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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). We reassess these arguments in the literature, particularly as to how they apply to supporting demonstration projects for decarbonizing industry. Conditions for the valley of death exist with: low appropriability, large chunky investments, unproven reliability, and uncertain future markets. We build a data set of 511 demonstration projects in nine technology areas and code characteristics for each project, including timing, motivations, and scale. We argue that 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: 1) prioritizing learning, 2) iterative upscaling, 3) private sector engagement, 4) broad knowledge dissemination, and 5) 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 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, 2014), 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 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.

We thus address the broad question: *how can public support for technology demonstration projects be structured to be most effective?* Our approach is to reexamine the arguments that lead to the notion of the valley of death and the technology pork barrel. We do this in two ways. First, starting with a simple model of government support for innovation based on technology push and demand pull, we review the literature to more precisely understand the conditions that can produce a technology valley of death. Similarly we revisit the arguments, and claims supporting them, that lead to the technology pork barrel view. Second, we build on this reassessment by characterizing important aspects of a large sample past demonstration projects. We develop a data set of 511 demonstration projects, which we code in several ways, including: 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. We hope 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).

Specifically, in this paper we review the state of the literature on technology push, demand pull, the valley of death, and the technology pork barrel. We summarize our approach to addressing our key research questions—this involves assembling a new data set of previous large scale demonstration projects. We develop a response to our research questions with descriptive results on 511 demonstration projects in 9 technology areas. We conclude with a discussion of the implications for policy making.

2 Literature, theory, and hypotheses

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; 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 including that: 1) both are necessary and neither is sufficient; given substantial variation among technologies, 2) technology push is important in early stages and demand pull in later stages, 3) incremental innovations depend on demand pull while radical innovations require technology push, and 4) successful innovations tend to be those that "couple" a technical opportunity with a market opportunity (Freeman, 1974; Pavitt, 1984; Arthur, 2007; Di Stefano et al., 2012).

This framework provides a meso-level model of public-private interactions—a simplification relative to the innovation systems perspective in which governments need to address *system failures* (Carlsson and Stankiewicz, 1991; Bergek et al., 2008), but involving more detail than an economic efficiency perspective in which governments exclusively focus on correcting *market failures* (Jaffe et al., 2005). In justifying government interventions one could look for systems failures such as inadequately performing *functions* by entrepreneurs and 'search' directions, or market failures such as: knowledge spillovers, asymmetric information, and risk aversion (Bleda and del Rio, 2013).

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:

> “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 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, 2003; Watson, 2008; Weyant, 2011). Figure 1 portrays the valley of death by showing the shift in funding over the course of the innovation lifecycle,

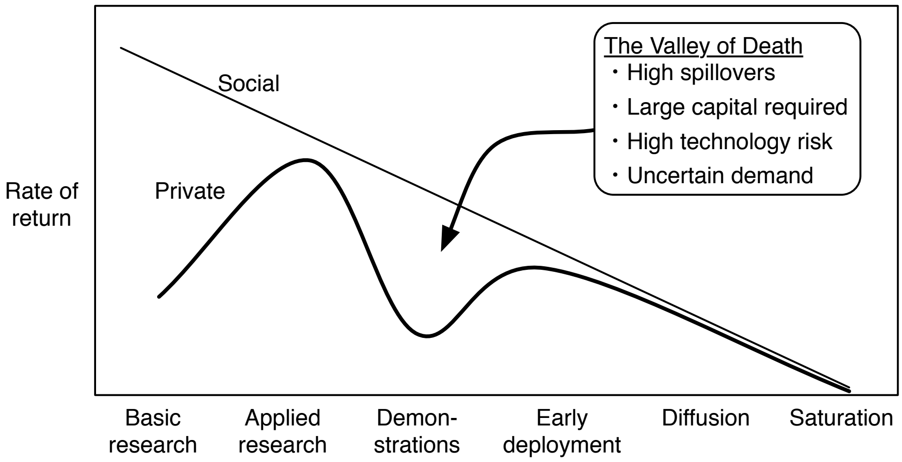

Figure 1: Innovation stages and the technology valley of death.

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. We describe these four reasons in more detail.

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 et al., 2009). Appropriability is low when knowledge created as a result of a firm's investment 'spills over' to other firms. The most tangible example of spillovers is when firms reverse engineer the products of others; they benefit by being able to imitate a novel design without investing in the expensive and risky process of developing it. Spillovers may also take less tangible forms. For example, employees who accumulate tacit knowledge in developing technology, take that knowledge with them when they move to a new firm. Even more indirectly, firms can observe the behavior of other firms; 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 100s 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). We also know that radical innovations 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 (Kalkuhl et al., 2016; Nemet et al., in review). 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 and Vining, 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, to which we return below. 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.

2.4.1 How big a problem are government failures?

While all of these have the potential to weaken the effectiveness of government innovation support, how big is the problem? A high profile strand of the literature argues that government failures are large, and further that they dominate the market failures. This strong version of the government failures argument implies that even if market failures exist in the valley of death, they are not worth addressing because governments don't have the capacity to address them effectively. Social welfare is actually higher by allowing market failure to exist than be implementing remedies. The closest we have in the literature to an empirical assessment of these claims comes from a book consisting of case studies of government demonstration programs (Cohen and Noll, 1991). The authors found problems in nearly every case study, with the exception of the U.S. photovoltaics program. They concluded that:

> "American political institutions introduce predictable systematic biases to R&D programs so that on balance, government projects will be susceptible to performance underruns and cost overruns." (Cohen and Noll, 1991)

Their explanation for these biases are all government failure arguments. Governments do not have the information and expertise that the private sector has, so governments make bad allocation decisions. Incentives in bureaucracy are likely highly risk averse which leads them to crowd out private sector investment. Most centrally they find that large projects lead to concentrated interest groups that make the projects difficult to end once started. Cohen & Noll characterize these dynamics as the 'technology pork barrel,' i.e. government demonstration programs are not managed with the objective of coupling technical and market opportunities, but rather are simply the results of politicians trading favors with each other in an effort to secure as much funding for their constituencies as possible with a focus on the near term.

2.4.2 'Governments should not pick winners'

While the Cohen & Noll arguments were focused on the U.S., they coalesced with a more international discourse about industrial policy in the 1970s and early 1980s (Lindbeck, 1981; Grant, 1982) that claimed that 'governments cannot'—and later more normatively that 'governments should not'—'pick winners." Nelson and Langlois (1983) applied these arguments in an innovation context looking back at their own case studies and found that a policy in which the "government attempts to 'pick winners' in commercial applied R&D, has been a clear cut failure." The cases they use are similar to those in Cohen & Noll, and focus on the most high profiles failures, the U.S. supersonic transport program, as well as its European equivalent, the Concorde. The U.S. Synthetic Fuels Corporation also features prominently. Their causal explanations rest on the complexity of the process of innovation and the "location of knowledge and the mechanism of its transmission in the R&D system." Governments simply are not able to access and make use of information as well as the private sector can.

Accepting these claims would have important implications for future technologies. If the government failures depicted in the technology pork barrel are inherent to government technology programs, and if certain technologies face a valley of death at the demonstration phase, then perhaps we should stop consideration of the possible future availability of those technologies. Or at least, we should leave that to other governments that somehow overcome the pork barrel problems or ignore the inefficiencies associated with overcoming the valley of death.

2.4.3 Reassessing failure

Looking back on this work, with multiple decades of hindsight, what is most striking is how difficult it is to distinguish a technology failure from a policy failure. The studies above tend to conflate the two; if a technology fails to become widely adopted, that provides evidence that the government program supporting it was a mistake. Quantifying the waste is a straightforward process of tallying the project's expenditures.

But we know that the returns to innovation investments are highly skewed, with a few in the money bets offsetting many more losers (Scherer and Harhoff, 2000). Investing in technology requires a portfolio approach to manage risk and address unknowable ex ante outcomes (Anadon et al., 2016). A recent reassessment of one of the central justifications for the technology pork barrel and the problems with picking winners—the U.S. Synthetic Fuels Corporation—found that the core reason for the 'failure' was the crash in global oil prices in the fall of 1985 (Anadon and Nemet, 2014). Several of the funded projects were completed on time and within budget; the technology performed so well that the core gasifier technology became widely used in China; and some have even argued that the potential for synthetic fuels influence the OPEC decisions to increase production and drop prices. The technology did not achieve its goal of offsetting 1/3 of U.S. oil imports by 1992, but with cheap oil that goal was abandoned. If the program is seen as a $6b insurance policy against the cost of the widely expected doubling in the price of oil (EIA, 2008) it is not clear that it was such a failure. Nor is it clear that the U.S. government had worse information and handling of it than did the private sector. The modern day equivalent of Synthetic Fuels is Solyndra, a manufacturer of photovoltaics that received \$0.5b in government loans to produce solar panels with less silicon. When the price of silicon crashed the company went bankrupt. Like oil in 1985, there were not many who were anticipating the crash in the price of silicon, and thus solar, in that period (Curtright et al., 2008). In an appropriately titled "Should We Give Up After Solyndra?" work on R&D portfolios, Webster et al. (2015) even find that poor performance early on is not sufficient evidence to justify program cancellation. Weyant (2011) provides an interesting interpretation of the valley of death problem: "the problem seems to be one of too few births and too many infants who need help breathing, not one of too many deaths."

3 Approach and data

To evaluate past demonstration projects, we investigate how public innovation support mechanisms can maximize the effectiveness of government support to overcome the valley of death, by analyzing past cases of large scale demonstration projects. We examine 511 cases in 9 technology areas over the past several decades, coding each demonstration project on the factors described in more detail in the next section. Given that all are part of a portfolio, we do not attempt to classify each as a success or failure. Rather we assemble a data set of characteristics of each and focus on evaluating what we do know from the literature about important attributes of government support for innovation at the demonstration stage. For example, we know that program design can enhance the likelihood of achieving overall objectives by: willingness of private sector to assume significant share of costs (Frishammar et al., 2015), engaging users (Schot et al., 2016), establishing clear participant responsibilities and project objectives, allowing for continuous experimentation, including interim failures and iteratively responding to mistakes (Leoncini, 2016), and plans for codification and effective reporting of results (Grubler and Nemet, 2014). Using these and other claims from the literature about demonstration projects, we develop hypotheses for several characteristics, which we code for each project.

3.1 Coding of case studies

Given the innovation market failures associated with the valley of death and the perception of a poor record of government performance epitomized by the technology pork barrel, our motivating question is: *how can public support for technology demonstration projects be structured to be most effective?* We address this question by systematically characterizing each previous projects in six areas which the literature has pointed to as important to creating new knowledge, i.e. learning.

1. Timing: 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). We code the timing of each project by the year the project was begun, when it became operational, and when it ended.

3. Motivation: Demonstration projects are undertaken to achieve diverse social goals. 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 that 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. Clarity in communicating these objectives, and participant responsibilities is also important (Harborne and Hendry, 2009). We code each project on the stated motivations including: production, creating knowledge, scale-up, proving technology, and other motivation. The category 'other motivation' includes environmental protection, job creation, and energy independence. These three were the main motivational drivers that we coded as other.

4. Contribution: Typically, some form of public funding is essential for demonstrations (Foxon, 2010). 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 also 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). Success depends on the private sector assuming a large share of both funding and management (Lefevre, 1984; Macey and Brown, 1990). For each project we calculate the total project cost and the public and private sector shares of those costs.

2. Scale: Increasing the scale of plants is a central function of the demonstration phase (Rai et al., 2010; Herzog, 2011; Zhou et al., 2015). Upscaling

however involves overcoming obstacles (Rosenberg and Steinmueller, 2013) and consequently takes considerable time (Wilson, 2012). We code each demonstration program by the scale of production, using equivalent units within each technology area. We compare the scales of demonstration plants to full commercial scale.

5. Knowledge dissemination: While generating new knowledge is a central objective, the social benefits of public investment in demonstrations also depend on codifying and disseminating that knowledge (Peters et al., 2012; Bednyagin and Gnansounou, 2012; Cappelli et al., 2014). Effective reporting of results is central to the public goods that projects provide (Frishammar et al., 2015), especially in that it allows for performance review (Thomsen et al., 2005). But firms have incentives to make the new knowledge proprietary (Lefevre, 1984) and lack of codification can lead to its depreciation (Grubler and Nemet, 2014). We aimed to track instances of technical improvement, codification, dissemination of these projects.

6. Markets: One of the central tenants of the technology pork barrel arguments are that governments are unable to access information about ultimate users (Nelson and Langlois, 1983). Work 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 (Di Stefano et al., 2012) and the particular issues of policy credibility for environmental technologies (Nemet et al., 2014). We connect each demonstration project to market indicators (prices) over time at the technology level. This allows comparing decisions to initiate, operate, and cancel projects with market expectations at the time.

We partially coded other factors but could not obtain information for a substantial portion of the sample. These include information about the structure of government funding, program governance (e.g. use of rules vs. discretion), firm's financing mechanisms, and intellectual property ownership.

3.2 Selecting case studies

We evaluate each of these six characteristics for a set of technologies 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. We select analogous technologies from three sectors:

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).

We identify demonstration projects in each of these technologies. Using the general definition of demonstrations by Frishammar et al. (2015) above we search for 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. The resulting set of 511 cases across the nine technology areas spans start dates from 1940–2015 (see Figure 2). The supporting information (SI) has additional detail on the cases, including a list of them.

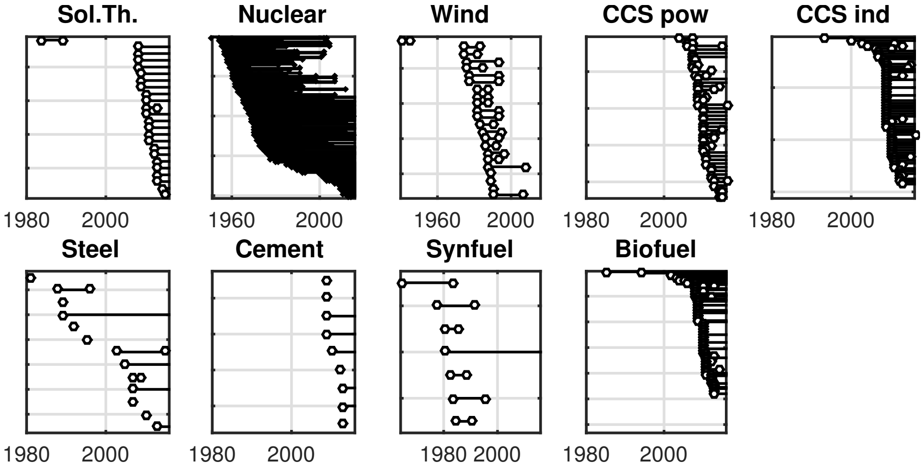

Figure 2: Timing of demonstration projects included in analysis.

