while others have modeled deployment based on 10 projects (Nemet et al., 2015). Clearly an empirically based pathway to commercialization will help inform this decision-making.

A second direction is how to consider public acceptance (Krause et al., 2014; Geels et al., 2016). That these projects are industrial scale and typically unfamiliar make them unlikely candidates for favorable and consistent embrace by various publics. Given the need for governments to take risk and tolerate failures, public attitudes are important to understand. If publics are skeptical, interim problems can become high profile failures and create insurmountable setbacks. This is particularly important if taking risks and experimenting. The abrupt ending of CCS deployment in Germany is a cautionary tale, as are early adoption of even apparently benign technologies such as solar water heaters in California (Taylor et al., 2014).

Coming back to the original technology pork barrel argument, a third direction is to account for the political economy dimensions of demonstration projects. But rather than an interpretation encapsulated in governments should avoid picking winners, here there is an opportunity to think more normatively about how to design programs within a setting of influential political actors (Antje Klitkou et al., 2013). For example, "advocacy coalitions" are a promising dimension to understand and address specifically in demonstration program design (Dasgupta et al., 2016)

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Appendix A

A.1. Motivations for demonstration projects

Motivations over time are shown in Fig. A.11.

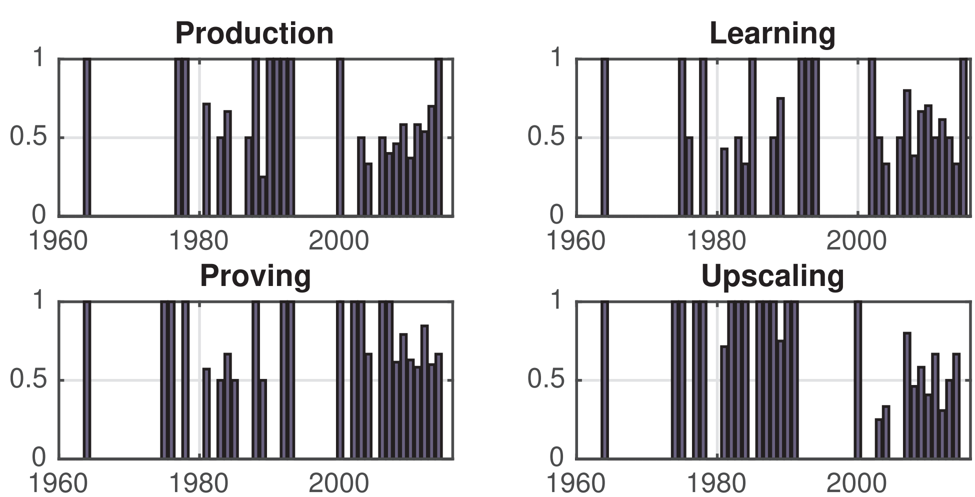

Fig. A.11. Motivations of demonstration projects included in analysis. Share of projects stating each motivation by year.

A.2. Timing of demonstration projects

Averages across projects for indicators of timing are shown in Table A.21.

A.3. Regression analysis of public funding share

The correlations of the share of public funding with the starting year of the projects, the market variable as well as the sequence variable, let us to investigate this relationship further in a regression framework. As the dependent variable is a percentage, which also takes values of zero and one, a fractional logit estimation is used. The fractional logit estimation was developed by Papke and Wooldridge (1993) to take account of the bounded nature of percentage values while at the same time allowing for values at the boundaries. A logit transformation of the data is not adequate as this is not defined for values at the boundaries. These are however present in our data, as Fig. A.31 shows.

Using the glm command in Stata (Baum, 2008), dummies for each technologies are specified and the budget in USD 2015 as our baseline explanatory variables. In subsequent estimations, the starting year of the project, the starting year lagged by one year, a dummy variable indicating whether the project was cancelled, the market variable, and the sequence variable are added one by one to the baseline specification. We abstain from a joint estimation of these explanatory variables, as they show significant and high correlations amongst each other. The estimation results are shown in Table A.31, with the baseline specification in column 2. No significant results are found, albeit the budget variable is slightly significant at the ten percent level in two out of six estimations with a negative sign. The dummy for the cancellation of projects is also found to be significantly negative. However, given these vague results, we are not able to draw conclusions from these estimations.

Table A.21
Timing of demonstration projects.