4 Characteristics of previous demonstrations

Based on coding these demonstration projects, we report: timing and scale-up; project motivations; private sector contributions; documentation of performance improvement; and connections to markets.

4.1 Timing

As shown in Figure 2, the projects span a 75 year period. Having coded the project start, completion, and cancellation dates (see table in SI), we found the following: 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, we considered lifetimes of < 30 years as cancellations rather than end of life shutdowns. 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.

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

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

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.

4.2 Motivation

Table 1 shows the motivations expressed by each project that we were able to code. We arrange the motivations 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. 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. We note that projects in some cases stated more than one motivation so that they sum to more than 100%. Figure 11 shows trends in motivation. We do not notice any distinct shift, although we note a broader mix of motivations (and thus lower shares for all) toward the end of the time period.

We approached this question with the prior hypothesis that projects tend to overemphasize production as an objective, at the expense of learning. The results we have found do not provide support, the shares of motivations are quite similar, at least across all projects. We note that solar thermal electric, 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 we discuss next (Figure 3). One possible explanation is some selection in terms of which cases provided information on motivations; we have motivation information for 60% of the cases. A second possibility is related to the option of multiple responses. In a secondary analysis we weighted the responses inversely by the number of objectives provided, e.g. each motivation weighted by 1/4 if four motivations were provided. In that case we see mainly similar outcomes with the additions that: production is important for wind power and proving technology is important for industrial CCS.

4.3 Public contribution

In Figure 3 we show the public share of expenditures for each project for which we could obtain data. Across all projects we see 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 we see substantially higher public sector participation in industrial CCS projects compared to power-sector CCS; the 25–75 ranges do not overlap. We note that some firms may be in a regulated environment that allows 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 we do not attempt to code them in this way.

To explore some of the possible factors affecting this wide dispersion, Figure

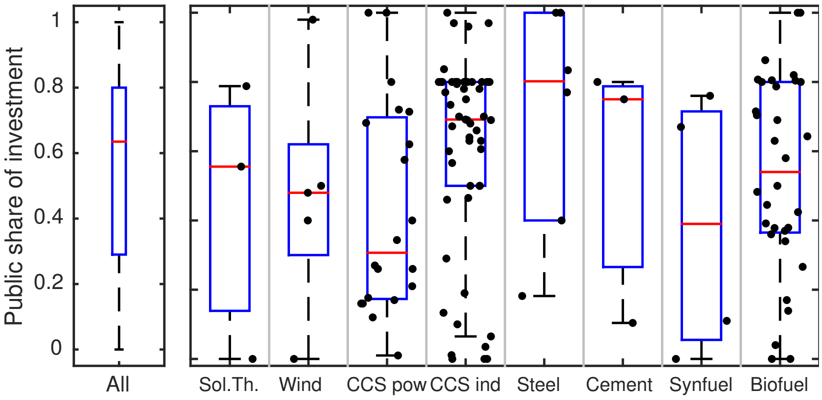

Figure 3: Contributions of public sector to demonstration projects included in analysis. Boxes represent 25–75th percentile ranges, red line is median, and dashed lines indicate full range.

4 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, we also estimated the determinants of the public sector share of public funding using fractional logit models. We do not find any significant results, although the budget coefficient is negative and slightly significant at the ten percent level in two out of seven estimations. We note that we have 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. We include these results in the SI.

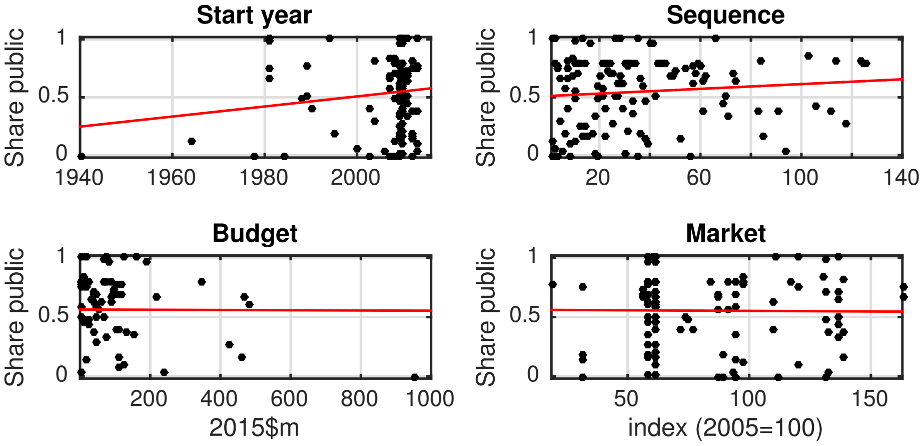

Figure 4: Contributions of private sector to demonstration projects included in analysis. Horizontal axes show: year project began, nth plant for each technology, total project budget, and price index for relevant market

4.4 Upscaling

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 (Figure 5). We selected these nine technology areas in part 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. We know 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 for which we have comprehensive data over 65 years, nuclear fission power plants (Figure 6). 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 at > 1MW using technology from the aerospace industry (Gipe, 1995). Yet, these approaches failed compared

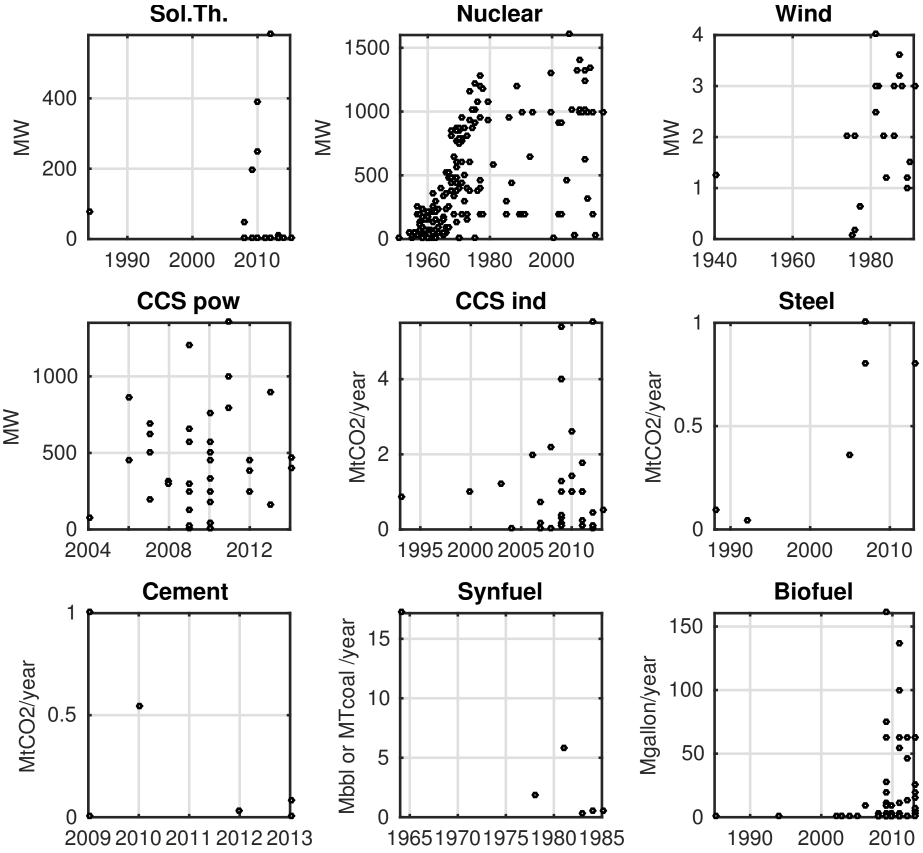

Figure 5: Scale of demonstration projects by project start year.

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).

4.5 Performance

We were unsuccessful in obtaining performance data for anything close to a representative sample of the projects we coded. On one hand this means we cannot make claims about performance data. On the other hand, that we made a reasonable attempt and failed, could be due to the lack of performance data that has been made publicly available. It is striking how little is available. As an

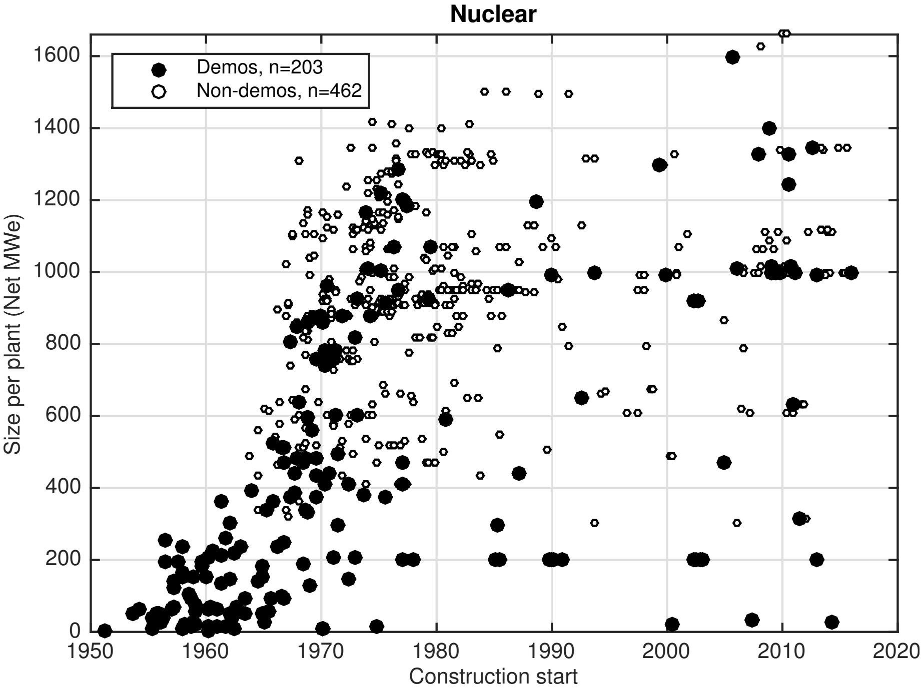

Figure 6: Nuclear power plants: scale of demonstration projects compared to commercial plants (non-demos). Demonstrations defined as: 1) first of a kind reactor type by supplier, 2) built at < 50% of minimum commercial scale (500MW), or 3) operating for < 25% of 60 year life.

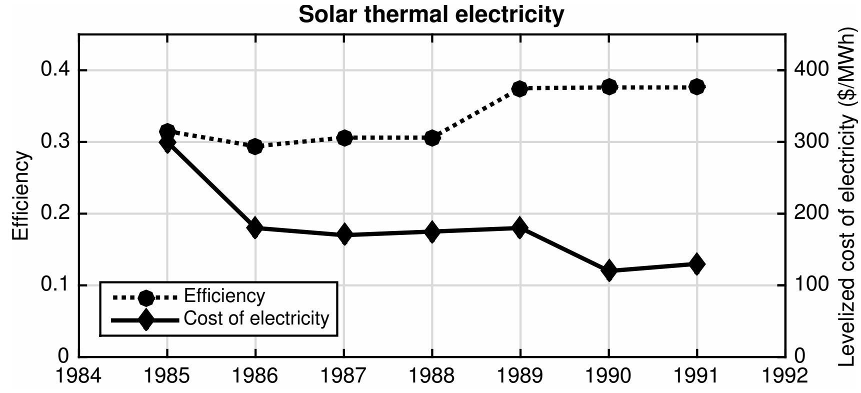

Figure 7: Performance of solar thermal electricity demonstration projects.

exception, we show the results from the first solar thermal electricity plants in California in the 1980s (Figure 7). These results show impressive cost reductions over sequential plants, including scale-up. Perhaps even more relevant to this paper is that we are only able to observe this improvement 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 we have reviewed, this post-project assessment represents the gold standard for knowledge codification and dissemination for demonstration plants.

4.6 Markets and expectations

To assess the markets in which these demonstration projects were ultimately to compete, we create price indices for each of the markets in which each of these 9 technologies competes (Figure 8). Prices are in real dollars and indexed so that 2005=100. In addition, we add a Hotelling curve 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). This descriptive comparison supports what is clear from the literature (Krautkraemer, 1998; Zaklan et al.,

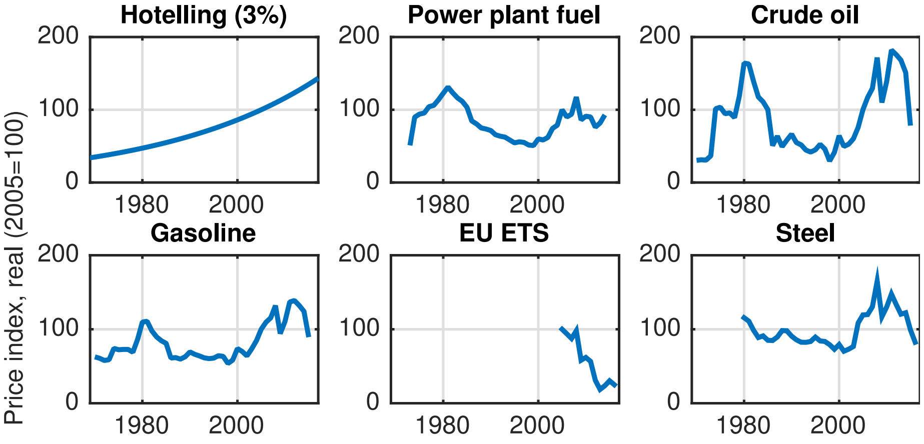

Figure 8: Price indices for markets relevant to each technology

2011), that price paths following Hotelling are the exceptions rather than the rule. It is important to consider that Hotelling is not merely an academic construct, it shapes expectations about future prices in a variety of contexts. Our data suggests that relying on a Hotelling path for future payoffs is a risky bet.

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. We see this clearly in synfuels (Figure 9), in which projects came on-line just as the market was disappearing. We see similar outcomes 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.

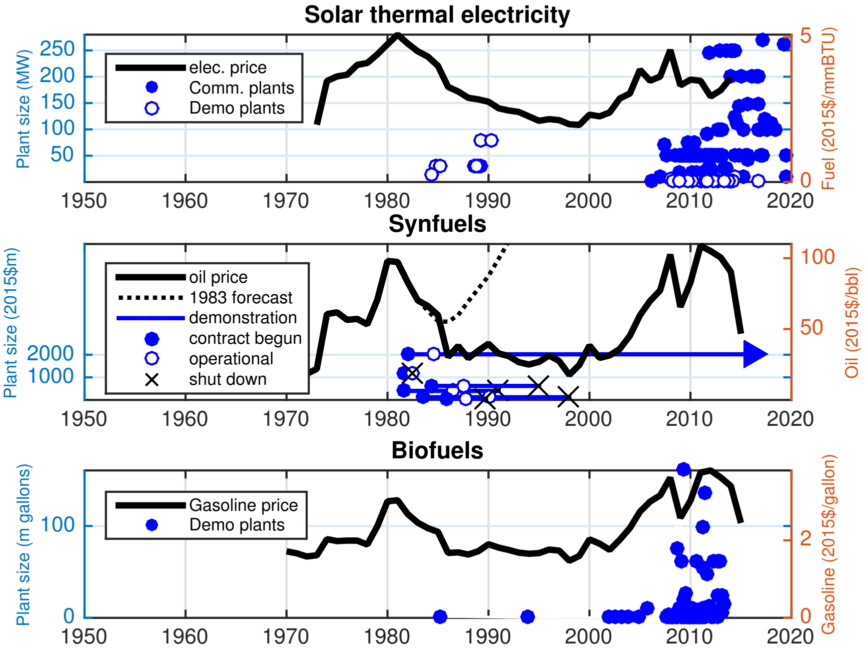

Figure 9: Markets for demonstration projects: solar thermal electric, synthetic fuels, and cellulosic biofuels.

CCS projects show a similar pattern; projects have come on-line just as the EU ETS price has crashed (Figure 10). Taking a more future oriented perspective, we also plot expectations of future carbon prices in 2030 (Usher and Strachan, 2013; Kalkuhl et al., 2016). We see expectations of higher prices than currently, but also wide dispersion implying 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.

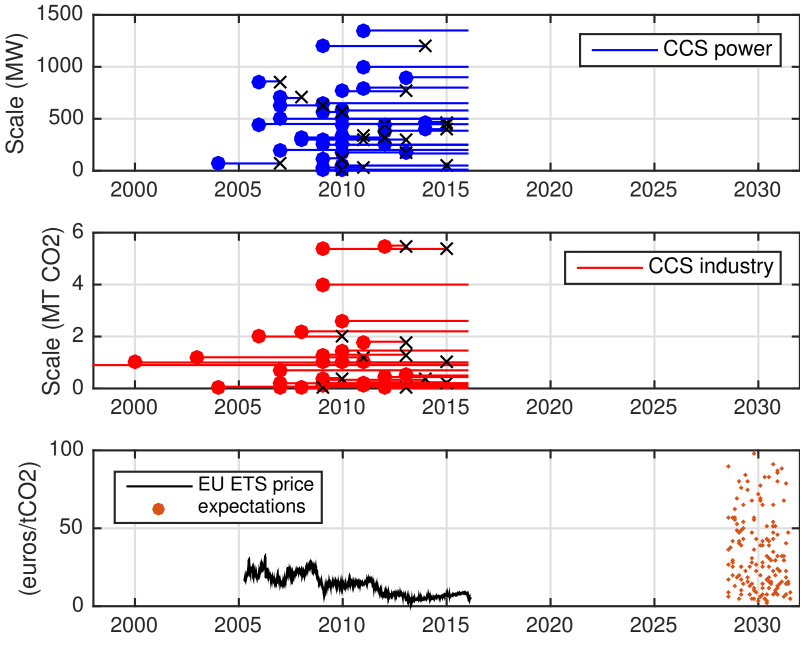

Figure 10: Markets for demonstration projects in CCS.

5 Discussion and conclusion

Looking at a a broad set of previous demonstration projects provides insights for how to make the most out of future government support for demonstrations.

5.1 Prioritizing learning and tolerating failures

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). Consequently, appropriate metrics for project selection or continuation are unlikely to be in terms of performance or cost per performance, which was a problem in NER300, a previous CCS demonstration solicitation (Lupion and Herzog, 2013). Rather goals should focus on maximizing learning or minimizing cost per learning. Production and costs are useful indicators of progress but are not worthy goals on their own, as they can often be achieved by avoiding risk and minimizing technical diversity, both of which inhibit learning.

Milestone payments provide help in this direction. To be sure, they raise the importance of defining meaningful milestones. If milestones were to be based on knowledge created, that would certainly be a promising direction.

Historically, many demonstration programs have been motivated by a larger social goal, which results in government goals that are much more production oriented, e.g. 20m gallons of biofuels, 2m bpd of synfuels, or 100 nuclear reactors. 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. Our review of past projects identified a wide range of motivations. More exemplar oriented items like "production" and "proving" were found at about the same rate as more learning oriented ones such as "up-scaling" and "learning." There was no significant trend over time in the occurrence of each motivation (Figure 11).

In short, demonstrations are best seen as experiments (Lefevre, 1984), part of a process of continuous experimentation (Hellsmark, 2010). Risk and failure are crucial to learning (Anadon et al., 2016). This set of activities is not the place for governments to be risk averse. Rather, we need to make mistakes not just to improve chances of hits, but also to learn from what did not work (Grubler and Wilson, 2014). Only 60% of the projects for which we could obtain motivation information 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.

5.2 Iterative upscaling and supporting diversity

Given learning as a prime objective, the programs of the past make clear that there are benefits to sequential iteration to enhance learning. Previous work has shown that a sequence of technical, organizational and market demo is needed (Bossink, 2015). Further, demonstration plants are tools for upscaling (Frishammar et al., 2015), which takes time, and requires passing 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). In contrast, our data show achieving full commercial scale took considerable time (Figure 5). For example, one can clearly see two decades of demonstrations and upscaling in nuclear (Figure 6). 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.

The strong effects of scale economies for these technologies also 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).

5.3 Engaging the private sector

The presence of knowledge spillovers mean public funding is needed (Foxon, 2010), but we also need private participation (Macey and Brown, 1990). Experiential learning, in which knowledge is created by participants, mean that the private sector must play an active role (Hendry et al., 2010). Coalitions of supportive private actors can create advocacy coalitions that support further efforts at commercialization (Klitkou et al., 2013), although the warning of the technology pork barrel is that they can go too far, and even crowd out earlier stage technologies (Lupion and Herzog, 2013). A central aspect of managing this intersection involves sharing risk (and rewards) between public and private

(Baer et al., 1976; Markusson et al., 2011). We found a very heterogenous mix of public-private contributions (Figure 3).

5.4 Disseminating knowledge

A 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). That was crucial for solar thermal electricity (Figure 7). Notably, those plants were completely privately funded. The public role was on markets, guaranteeing prices as well as funding R&D to go back and review progress. Reiner (2016) mentions that the UK CCS plants benefitted from access to the engineering plans for plants not built. All of this means that R&D is needed post- and during the demo phase, in part to support knowledge codification, analysis, etc. but also to work on new problems that building at larger scales reveal. It also implies that 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.

5.5 Robust demand pull

Because the ultimate (but not immediate) goal of supporting demonstrations is to facilitate widespread adoption, demand and thus markets are of course key (Kingsley et al., 1996). In climate change, policies are central to those markets (Taylor et al., 2003; Zhou et al., 2015), thus credibility in those policies is also central (Rai et al., 2010; Finon, 2012). But it is striking how many demonstration programs confronted markets that involved negative shocks around the time that projects came on-line—we see it in synfuels, biofuels, and solar thermal electricity (Figure 9), and CCS (Figure 10). The 1.9 year average lag from project initiation to time on-line is crucial. It would be a mistake to assume a Hotelling price path in which prices of an exhaustible resource (e.g. oil, atmospheric storage of CO_2) rise at a constant pure rate of time preference. In this case the relevant price is the level at which avoided CO_2 emissions are remunerated. Rather the experience of the past suggests we are more likely to see shocks and boom–bust cycles (Krautkraemer, 1998; Zaklan et al., 2011). We see it in our data in the prices related to each demonstration program (Figure 8). Lupion and Herzog (2013) attribute the failure of the NER300 program to stimulate the construction of any CCS projects to 4 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. Features of robust demand pull include niche markets (Kemp et al., 1998), hedging across jurisdictions (Nemet, 2010), and flexible production (Sanchez and Kammen, 2016). Government price guarantees have played an important role as we have seen on synfuels, solar thermal electricity, and on a smaller scale, photovoltaics.

5.6 Towards a demonstration strategy

Our assessment is that these five items explained above are important policy design elements to include as several countries consider how to support innovation for large scale decarbonization. We also acknowledge that policy makers would benefit from resolving uncertainty in a few additional areas.

Foremost, two very specific questions need answers: 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. For all projects in our data set, the median cost is \$64m and the 10-90% range is \$5million to \$2.4 billion. 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 \$200m 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., 2007).

Coming back to the original technology pork barrel argument (Cohen and Noll, 1991), 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 (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)

In short, 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.

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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%

Table 2: Timing of demonstration projects.

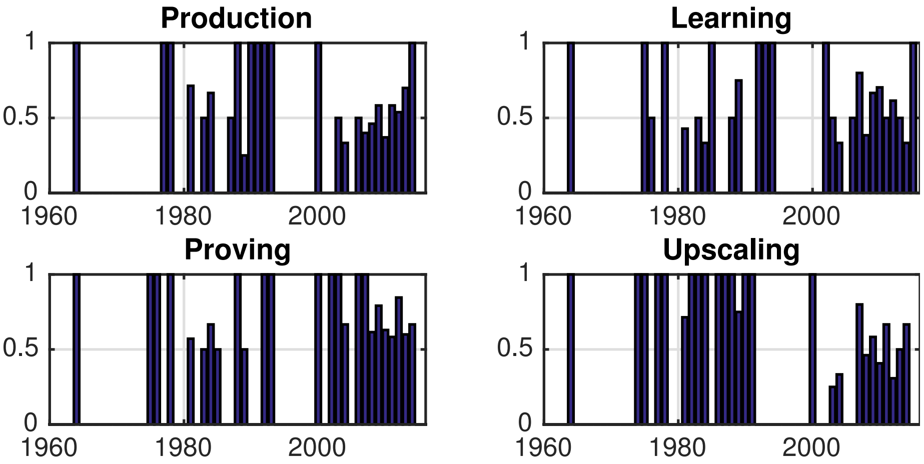


Figure 11: Motivations of demonstration projects included in analysis. Share of projects stating each motivation by year.

A Supporting Information Document

A.1 Timing of demonstration projects

We show averages across projects for indicators of timing in Table 2.

A.2 Motivations for demonstration projects

We show motivations over time in Figure 11.

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, we use a fractional logit estimation. 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 Figure 12 shows.

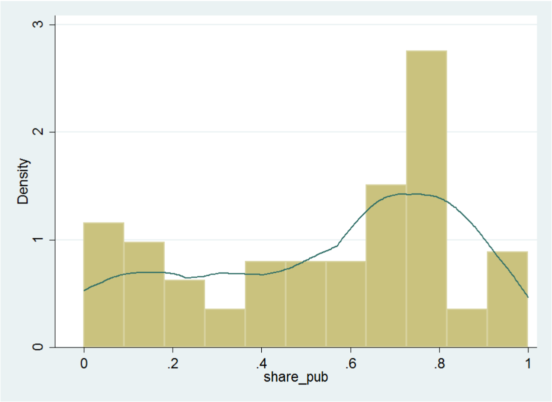


Figure 12: Histogram with kernel density of public share

Using the glm command in Stata (Baum, 2008), we specify dummies for each technologies and the budget in USD 2015 as our baseline explanatory variables. In subsequent estimations we add 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 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 3, with the baseline specification in column 2. We do not find any significant results, 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.

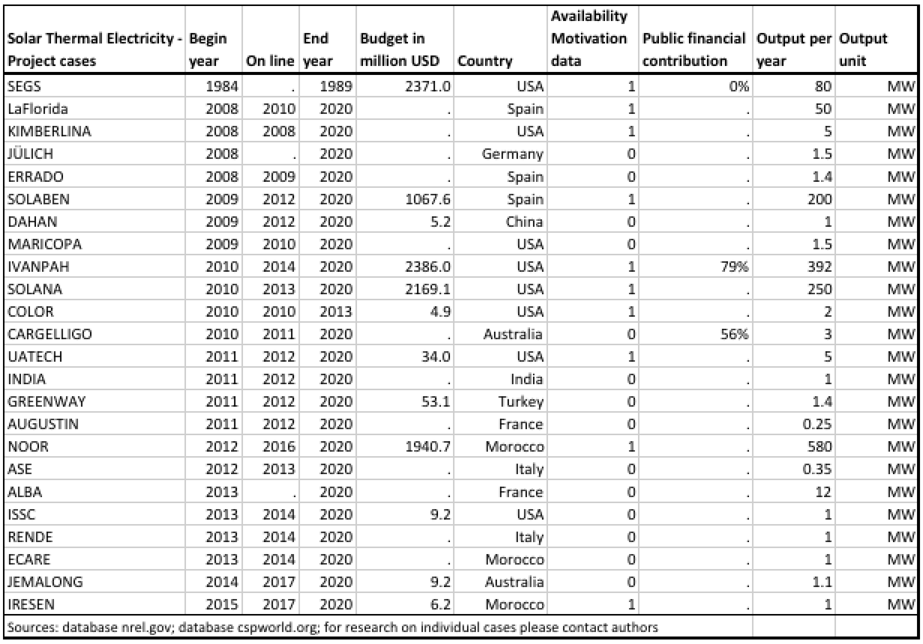
Table 3: Fractional logit estimation for public funding share

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 (-0.77)	-0.32 (-1.17)	-110.1 (-86.22)	-101.1 (-86.17)	-0.32 (-1.17)	-1.12 (-1.48)	-0.35 (-1.17)
D Wind power	-0.11 (-0.56)	0.64 (-0.59)	-108.5 (-85.67)	-108.4 (-85.62)	1.004 (-0.7)	-0.1 (-0.83)	0.61 (-0.6)
D CCS energy	-0.27 (-0.27)	-0.15 (-0.28)	-110.6 (-86.63)	-110.5 (-86.59)	0.15 (-0.32)	-0.65 (-0.57)	-0.26 (-0.31)
D CCS industry	0.43*** (-0.16)	0.46*** (-0.17)	-109.9 (-86.62)	-109.9 (-86.57)	0.6*** (-0.16)	0.12 (-0.5)	0.22 (-0.38)
D Steel	0.84 (-0.59)	0.74 (-0.66)	-109.2 (-86.26)	-109.1 (-86.21)	0.75 (-0.67)	-0.066 (-1.02)	0.69 (-0.66)
D Cement	0.21 (-0.74)	0.23 (-0.75)	-110.3 (-86.71)	-110.3 (-86.67)	0.23 (-0.75)	-0.72 (-1.22)	0.21 (-0.76)
D Synfuels	-0.47 (-0.71)	-0.19 (-0.79)	-108.8 (-85.15)	-108.7 (-85.11)	0.21 (-0.74)	-0.91 (-1.45)	-0.23 (-0.78)
D Biofuels	0.14 (-0.2)	0.19 (-0.22)	-110.2 (-86.7)	-110.2 (-86.65)	0.29 (-0.24)	-0.75 (-1.01)	0.065 (-0.28)
Budget		-0.000046 (0)	-0.000047 (0)	-0.000047 (0)	-0.000048* (0)	-0.00005* (0)	-0.00004 (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 * $p<0.10$, ** $p<0.05$, *** $p<0.01$