Technology	1. Start	2. Online	3. End	col.2-1	col.3-1	col.3-2	% cancel
1) Sol. Th. Elec.	2010	2012	2017	2.7	6.8	4.1	1%
2) Nuclear Power	1974	1976	1991	2.5	17.6	15.1	56%
3) Wind Power	1981	1983	1990	1.8	8.8	6.9	13%
4) CCS Power	2010	2016	2013	6.0	3.5	−2.5	17%
5) CCS Industry	2009	2011	2013	2.2	4.0	1.8	6%
6) Steel	1999	2003	1996	4.0	−2.9	−6.9	0%
7) Cement	2011	2013	–	2.5	–	–	0%
8) Syn. Fuels	1979	1985	1989	5.6	9.7	4.2	3%
9) Cell. Biofuels	2009	2011	2012	1.8	2.7	0.9	3%
All Sectors	1992	1994	1997	1.9	4.6	2.8	36%

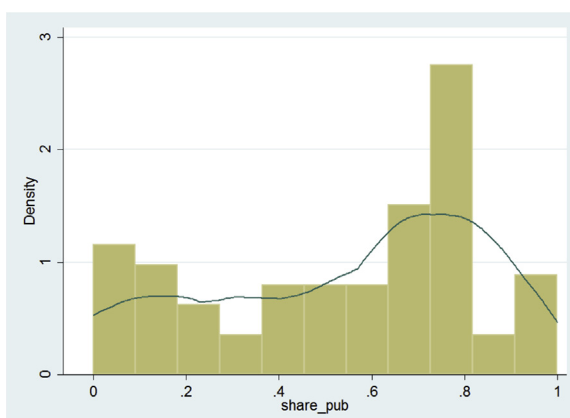

Fig. A.31. Histogram with kernel density of public share.

Table A.31
Fractional logit estimation for public funding share.

Dep variable: Public share	(1) share_pub	(2) share_pub	(3) share_pub	(4) share_pub	(5) share_pub	(6) share_pub	(7) share_pub
D STE	−0.21	−0.32	−110.1	−101.1	−0.32	−1.12	−0.35
	(−0.77)	(−1.17)	(−86.22)	(−86.17)	(−1.17)	(−1.48)	(−1.17)
D Wind power	−0.11	0.64	−108.5	−108.4	1.004	−0.1	0.61
	(−0.56)	(−0.59)	(−85.67)	(−85.62)	(−0.7)	(−0.83)	(−0.6)
D CCS energy	−0.27	−0.15	−110.6	−110.5	0.15	−0.65	−0.26
	(−0.27)	(−0.28)	(−86.63)	(−86.59)	(−0.32)	(−0.57)	(−0.31)
D CCS industry	0.43***	0.46***	−109.9	−109.9	0.6***	0.12	0.22

(continued on next page)

Table A.31 (*continued*)

Dep variable: Public share	(1) share_pub	(2) share_pub	(3) share_pub	(4) share_pub	(5) share_pub	(6) share_pub	(7) share_pub
	(−0.16)	(−0.17)	(−86.62)	(−86.57)	(−0.16)	(−0.5)	(−0.38)
D Steel	0.84	0.74	−109.2	−109.1	0.75	−0.066	0.69
	(−0.59)	(−0.66)	(−86.26)	(−86.21)	(−0.67)	(−1.02)	(−0.66)
D Cement	0.21	0.23	−110.3	−110.3	0.23	−0.72	0.21
	(−0.74)	(−0.75)	(−86.71)	(−86.67)	(−0.75)	(−1.22)	(−0.76)
D Synfuels	−0.47	−0.19	−108.8	−108.7	0.21	−0.91	−0.23
	(−0.71)	(−0.79)	(−85.15)	(−85.11)	(−0.74)	(−1.45)	(−0.78)
D Biofuels	0.14	0.19	−110.2	−110.2	0.29	−0.75	0.065
	(−0.2)	(−0.22)	(−86.7)	(−86.65)	(−0.24)	(−1.01)	(−0.28)
Budget		−0.000046	−0.000047	−0.000047	−0.000048*	−0.00005*	−0.00004
		(0)	(0)	(0)	(0)	(0)	(0)
Year begin			0.055				
			(−0.04)				
L1 Year begin				0.055			
				−0.04			
D Cancelled					−0.54**		
					(−0.27)		
Market						0.008	
						(−0.01)	
Sequence							0.01
							(−0.01)
N	126	107	107	107	107	103	107

Note: Standard errors in parentheses. Significance levels * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. 'D' stands for dummy variable.

Appendix B. Supplementary data

Supplementary data associated with this article, including the case study protocol and the dataset with the basic characteristics of the case studies, can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2018.04.008.

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