A.4 Project Characteristics

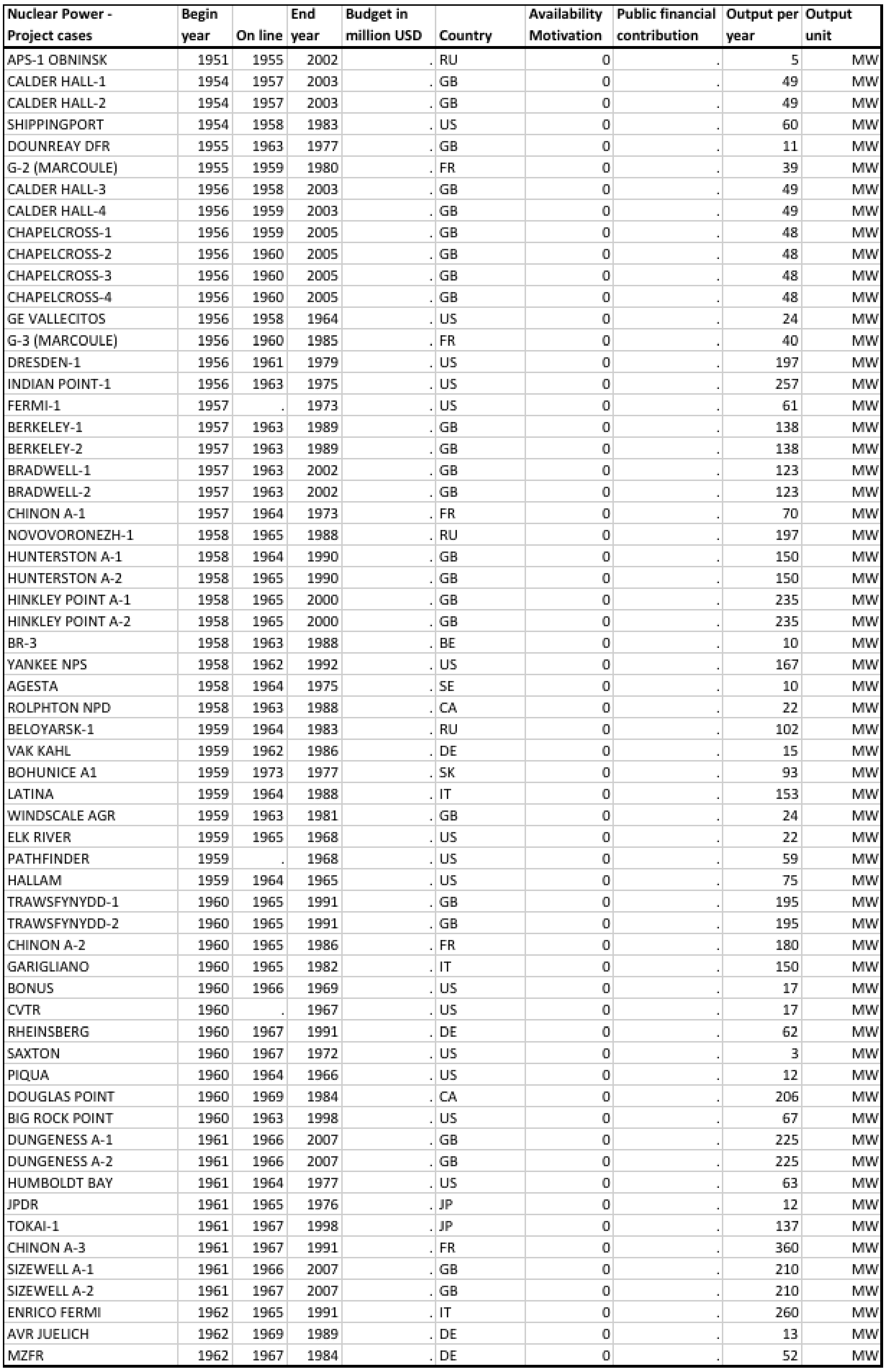
We include basic characteristics in tables of demonstration projects for electricity sector technologies: solar thermal electricity (Table 13), nuclear power (Tables 14, 15, 16, and 17), wind power (Table 18), and CCS for power plants (Table 19). Industrial sectors are shown for industrial CCS (Table 20), steel (Table 21), and cement (Table 22). Liquid fuels are shown for synthetic fuels (Tables 23) and cellulosic biofuels (Tables 24 and 25).



Solar Thermal Electricity - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
SEGS	1984	.	1989	2371.0	USA	1	0%	80	MW
LaFlorida	2008	2010	2020	.	Spain	1	.	50	MW
KIMBERLINA	2008	2008	2020	.	USA	1	.	5	MW
JÜLICH	2008	.	2020	.	Germany	0	.	1.5	MW
ERRADO	2008	2009	2020	.	Spain	0	.	1.4	MW
SOLABEN	2009	2012	2020	1067.6	Spain	1	.	200	MW
DAHAN	2009	2012	2020	5.2	China	0	.	1	MW
MARICOPA	2009	2010	2020	.	USA	0	.	1.5	MW
IVANPAH	2010	2014	2020	2386.0	USA	1	79%	392	MW
SOLANA	2010	2013	2020	2169.1	USA	1	.	250	MW
COLOR	2010	2010	2013	4.9	USA	1	.	2	MW
CARGELLIGO	2010	2011	2020	.	Australia	0	56%	3	MW
UATECH	2011	2012	2020	34.0	USA	1	.	5	MW
INDIA	2011	2012	2020	.	India	0	.	1	MW
GREENWAY	2011	2012	2020	53.1	Turkey	0	.	1.4	MW
AUGUSTIN	2011	2012	2020	.	France	0	.	0.25	MW
NOOR	2012	2016	2020	1940.7	Morocco	1	.	580	MW
ASE	2012	2013	2020	.	Italy	0	.	0.35	MW
ALBA	2013	.	2020	.	France	0	.	12	MW
ISSC	2013	2014	2020	9.2	USA	0	.	1	MW
RENDE	2013	2014	2020	.	Italy	0	.	1	MW
ECARE	2013	2014	2020	.	Morocco	0	.	1	MW
JEMALONG	2014	2017	2020	9.2	Australia	0	.	1.1	MW
IRESEN	2015	2017	2020	6.2	Morocco	1	.	1	MW

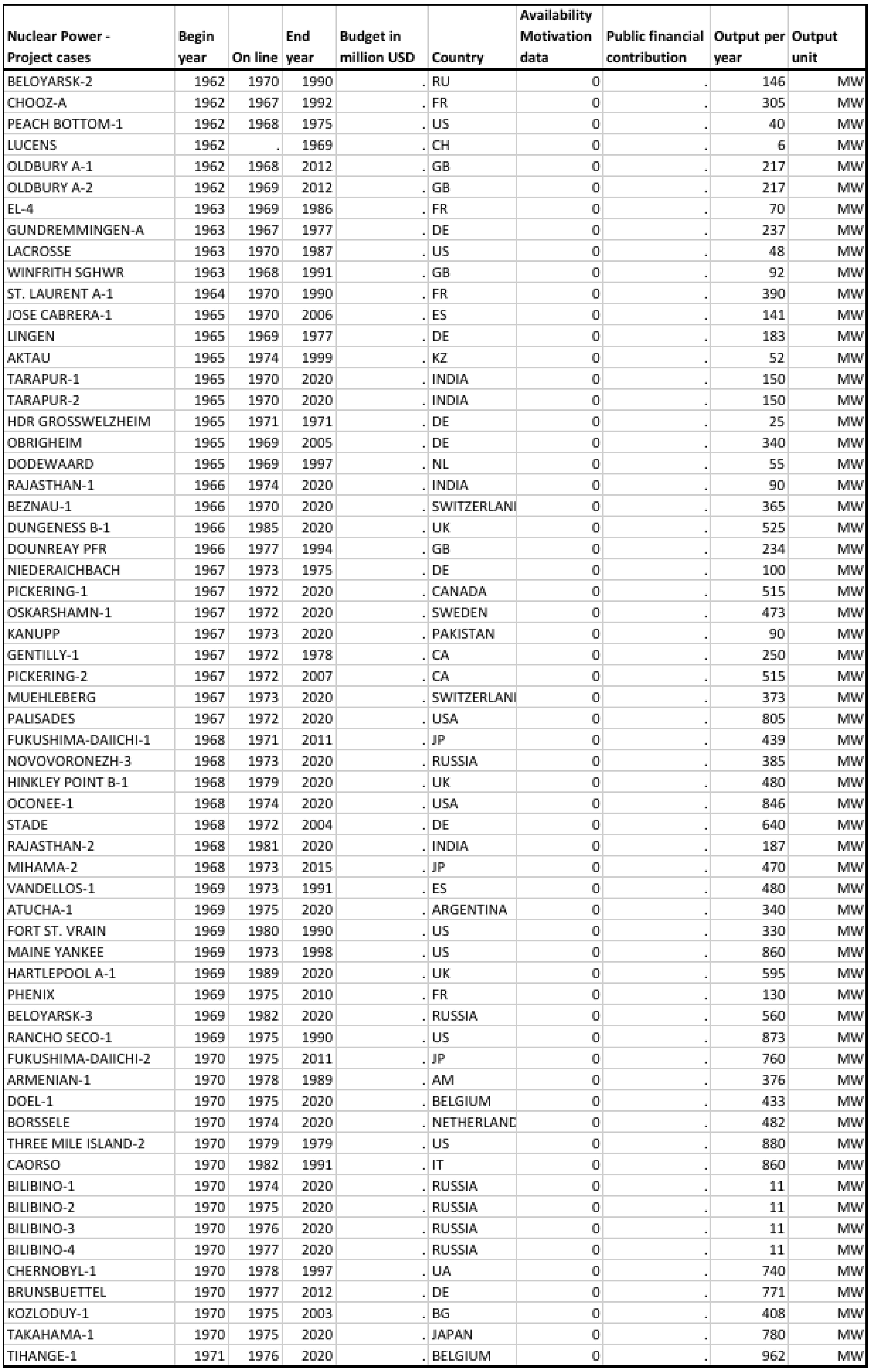
Sources: database nrel.gov; database cspworld.org; for research on individual cases please contact authors

Figure 13: Demonstration projects: 1. Solar Thermal Electricity



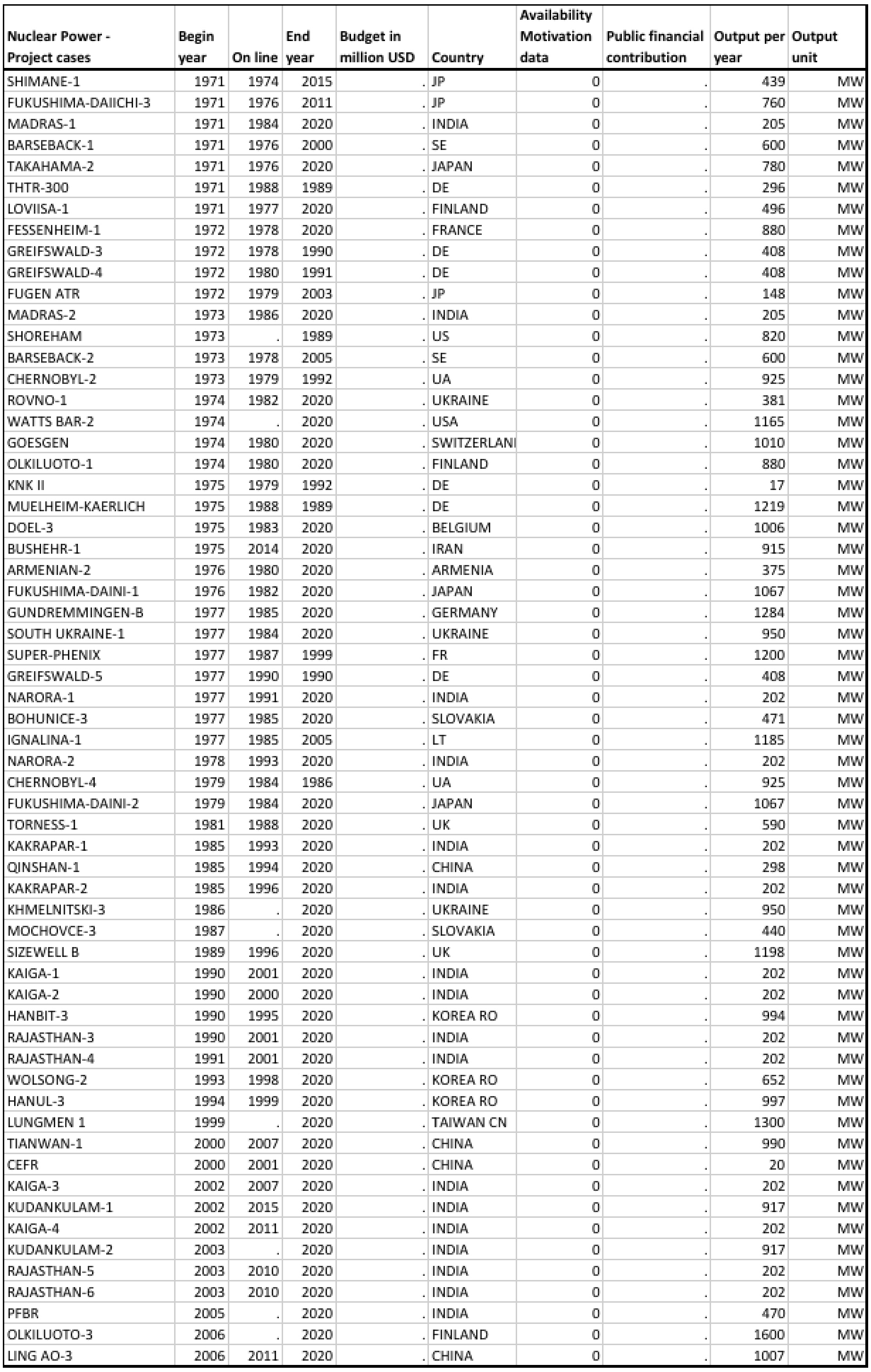
Nuclear Power - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation	Public financial contribution	Output per year	Output unit
APS-1 OBNINSK	1951	1955	2002	.	RU	0	.	5	MW
CALDER HALL-1	1954	1957	2003	.	GB	0	.	49	MW
CALDER HALL-2	1954	1957	2003	.	GB	0	.	49	MW
SHIPPINGPORT	1954	1958	1983	.	US	0	.	60	MW
DOUNREAY DFR	1955	1963	1977	.	GB	0	.	11	MW
G-2 (MARCOULE)	1955	1959	1980	.	FR	0	.	39	MW
CALDER HALL-3	1956	1958	2003	.	GB	0	.	49	MW
CALDER HALL-4	1956	1959	2003	.	GB	0	.	49	MW
CHAPELCROSS-1	1956	1959	2005	.	GB	0	.	48	MW
CHAPELCROSS-2	1956	1960	2005	.	GB	0	.	48	MW
CHAPELCROSS-3	1956	1960	2005	.	GB	0	.	48	MW
CHAPELCROSS-4	1956	1960	2005	.	GB	0	.	48	MW
GE VALLECITOS	1956	1958	1964	.	US	0	.	24	MW
G-3 (MARCOULE)	1956	1960	1985	.	FR	0	.	40	MW
DRESDEN-1	1956	1961	1979	.	US	0	.	197	MW
INDIAN POINT-1	1956	1963	1975	.	US	0	.	257	MW
FERMI-1	1957	.	1973	.	US	0	.	61	MW
BERKELEY-1	1957	1963	1989	.	GB	0	.	138	MW
BERKELEY-2	1957	1963	1989	.	GB	0	.	138	MW
BRADWELL-1	1957	1963	2002	.	GB	0	.	123	MW
BRADWELL-2	1957	1963	2002	.	GB	0	.	123	MW
CHINON A-1	1957	1964	1973	.	FR	0	.	70	MW
NOVOVORONEZH-1	1958	1965	1988	.	RU	0	.	197	MW
HUNTERSTON A-1	1958	1964	1990	.	GB	0	.	150	MW
HUNTERSTON A-2	1958	1965	1990	.	GB	0	.	150	MW
HINKLEY POINT A-1	1958	1965	2000	.	GB	0	.	235	MW
HINKLEY POINT A-2	1958	1965	2000	.	GB	0	.	235	MW
BR-3	1958	1963	1988	.	BE	0	.	10	MW
YANKEE NPS	1958	1962	1992	.	US	0	.	167	MW
AGESTA	1958	1964	1975	.	SE	0	.	10	MW
ROLPHTON NPD	1958	1963	1988	.	CA	0	.	22	MW
BELOYARSK-1	1959	1964	1983	.	RU	0	.	102	MW
VAK KAHL	1959	1962	1986	.	DE	0	.	15	MW
BOHUNICE A1	1959	1973	1977	.	SK	0	.	93	MW
LATINA	1959	1964	1988	.	IT	0	.	153	MW
WINDSCALE AGR	1959	1963	1981	.	GB	0	.	24	MW
ELK RIVER	1959	1965	1968	.	US	0	.	22	MW
PATHFINDER	1959	.	1968	.	US	0	.	59	MW
HALLAM	1959	1964	1965	.	US	0	.	75	MW
TRAWSFYNYDD-1	1960	1965	1991	.	GB	0	.	195	MW
TRAWSFYNYDD-2	1960	1965	1991	.	GB	0	.	195	MW
CHINON A-2	1960	1965	1986	.	FR	0	.	180	MW
GARIGLIANO	1960	1965	1982	.	IT	0	.	150	MW
BONUS	1960	1966	1969	.	US	0	.	17	MW
CVTR	1960	.	1967	.	US	0	.	17	MW
RHEINSBERG	1960	1967	1991	.	DE	0	.	62	MW
SAXTON	1960	1967	1972	.	US	0	.	3	MW
PIQUA	1960	1964	1966	.	US	0	.	12	MW
DOUGLAS POINT	1960	1969	1984	.	CA	0	.	206	MW
BIG ROCK POINT	1960	1963	1998	.	US	0	.	67	MW
DUNGENESS A-1	1961	1966	2007	.	GB	0	.	225	MW
DUNGENESS A-2	1961	1966	2007	.	GB	0	.	225	MW
HUMBOLDT BAY	1961	1964	1977	.	US	0	.	63	MW
JPDR	1961	1965	1976	.	JP	0	.	12	MW
TOKAI-1	1961	1967	1998	.	JP	0	.	137	MW
CHINON A-3	1961	1967	1991	.	FR	0	.	360	MW
SIZEWELL A-1	1961	1966	2007	.	GB	0	.	210	MW
SIZEWELL A-2	1961	1967	2007	.	GB	0	.	210	MW
ENRICO FERMI	1962	1965	1991	.	IT	0	.	260	MW
AVR JUELICH	1962	1969	1989	.	DE	0	.	13	MW
MZFR	1962	1967	1984	.	DE	0	.	52	MW

Figure 14: Demonstration projects: 2. Nuclear power, part 1.



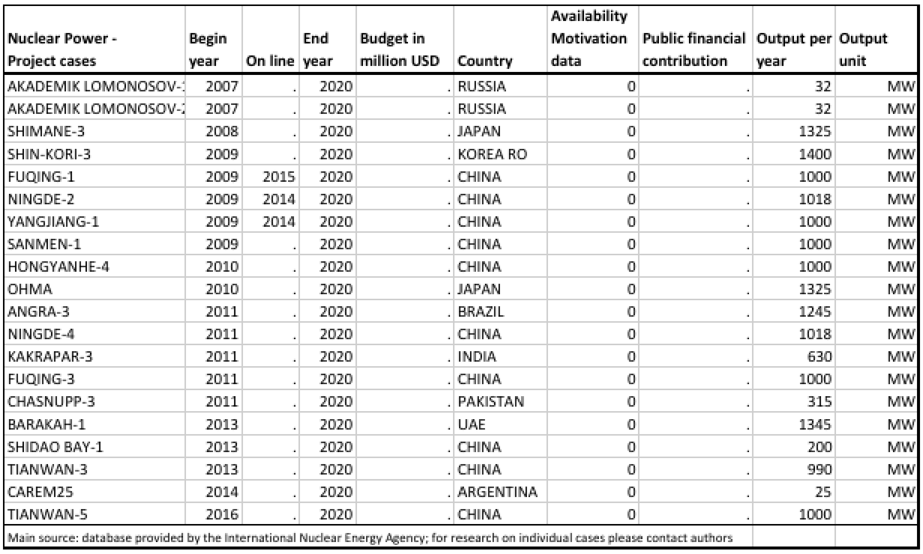
Nuclear Power - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
BELOYARSK-2	1962	1970	1990	.	RU	0	.	146	MW
CHOOZ-A	1962	1967	1992	.	FR	0	.	305	MW
PEACH BOTTOM-1	1962	1968	1975	.	US	0	.	40	MW
LUCENS	1962	.	1969	.	CH	0	.	6	MW
OLDBURY A-1	1962	1968	2012	.	GB	0	.	217	MW
OLDBURY A-2	1962	1969	2012	.	GB	0	.	217	MW
EL-4	1963	1969	1986	.	FR	0	.	70	MW
GUNDREMMINGEN-A	1963	1967	1977	.	DE	0	.	237	MW
LACROSSE	1963	1970	1987	.	US	0	.	48	MW
WINFRITH SGHWR	1963	1968	1991	.	GB	0	.	92	MW
ST. LAURENT A-1	1964	1970	1990	.	FR	0	.	390	MW
JOSE CABRERA-1	1965	1970	2006	.	ES	0	.	141	MW
LINGEN	1965	1969	1977	.	DE	0	.	183	MW
AKTAU	1965	1974	1999	.	KZ	0	.	52	MW
TARAPUR-1	1965	1970	2020	.	INDIA	0	.	150	MW
TARAPUR-2	1965	1970	2020	.	INDIA	0	.	150	MW
HDR GROSSWELZHEIM	1965	1971	1971	.	DE	0	.	25	MW
OBRIGHEIM	1965	1969	2005	.	DE	0	.	340	MW
DODEWAARD	1965	1969	1997	.	NL	0	.	55	MW
RAJASTHAN-1	1966	1974	2020	.	INDIA	0	.	90	MW
BEZNAU-1	1966	1970	2020	.	SWITZERLANI	0	.	365	MW
DUNGENESS B-1	1966	1985	2020	.	UK	0	.	525	MW
DOUNREAY PFR	1966	1977	1994	.	GB	0	.	234	MW
NIEDERAICHBACH	1967	1973	1975	.	DE	0	.	100	MW
PICKERING-1	1967	1972	2020	.	CANADA	0	.	515	MW
OSKARSHAMN-1	1967	1972	2020	.	SWEDEN	0	.	473	MW
KANUPP	1967	1973	2020	.	PAKISTAN	0	.	90	MW
GENTILLY-1	1967	1972	1978	.	CA	0	.	250	MW
PICKERING-2	1967	1972	2007	.	CA	0	.	515	MW
MUEHLEBERG	1967	1973	2020	.	SWITZERLANI	0	.	373	MW
PALISADES	1967	1972	2020	.	USA	0	.	805	MW
FUKUSHIMA-DAIICHI-1	1968	1971	2011	.	JP	0	.	439	MW
NOVOVORONEZH-3	1968	1973	2020	.	RUSSIA	0	.	385	MW
HINKLEY POINT B-1	1968	1979	2020	.	UK	0	.	480	MW
OCONEE-1	1968	1974	2020	.	USA	0	.	846	MW
STADE	1968	1972	2004	.	DE	0	.	640	MW
RAJASTHAN-2	1968	1981	2020	.	INDIA	0	.	187	MW
MIHAMA-2	1968	1973	2015	.	JP	0	.	470	MW
VANDELLOS-1	1969	1973	1991	.	ES	0	.	480	MW
ATUCHA-1	1969	1975	2020	.	ARGENTINA	0	.	340	MW
FORT ST. VRAIN	1969	1980	1990	.	US	0	.	330	MW
MAINE YANKEE	1969	1973	1998	.	US	0	.	860	MW
HARTLEPOOL A-1	1969	1989	2020	.	UK	0	.	595	MW
PHENIX	1969	1975	2010	.	FR	0	.	130	MW
BELOYARSK-3	1969	1982	2020	.	RUSSIA	0	.	560	MW
RANCHO SECO-1	1969	1975	1990	.	US	0	.	873	MW
FUKUSHIMA-DAIICHI-2	1970	1975	2011	.	JP	0	.	760	MW
ARMENIAN-1	1970	1978	1989	.	AM	0	.	376	MW
DOEL-1	1970	1975	2020	.	BELGIUM	0	.	433	MW
BORSSELE	1970	1974	2020	.	NETHERLANC	0	.	482	MW
THREE MILE ISLAND-2	1970	1979	1979	.	US	0	.	880	MW
CAORSO	1970	1982	1991	.	IT	0	.	860	MW
BILIBINO-1	1970	1974	2020	.	RUSSIA	0	.	11	MW
BILIBINO-2	1970	1975	2020	.	RUSSIA	0	.	11	MW
BILIBINO-3	1970	1976	2020	.	RUSSIA	0	.	11	MW
BILIBINO-4	1970	1977	2020	.	RUSSIA	0	.	11	MW
CHERNOBYL-1	1970	1978	1997	.	UA	0	.	740	MW
BRUNSBUETTEL	1970	1977	2012	.	DE	0	.	771	MW
KOZLODUY-1	1970	1975	2003	.	BG	0	.	408	MW
TAKAHAMA-1	1970	1975	2020	.	JAPAN	0	.	780	MW
TIHANGE-1	1971	1976	2020	.	BELGIUM	0	.	962	MW

Figure 15: Demonstration projects: 2. Nuclear power, part 2.



Nuclear Power - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
SHIMANE-1	1971	1974	2015	.	JP	0	.	439	MW
FUKUSHIMA-DAIICHI-3	1971	1976	2011	.	JP	0	.	760	MW
MADRAS-1	1971	1984	2020	.	INDIA	0	.	205	MW
BARSEBACK-1	1971	1976	2000	.	SE	0	.	600	MW
TAKAHAMA-2	1971	1976	2020	.	JAPAN	0	.	780	MW
THTR-300	1971	1988	1989	.	DE	0	.	296	MW
LOVIISA-1	1971	1977	2020	.	FINLAND	0	.	496	MW
FESSENHEIM-1	1972	1978	2020	.	FRANCE	0	.	880	MW
GREIFSWALD-3	1972	1978	1990	.	DE	0	.	408	MW
GREIFSWALD-4	1972	1980	1991	.	DE	0	.	408	MW
FUGEN ATR	1972	1979	2003	.	JP	0	.	148	MW
MADRAS-2	1973	1986	2020	.	INDIA	0	.	205	MW
SHOREHAM	1973	.	1989	.	US	0	.	820	MW
BARSEBACK-2	1973	1978	2005	.	SE	0	.	600	MW
CHERNOBYL-2	1973	1979	1992	.	UA	0	.	925	MW
ROVNO-1	1974	1982	2020	.	UKRAINE	0	.	381	MW
WATTS BAR-2	1974	.	2020	.	USA	0	.	1165	MW
GOESGEN	1974	1980	2020	.	SWITZERLANI	0	.	1010	MW
OLKILUOTO-1	1974	1980	2020	.	FINLAND	0	.	880	MW
KNK II	1975	1979	1992	.	DE	0	.	17	MW
MUELHEIM-KAERLICH	1975	1988	1989	.	DE	0	.	1219	MW
DOEL-3	1975	1983	2020	.	BELGIUM	0	.	1006	MW
BUSHEHR-1	1975	2014	2020	.	IRAN	0	.	915	MW
ARMENIAN-2	1976	1980	2020	.	ARMENIA	0	.	375	MW
FUKUSHIMA-DAINI-1	1976	1982	2020	.	JAPAN	0	.	1067	MW
GUNDREMMINGEN-B	1977	1985	2020	.	GERMANY	0	.	1284	MW
SOUTH UKRAINE-1	1977	1984	2020	.	UKRAINE	0	.	950	MW
SUPER-PHENIX	1977	1987	1999	.	FR	0	.	1200	MW
GREIFSWALD-5	1977	1990	1990	.	DE	0	.	408	MW
NARORA-1	1977	1991	2020	.	INDIA	0	.	202	MW
BOHUNICE-3	1977	1985	2020	.	SLOVAKIA	0	.	471	MW
IGNALINA-1	1977	1985	2005	.	LT	0	.	1185	MW
NARORA-2	1978	1993	2020	.	INDIA	0	.	202	MW
CHERNOBYL-4	1979	1984	1986	.	UA	0	.	925	MW
FUKUSHIMA-DAINI-2	1979	1984	2020	.	JAPAN	0	.	1067	MW
TORNESS-1	1981	1988	2020	.	UK	0	.	590	MW
KAKRAPAR-1	1985	1993	2020	.	INDIA	0	.	202	MW
QINSHAN-1	1985	1994	2020	.	CHINA	0	.	298	MW
KAKRAPAR-2	1985	1996	2020	.	INDIA	0	.	202	MW
KHMELNITSKI-3	1986	.	2020	.	UKRAINE	0	.	950	MW
MOCHOVCE-3	1987	.	2020	.	SLOVAKIA	0	.	440	MW
SIZEWELL B	1989	1996	2020	.	UK	0	.	1198	MW
KAIGA-1	1990	2001	2020	.	INDIA	0	.	202	MW
KAIGA-2	1990	2000	2020	.	INDIA	0	.	202	MW
HANBIT-3	1990	1995	2020	.	KOREA RO	0	.	994	MW
RAJASTHAN-3	1990	2001	2020	.	INDIA	0	.	202	MW
RAJASTHAN-4	1991	2001	2020	.	INDIA	0	.	202	MW
WOLSONG-2	1993	1998	2020	.	KOREA RO	0	.	652	MW
HANUL-3	1994	1999	2020	.	KOREA RO	0	.	997	MW
LUNGMEN 1	1999	.	2020	.	TAIWAN CN	0	.	1300	MW
TIANWAN-1	2000	2007	2020	.	CHINA	0	.	990	MW
CEFR	2000	2001	2020	.	CHINA	0	.	20	MW
KAIGA-3	2002	2007	2020	.	INDIA	0	.	202	MW
KUDANKULAM-1	2002	2015	2020	.	INDIA	0	.	917	MW
KAIGA-4	2002	2011	2020	.	INDIA	0	.	202	MW
KUDANKULAM-2	2003	.	2020	.	INDIA	0	.	917	MW
RAJASTHAN-5	2003	2010	2020	.	INDIA	0	.	202	MW
RAJASTHAN-6	2003	2010	2020	.	INDIA	0	.	202	MW
PFBR	2005	.	2020	.	INDIA	0	.	470	MW
OLKILUOTO-3	2006	.	2020	.	FINLAND	0	.	1600	MW
LING AO-3	2006	2011	2020	.	CHINA	0	.	1007	MW

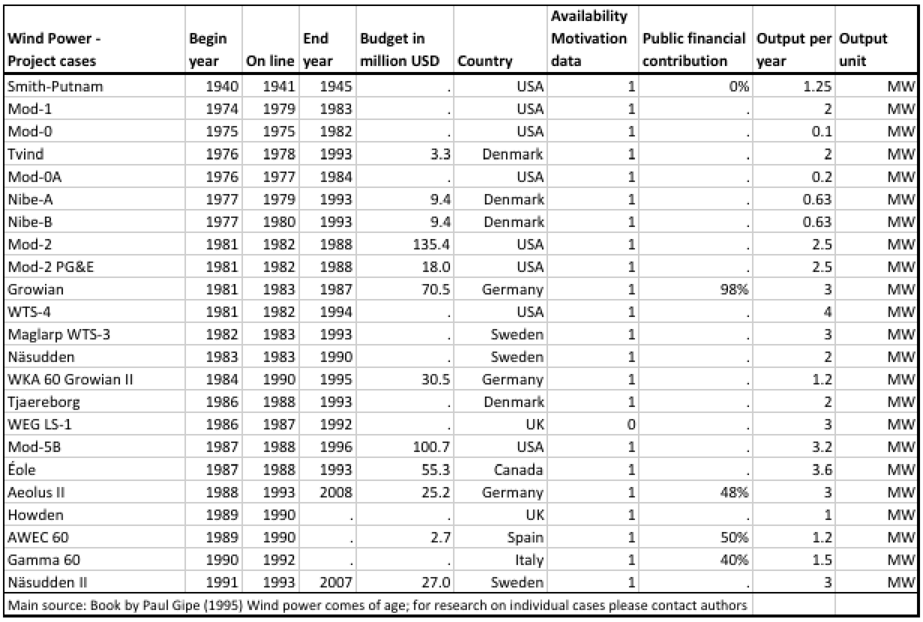
Figure 16: Demonstration projects: 2. Nuclear power, part 3.



Nuclear Power - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
AKADEMIK LOMONOSOV-	2007	.	2020	.	RUSSIA	0	.	32	MW
AKADEMIK LOMONOSOV-	2007	.	2020	.	RUSSIA	0	.	32	MW
SHIMANE-3	2008	.	2020	.	JAPAN	0	.	1325	MW
SHIN-KORI-3	2009	.	2020	.	KOREA RO	0	.	1400	MW
FUQING-1	2009	2015	2020	.	CHINA	0	.	1000	MW
NINGDE-2	2009	2014	2020	.	CHINA	0	.	1018	MW
YANGJIANG-1	2009	2014	2020	.	CHINA	0	.	1000	MW
SANMEN-1	2009	.	2020	.	CHINA	0	.	1000	MW
HONGYANHE-4	2010	.	2020	.	CHINA	0	.	1000	MW
OHMA	2010	.	2020	.	JAPAN	0	.	1325	MW
ANGRA-3	2011	.	2020	.	BRAZIL	0	.	1245	MW
NINGDE-4	2011	.	2020	.	CHINA	0	.	1018	MW
KAKRAPAR-3	2011	.	2020	.	INDIA	0	.	630	MW
FUQING-3	2011	.	2020	.	CHINA	0	.	1000	MW
CHASNUPP-3	2011	.	2020	.	PAKISTAN	0	.	315	MW
BARAKAH-1	2013	.	2020	.	UAE	0	.	1345	MW
SHIDAO BAY-1	2013	.	2020	.	CHINA	0	.	200	MW
TIANWAN-3	2013	.	2020	.	CHINA	0	.	990	MW
CAREM25	2014	.	2020	.	ARGENTINA	0	.	25	MW
TIANWAN-5	2016	.	2020	.	CHINA	0	.	1000	MW

Main source: database provided by the International Nuclear Energy Agency; for research on individual cases please contact authors

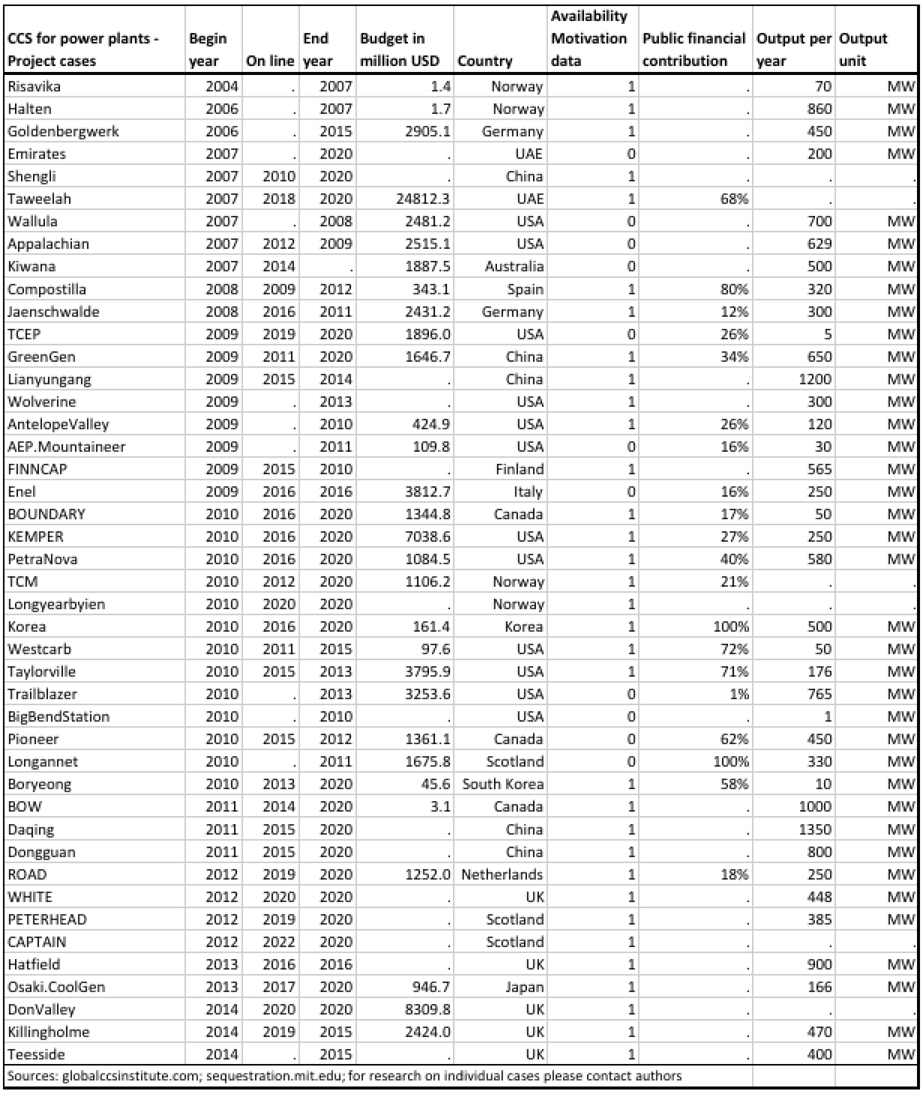
Figure 17: Demonstration projects: 2. Nuclear power, part 4.



Wind Power - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
Smith-Putnam	1940	1941	1945	.	USA	1	0%	1.25	MW
Mod-1	1974	1979	1983	.	USA	1	.	2	MW
Mod-0	1975	1975	1982	.	USA	1	.	0.1	MW
Tvind	1976	1978	1993	3.3	Denmark	1	.	2	MW
Mod-0A	1976	1977	1984	.	USA	1	.	0.2	MW
Nibe-A	1977	1979	1993	9.4	Denmark	1	.	0.63	MW
Nibe-B	1977	1980	1993	9.4	Denmark	1	.	0.63	MW
Mod-2	1981	1982	1988	135.4	USA	1	.	2.5	MW
Mod-2 PG&E	1981	1982	1988	18.0	USA	1	.	2.5	MW
Growian	1981	1983	1987	70.5	Germany	1	98%	3	MW
WTS-4	1981	1982	1994	.	USA	1	.	4	MW
Maglarp WTS-3	1982	1983	1993	.	Sweden	1	.	3	MW
Näsudden	1983	1983	1990	.	Sweden	1	.	2	MW
WKA 60 Growian II	1984	1990	1995	30.5	Germany	1	.	1.2	MW
Tjaereborg	1986	1988	1993	.	Denmark	1	.	2	MW
WEG LS-1	1986	1987	1992	.	UK	0	.	3	MW
Mod-5B	1987	1988	1996	100.7	USA	1	.	3.2	MW
Éole	1987	1988	1993	55.3	Canada	1	.	3.6	MW
Aeolus II	1988	1993	2008	25.2	Germany	1	48%	3	MW
Howden	1989	1990	.	.	UK	1	.	1	MW
AWEC 60	1989	1990	.	2.7	Spain	1	50%	1.2	MW
Gamma 60	1990	1992	.	.	Italy	1	40%	1.5	MW
Näsudden II	1991	1993	2007	27.0	Sweden	1	.	3	MW

Main source: Book by Paul Gipe (1995) Wind power comes of age; for research on individual cases please contact authors

Figure 18: Demonstration projects: 3. Wind power.



CCS for power plants - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
Risavika	2004	.	2007	1.4	Norway	1	.	70	MW
Halten	2006	.	2007	1.7	Norway	1	.	860	MW
Goldenbergwerk	2006	.	2015	2905.1	Germany	1	.	450	MW
Emirates	2007	.	2020	.	UAE	0	.	200	MW
Shengli	2007	2010	2020	.	China	1	.	.	.
Taweelah	2007	2018	2020	24812.3	UAE	1	68%	.	.
Wallula	2007	.	2008	2481.2	USA	0	.	700	MW
Appalachian	2007	2012	2009	2515.1	USA	0	.	629	MW
Kiwana	2007	2014	.	1887.5	Australia	0	.	500	MW
Compostilla	2008	2009	2012	343.1	Spain	1	80%	320	MW
Jaenschwalde	2008	2016	2011	2431.2	Germany	1	12%	300	MW
TCEP	2009	2019	2020	1896.0	USA	0	26%	5	MW
GreenGen	2009	2011	2020	1646.7	China	1	34%	650	MW
Lianyungang	2009	2015	2014	.	China	1	.	1200	MW
Wolverine	2009	.	2013	.	USA	1	.	300	MW
AntelopeValley	2009	.	2010	424.9	USA	1	26%	120	MW
AEP.Mountaineer	2009	.	2011	109.8	USA	0	16%	30	MW
FINNCAP	2009	2015	2010	.	Finland	1	.	565	MW
Enel	2009	2016	2016	3812.7	Italy	0	16%	250	MW
BOUNDARY	2010	2016	2020	1344.8	Canada	1	17%	50	MW
KEMPER	2010	2016	2020	7038.6	USA	1	27%	250	MW
PetraNova	2010	2016	2020	1084.5	USA	1	40%	580	MW
TCM	2010	2012	2020	1106.2	Norway	1	21%	.	.
Longyearbyien	2010	2020	2020	.	Norway	1	.	.	.
Korea	2010	2016	2020	161.4	Korea	1	100%	500	MW
Westcarb	2010	2011	2015	97.6	USA	1	72%	50	MW
Taylorville	2010	2015	2013	3795.9	USA	1	71%	176	MW
Trailblazer	2010	.	2013	3253.6	USA	0	1%	765	MW
BigBendStation	2010	.	2010	.	USA	0	.	1	MW
Pioneer	2010	2015	2012	1361.1	Canada	0	62%	450	MW
Longannet	2010	.	2011	1675.8	Scotland	0	100%	330	MW
Boryeong	2010	2013	2020	45.6	South Korea	1	58%	10	MW
BOW	2011	2014	2020	3.1	Canada	1	.	1000	MW
Daqing	2011	2015	2020	.	China	1	.	1350	MW
Dongguan	2011	2015	2020	.	China	1	.	800	MW
ROAD	2012	2019	2020	1252.0	Netherlands	1	18%	250	MW
WHITE	2012	2020	2020	.	UK	1	.	448	MW
PETERHEAD	2012	2019	2020	.	Scotland	1	.	385	MW
CAPTAIN	2012	2022	2020	.	Scotland	1	.	.	.
Hatfield	2013	2016	2016	.	UK	1	.	900	MW
Osaki.CoolGen	2013	2017	2020	946.7	Japan	1	.	166	MW
DonValley	2014	2020	2020	8309.8	UK	1	.	.	.
Killingholme	2014	2019	2015	2424.0	UK	1	.	470	MW
Teesside	2014	.	2015	.	UK	1	.	400	MW

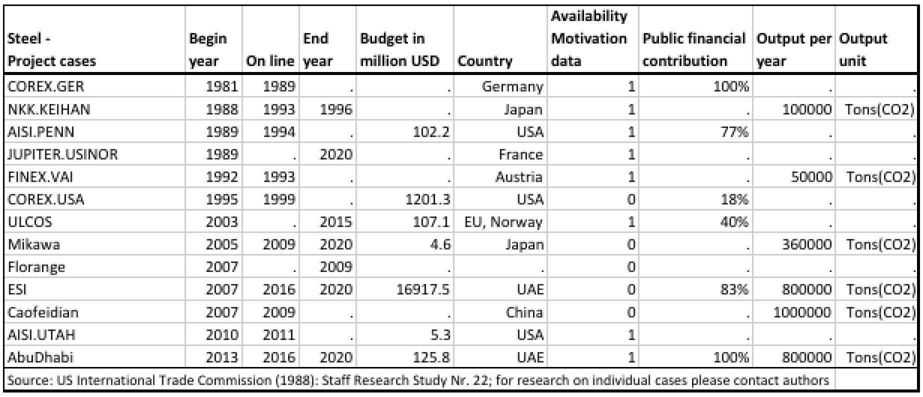
Sources: globalccsinstitute.com; sequestration.mit.edu; for research on individual cases please contact authors

Figure 19: Demonstration projects: 4. CCS power plants.

CCS for industry - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
Sleipner	1993	1996	2020	.	Norway	1	.	900000	Tons(CO2)
Weyburn	2000	2001	2020	107.2	Canada	1	7%	1000000	Tons(CO2)
InSalah	2003	2004	2011	3417.5	Algeria	1	0%	1200000	Tons(CO2)
Ketzin	2004	2008	2013	45.9	Germany	1	29%	67271	Tons(CO2)
ZeroGen	2006	2015	2010	4.1	Australia	0	4%	2000000	Tons(CO2)
Farnsworth	2007	2013	2018	89.0	USA	1	67%	200000	Tons(CO2)
Snohvit	2007	2008	2020	11217.4	Norway	1	0%	700000	Tons(CO2)
Otway	2007	2008	2020	56.6	Australia	1	57%	65000	Tons(CO2)
FortNelson	2008	2014	2020	13.8	Canada	1	80%	2200000	Tons(CO2)
PleasantPrairie	2008	2008	2009	9.5	USA	1	84%	15000	Tons(CO2)
Cranfield	2009	2010	2015	103.2	USA	1	69%	5371643	Tons(CO2)
Decatur	2009	2011	2014	92.2	USA	1	79%	333000	Tons(CO2)
Ordos	2009	2011	2020	5533.1	China	1	.	100000	Tons(CO2)
Gorgon	2009	2016	2020	60380.7	Australia	1	1%	4000000	Tons(CO2)
LEUCADIA	2009	2010	.	478.7	USA	1	60%	4000000	Tons(CO2)
Alcoa	2009	2010	2013	18.6	USA	1	80%	.	.
Novomer	2009	.	2020	28.1	USA	1	80%	.	.
Touchstone	2009	2010	.	9.2	USA	0	80%	.	.
HighlandHeights	2009	2010	.	71.4	USA	0	80%	.	.
Skyonic	2009	.	2020	43.5	USA	0	70%	.	.
Calera	2009	2010	.	46.9	USA	0	50%	.	.
Allentown	2009	2012	.	82.3	USA	1	96%	1000000	Tons(CO2)
Schenectady	2009	.	2020	68.7	USA	0	50%	.	.
Ramgen	2009	2010	.	87.8	USA	0	63%	.	.
Praxair	2009	.	2020	61.0	USA	0	63%	.	.
Pittsburgh	2009	.	2020	20.6	USA	0	80%	.	.
Sandia	2009	.	2020	6.2	USA	0	78%	.	.
Columbia	2009	.	2020	6.9	USA	0	80%	.	.
Tuscaloosa	2009	.	2020	11.9	USA	0	46%	.	.
Lawrence	2009	.	2020	6.9	USA	0	80%	.	.
Laramie	2009	.	2020	5.5	USA	0	100%	.	.
SwanHills	2009	2014	2013	1646.7	Canada	0	19%	1300000	Tons(CO2)
Barendrecht	2009	.	2010	.	Netherlands	0	.	400000	Tons(CO2)
Jilin	2009	2009	2020	12.1	China	1	.	200000	Tons(CO2)
Shidongkou	2009	2011	2020	25.7	China	1	.	120000	Tons(CO2)
PortArthur	2010	2013	2020	467.4	USA	1	66%	1000000	Tons(CO2)
AlbertaTrunk	2010	2017	2020	1301.4	Canada	1	47%	1460000	Tons(CO2)
HECA	2010	.	2016	4368.5	USA	1	10%	2600000	Tons(CO2)
Eltron	2010	2011	.	79.9	USA	0	97%	.	.
Triangle	2010	.	2020	188.7	USA	0	97%	.	.
Orlando	2010	.	2020	70.2	USA	0	50%	.	.
Windsor	2010	.	2020	13.6	USA	0	80%	.	.
Menlo	2010	.	2020	20.4	USA	0	80%	.	.
Arcadia	2010	.	2020	6.8	USA	0	80%	.	.
Utexas	2010	.	2020	6.8	USA	0	80%	.	.
FutureGen	2010	.	2015	1789.5	USA	1	61%	1000000	Tons(CO2)
Citronelle	2011	2011	2015	118.4	USA	1	69%	240000	Tons(CO2)
ILCCS	2011	2016	2020	221.0	USA	1	68%	1000000	Tons(CO2)
BellCreek	2011	2013	2020	99.9	USA	1	73%	1000000	Tons(CO2)
Belchatow	2011	.	2013	.	Poland	1	.	1800000	Tons(CO2)
HUST	2011	2017	2020	.	China	1	.	100000	Tons(CO2)
QUEST	2012	2015	2020	1408.5	Canada	1	13%	392	Tons(CO2)
Kevin	2012	2016	2020	1.0	USA	1	75%	125000	Tons(CO2)
IndianaGasification	2012	.	2013	2921.4	USA	1	0%	5500000	Tons(CO2)
Jingbian	2012	2012	2020	.	China	0	.	440000	Tons(CO2)
Tomakomai	2012	2016	2020	.	Japan	1	.	100000	Tons(CO2)
NorthernReef	2013	2013	2020	117.9	USA	1	78%	500000	Tons(CO2)
Rancho	.	.	.	.	USA	0	70%	.	.
Littleton	.	.	.	.	USA	0	80%	.	.
Champaign	.	.	.	.	USA	0	77%	.	.
Greenwood	.	.	.	.	USA	0	64%	.	.
Salt	.	.	.	.	USA	0	69%	.	.

Sources: globalccsinstitute.com; sequestration.mit.edu; DOE report (2014): Carbon Capture and Sequestration; for research on individual cases please contact authors

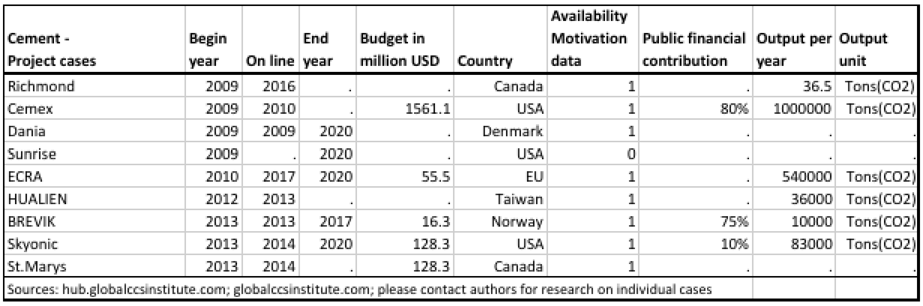
Figure 20: Demonstration projects: 5. CCS industry.



Steel - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
COREX.GER	1981	1989	.	.	Germany	1	100%	.	.
NKK.KEIHAN	1988	1993	1996	.	Japan	1	.	100000	Tons(CO2)
AISI.PENN	1989	1994	.	102.2	USA	1	77%	.	.
JUPITER.USINOR	1989	.	2020	.	France	1	.	.	.
FINEX.VAI	1992	1993	.	.	Austria	1	.	50000	Tons(CO2)
COREX.USA	1995	1999	.	1201.3	USA	0	18%	.	.
ULCOS	2003	.	2015	107.1	EU, Norway	1	40%	.	.
Mikawa	2005	2009	2020	4.6	Japan	0	.	360000	Tons(CO2)
Florange	2007	.	2009	.	.	0	.	.	.
ESI	2007	2016	2020	16917.5	UAE	0	83%	800000	Tons(CO2)
Caofeidian	2007	2009	.	.	China	0	.	1000000	Tons(CO2)
AISI.UTAH	2010	2011	.	5.3	USA	1	.	.	.
AbuDhabi	2013	2016	2020	125.8	UAE	1	100%	800000	Tons(CO2)

Source: US International Trade Commission (1988): Staff Research Study Nr. 22; for research on individual cases please contact authors

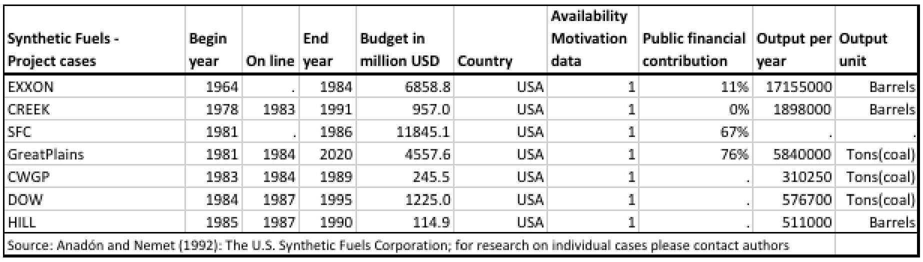
Figure 21: Demonstration projects: 6. Steel.



Cement - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
Richmond	2009	2016	.	.	Canada	1	.	36.5	Tons(CO2)
Cemex	2009	2010	.	1561.1	USA	1	80%	1000000	Tons(CO2)
Dania	2009	2009	2020	.	Denmark	1	.	.	.
Sunrise	2009	.	2020	.	USA	0	.	.	.
ECRA	2010	2017	2020	55.5	EU	1	.	540000	Tons(CO2)
HUALIEN	2012	2013	.	.	Taiwan	1	.	36000	Tons(CO2)
BREVIK	2013	2013	2017	16.3	Norway	1	75%	10000	Tons(CO2)
Skyonic	2013	2014	2020	128.3	USA	1	10%	83000	Tons(CO2)
St.Marys	2013	2014	.	128.3	Canada	1	.	.	.

Sources: hub.globalccsinstitute.com; globalccsinstitute.com; please contact authors for research on individual cases

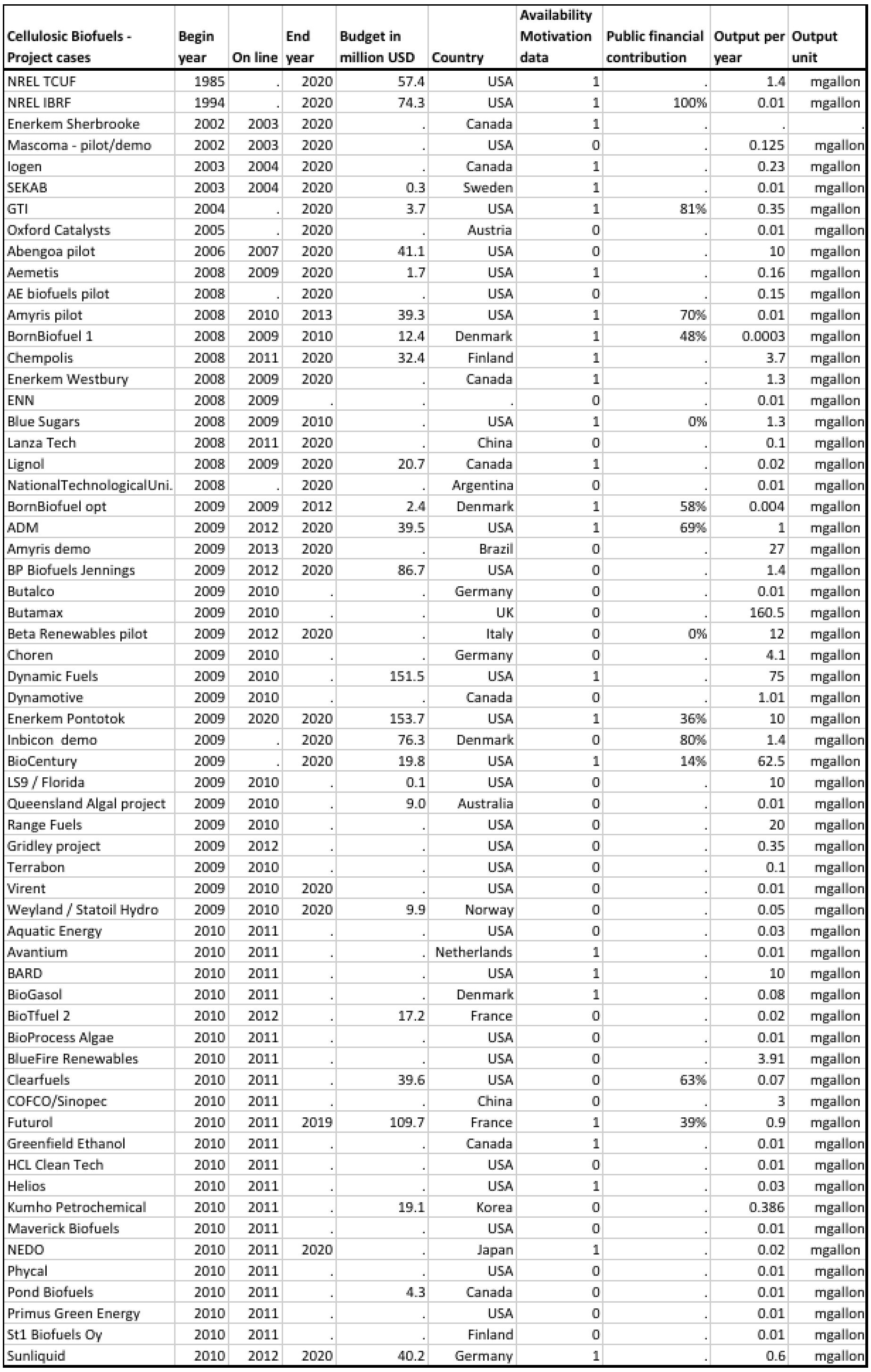
Figure 22: Demonstration projects: 7. Cement.



Synthetic Fuels - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
EXXON	1964	.	1984	6858.8	USA	1	11%	17155000	Barrels
CREEK	1978	1983	1991	957.0	USA	1	0%	1898000	Barrels
SFC	1981	.	1986	11845.1	USA	1	67%	.	.
GreatPlains	1981	1984	2020	4557.6	USA	1	76%	5840000	Tons(coal)
CWGP	1983	1984	1989	245.5	USA	1	.	310250	Tons(coal)
DOW	1984	1987	1995	1225.0	USA	1	.	576700	Tons(coal)
HILL	1985	1987	1990	114.9	USA	1	.	511000	Barrels

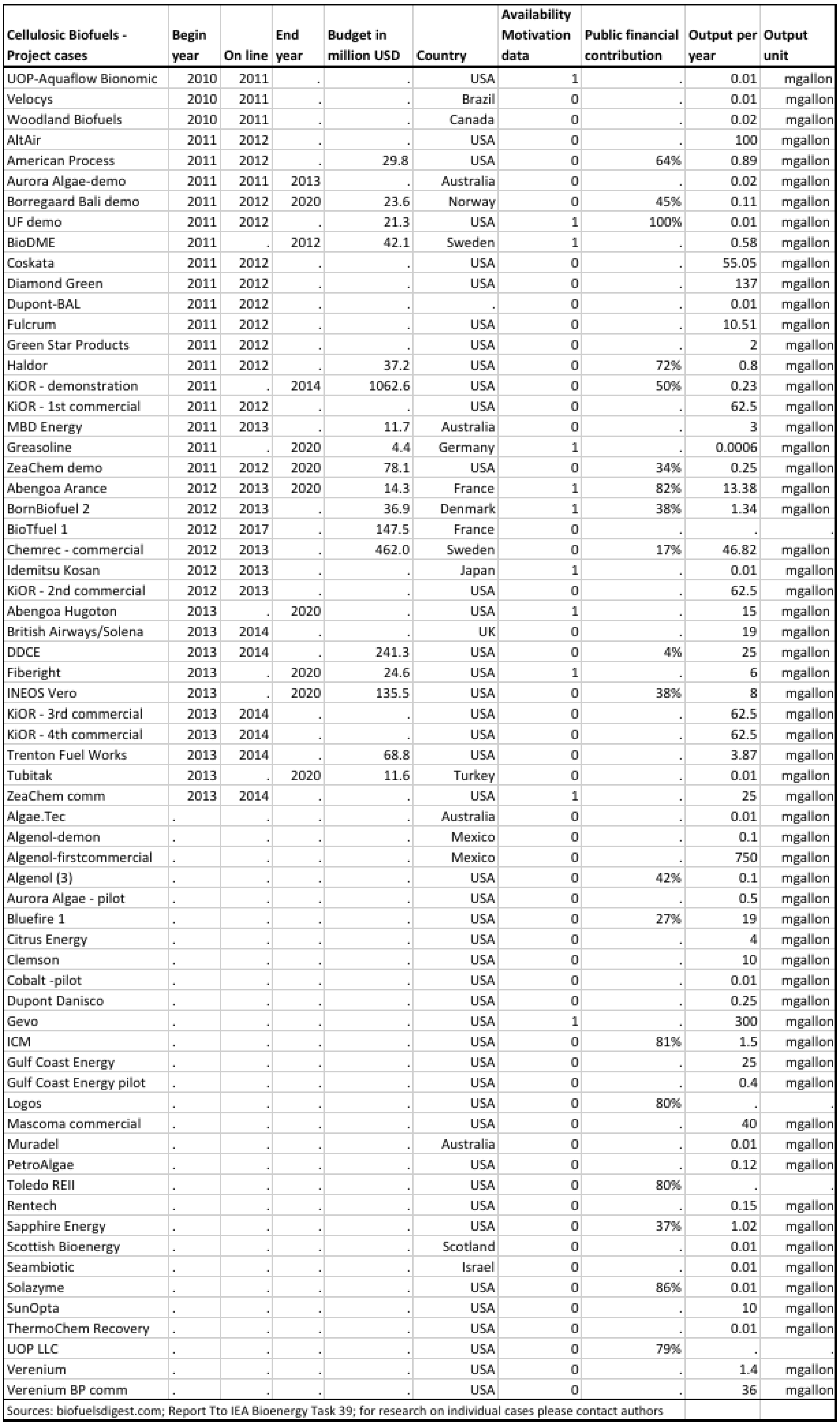
Source: Anadón and Nemet (1992): The U.S. Synthetic Fuels Corporation; for research on individual cases please contact authors

Figure 23: Demonstration projects: 8. Synthetic fuels.



Cellulosic Biofuels - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
NREL TCUF	1985	.	2020	57.4	USA	1	.	1.4	mgallon
NREL IBRF	1994	.	2020	74.3	USA	1	100%	0.01	mgallon
Enerkem Sherbrooke	2002	2003	2020	.	Canada	1	.	.	.
Mascoma - pilot/demo	2002	2003	2020	.	USA	0	.	0.125	mgallon
Iogen	2003	2004	2020	.	Canada	1	.	0.23	mgallon
SEKAB	2003	2004	2020	0.3	Sweden	1	.	0.01	mgallon
GTI	2004	.	2020	3.7	USA	1	81%	0.35	mgallon
Oxford Catalysts	2005	.	2020	.	Austria	0	.	0.01	mgallon
Abengoa pilot	2006	2007	2020	41.1	USA	0	.	10	mgallon
Aemetis	2008	2009	2020	1.7	USA	1	.	0.16	mgallon
AE biofuels pilot	2008	.	2020	.	USA	0	.	0.15	mgallon
Amyris pilot	2008	2010	2013	39.3	USA	1	70%	0.01	mgallon
BornBiofuel 1	2008	2009	2010	12.4	Denmark	1	48%	0.0003	mgallon
Chempolis	2008	2011	2020	32.4	Finland	1	.	3.7	mgallon
Enerkem Westbury	2008	2009	2020	.	Canada	1	.	1.3	mgallon
ENN	2008	2009	.	.	.	0	.	0.01	mgallon
Blue Sugars	2008	2009	2010	.	USA	1	0%	1.3	mgallon
Lanza Tech	2008	2011	2020	.	China	0	.	0.1	mgallon
Lignol	2008	2009	2020	20.7	Canada	1	.	0.02	mgallon
NationalTechnologicalUni.	2008	.	2020	.	Argentina	0	.	0.01	mgallon
BornBiofuel opt	2009	2009	2012	2.4	Denmark	1	58%	0.004	mgallon
ADM	2009	2012	2020	39.5	USA	1	69%	1	mgallon
Amyris demo	2009	2013	2020	.	Brazil	0	.	27	mgallon
BP Biofuels Jennings	2009	2012	2020	86.7	USA	0	.	1.4	mgallon
Butalco	2009	2010	.	.	Germany	0	.	0.01	mgallon
Butamax	2009	2010	.	.	UK	0	.	160.5	mgallon
Beta Renewables pilot	2009	2012	2020	.	Italy	0	0%	12	mgallon
Choren	2009	2010	.	.	Germany	0	.	4.1	mgallon
Dynamic Fuels	2009	2010	.	151.5	USA	1	.	75	mgallon
Dynamotive	2009	2010	.	.	Canada	0	.	1.01	mgallon
Enerkem Pontotok	2009	2020	2020	153.7	USA	1	36%	10	mgallon
Inbicon demo	2009	.	2020	76.3	Denmark	0	80%	1.4	mgallon
BioCentury	2009	.	2020	19.8	USA	1	14%	62.5	mgallon
LS9 / Florida	2009	2010	.	0.1	USA	0	.	10	mgallon
Queensland Algal project	2009	2010	.	9.0	Australia	0	.	0.01	mgallon
Range Fuels	2009	2010	.	.	USA	0	.	20	mgallon
Gridley project	2009	2012	.	.	USA	0	.	0.35	mgallon
Terrabon	2009	2010	.	.	USA	0	.	0.1	mgallon
Virent	2009	2010	2020	.	USA	0	.	0.01	mgallon
Weyland / Statoil Hydro	2009	2010	2020	9.9	Norway	0	.	0.05	mgallon
Aquatic Energy	2010	2011	.	.	USA	0	.	0.03	mgallon
Avantium	2010	2011	.	.	Netherlands	1	.	0.01	mgallon
BARD	2010	2011	.	.	USA	1	.	10	mgallon
BioGasol	2010	2011	.	.	Denmark	1	.	0.08	mgallon
BioTfuel 2	2010	2012	.	17.2	France	0	.	0.02	mgallon
BioProcess Algae	2010	2011	.	.	USA	0	.	0.01	mgallon
BlueFire Renewables	2010	2011	.	.	USA	0	.	3.91	mgallon
Clearfuels	2010	2011	.	39.6	USA	0	63%	0.07	mgallon
COFCO/Sinopec	2010	2011	.	.	China	0	.	3	mgallon
Futurol	2010	2011	2019	109.7	France	1	39%	0.9	mgallon
Greenfield Ethanol	2010	2011	.	.	Canada	1	.	0.01	mgallon
HCL Clean Tech	2010	2011	.	.	USA	0	.	0.01	mgallon
Helios	2010	2011	.	.	USA	1	.	0.03	mgallon
Kumho Petrochemical	2010	2011	.	19.1	Korea	0	.	0.386	mgallon
Maverick Biofuels	2010	2011	.	.	USA	0	.	0.01	mgallon
NEDO	2010	2011	2020	.	Japan	1	.	0.02	mgallon
Phycal	2010	2011	.	.	USA	0	.	0.01	mgallon
Pond Biofuels	2010	2011	.	4.3	Canada	0	.	0.01	mgallon
Primus Green Energy	2010	2011	.	.	USA	0	.	0.01	mgallon
St1 Biofuels Oy	2010	2011	.	.	Finland	0	.	0.01	mgallon
Sunliquid	2010	2012	2020	40.2	Germany	1	.	0.6	mgallon

Figure 24: Demonstration projects: 9. Cellulosic biofuels, part 1.



Cellulosic Biofuels - Project cases	Begin year	On line	End year	Budget in million USD	Country	Availability Motivation data	Public financial contribution	Output per year	Output unit
UOP-Aquaflow Bionomic	2010	2011	.	.	USA	1	.	0.01	mgallon
Velocys	2010	2011	.	.	Brazil	0	.	0.01	mgallon
Woodland Biofuels	2010	2011	.	.	Canada	0	.	0.02	mgallon
AltAir	2011	2012	.	.	USA	0	.	100	mgallon
American Process	2011	2012	.	29.8	USA	0	64%	0.89	mgallon
Aurora Algae-demo	2011	2011	2013	.	Australia	0	.	0.02	mgallon
Borregaard Bali demo	2011	2012	2020	23.6	Norway	0	45%	0.11	mgallon
UF demo	2011	2012	.	21.3	USA	1	100%	0.01	mgallon
BioDME	2011	.	2012	42.1	Sweden	1	.	0.58	mgallon
Coskata	2011	2012	.	.	USA	0	.	55.05	mgallon
Diamond Green	2011	2012	.	.	USA	0	.	137	mgallon
Dupont-BAL	2011	2012	.	.	.	0	.	0.01	mgallon
Fulcrum	2011	2012	.	.	USA	0	.	10.51	mgallon
Green Star Products	2011	2012	.	.	USA	0	.	2	mgallon
Haldor	2011	2012	.	37.2	USA	0	72%	0.8	mgallon
KiOR - demonstration	2011	.	2014	1062.6	USA	0	50%	0.23	mgallon
KiOR - 1st commercial	2011	2012	.	.	USA	0	.	62.5	mgallon
MBD Energy	2011	2013	.	11.7	Australia	0	.	3	mgallon
Greasoline	2011	.	2020	4.4	Germany	1	.	0.0006	mgallon
ZeaChem demo	2011	2012	2020	78.1	USA	0	34%	0.25	mgallon
Abengoa Arance	2012	2013	2020	14.3	France	1	82%	13.38	mgallon
BornBiofuel 2	2012	2013	.	36.9	Denmark	1	38%	1.34	mgallon
BioTfuel 1	2012	2017	.	147.5	France	0	.	.	.
Chemrec - commercial	2012	2013	.	462.0	Sweden	0	17%	46.82	mgallon
Idemitsu Kosan	2012	2013	.	.	Japan	1	.	0.01	mgallon
KiOR - 2nd commercial	2012	2013	.	.	USA	0	.	62.5	mgallon
Abengoa Hugoton	2013	.	2020	.	USA	1	.	15	mgallon
British Airways/Solena	2013	2014	.	.	UK	0	.	19	mgallon
DDCE	2013	2014	.	241.3	USA	0	4%	25	mgallon
Fiberight	2013	.	2020	24.6	USA	1	.	6	mgallon
INEOS Vero	2013	.	2020	135.5	USA	0	38%	8	mgallon
KiOR - 3rd commercial	2013	2014	.	.	USA	0	.	62.5	mgallon
KiOR - 4th commercial	2013	2014	.	.	USA	0	.	62.5	mgallon
Trenton Fuel Works	2013	2014	.	68.8	USA	0	.	3.87	mgallon
Tubitak	2013	.	2020	11.6	Turkey	0	.	0.01	mgallon
ZeaChem comm	2013	2014	.	.	USA	1	.	25	mgallon
Algae.Tec	.	.	.	.	Australia	0	.	0.01	mgallon
Algenol-demon	.	.	.	.	Mexico	0	.	0.1	mgallon
Algenol-firstcommercial	.	.	.	.	Mexico	0	.	750	mgallon
Algenol (3)	.	.	.	.	USA	0	42%	0.1	mgallon
Aurora Algae - pilot	.	.	.	.	USA	0	.	0.5	mgallon
Bluefire 1	.	.	.	.	USA	0	27%	19	mgallon
Citrus Energy	.	.	.	.	USA	0	.	4	mgallon
Clemson	.	.	.	.	USA	0	.	10	mgallon
Cobalt -pilot	.	.	.	.	USA	0	.	0.01	mgallon
Dupont Danisco	.	.	.	.	USA	0	.	0.25	mgallon
Gevo	.	.	.	.	USA	1	.	300	mgallon
ICM	.	.	.	.	USA	0	81%	1.5	mgallon
Gulf Coast Energy	.	.	.	.	USA	0	.	25	mgallon
Gulf Coast Energy pilot	.	.	.	.	USA	0	.	0.4	mgallon
Logos	.	.	.	.	USA	0	80%	.	.
Mascoma commercial	.	.	.	.	USA	0	.	40	mgallon
Muradel	.	.	.	.	Australia	0	.	0.01	mgallon
PetroAlgae	.	.	.	.	USA	0	.	0.12	mgallon
Toledo REII	.	.	.	.	USA	0	80%	.	.
Rentech	.	.	.	.	USA	0	.	0.15	mgallon
Sapphire Energy	.	.	.	.	USA	0	37%	1.02	mgallon
Scottish Bioenergy	.	.	.	.	Scotland	0	.	0.01	mgallon
Seambiotic	.	.	.	.	Israel	0	.	0.01	mgallon
Solazyme	.	.	.	.	USA	0	86%	0.01	mgallon
SunOpta	.	.	.	.	USA	0	.	10	mgallon
ThermoChem Recovery	.	.	.	.	USA	0	.	0.01	mgallon
UOP LLC	.	.	.	.	USA	0	79%	.	.
Verenium	.	.	.	.	USA	0	.	1.4	mgallon
Verenium BP comm	.	.	.	.	USA	0	.	36	mgallon
Sources: biofuelsdigest.com; Report Tto IEA Bioenergy Task 39; for research on individual cases please contact authors									

Figure 25: Demonstration projects: 9. Cellulosic biofuels, part 2.