Shifting patterns of expectations management in innovation policy:

A comparative analysis of solar energy policy in the United States, Japan and Germany

1. Introduction

Since the Oil Crises of the 1970s, solar-generated electricity has been regarded as an alternative to conventional fossil and nuclear sources of energy. Policy-makers in most advanced economies have since then supported photovoltaics through a variety of policy instruments. Extensive and continuous supportive interventions were undertaken despite fundamental uncertainty about the prospects of the technology. Multiple studies have hitherto documented how states have supported photovoltaic technology with demand stimuli, research inputs, monetary transfers, and public relations campaigns [1,1]. Leveraging case studies of the photovoltaic sector in Germany, Japan and the United States between 1973 and 2008, this article adds to the empirical literature with a comparative historical analysis of how collective governance institutions (such as associations, state agencies and research institutions) managed sociotechnical imaginaries in the nascent industry. The alignment of imagined futures about the technology in research, government, industry and the broader public was a crucial prerequisite to continuous complementary commitments by relevant stakeholders.

Theoretically, our paper adds to the literature on the role of sociotechnical imaginaries and expectations in innovation, science and technology [2,3,4,5]. Research on expectations in science and technology has been singled out for its difficulties in developing generalizations about the determinants and effects of imagined futures [6,7]. On the basis of in-depth historical analysis, this article contributes to filling this gap. We develop two theoretical points. First, we demonstrate that the alignment of sociotechnical imaginaries requires extensive institutional work, collective governance and statecraft. Associations, intermediary organizations, social movements and state agencies work towards the alignment of sociotechnical imaginaries through the organization of knowledge exchange, mediation in case of conflicts, development of roadmaps, and financing of field-defining investments. Focus on the realms of collective governance and contentious politics connects the analysis of sociotechnical imaginaries to current much-discussed issues of developmentalism [9] and mission-oriented innovation policies in the energy field [10]. It also helps to move the theoretical framework beyond its often-implicit focus on early-stage, emergent technological futures and towards questions of structural change as highlighted in research on sustainability transitions [10]. Our second contribution is that we develop a taxonomy of the ways in which collective governance aligns imaginaries across the innovation process. We focus on three critical historical episodes representing different types of expectation management, which we refer to as the *creation*, *adaptation*, and *materialization* of sociotechnical imaginaries. By linking our conceptualization to stages of technological development, we do not want to suggest a teleological or linear process. In fact, in all three historical cases, intermediary successes led to later setbacks. Rather, we try to emphasize that innovation policy faced quite different challenges across different stages of technological development [11]. Based on archival material from the three countries, we discuss how American research and state institutions *created* the shared narrative of a photovoltaics-driven energy future through conferences and sector-spanning development programs in the early 1970s; how Japanese intermediary organizations steered the industry and stakeholders through successive crises and *adapted* sociotechnical imaginaries and expectations with the help of information exchange and forecasting activities; and how German state programs significantly contributed to the *materialization*, or the "lock in" of industry into a specific technological path through the massive financial support of grid-connected operators of photovoltaic equipment in the early 2000s.

This article is structured as follows. The next section reviews the existing literature on sociotechnical imaginaries and the sociology of expectations and situates our work within the relevant fields. We then analyze three critical historical episodes in the development of photovoltaic technology to develop how actors managed the emergence, adaptation and materialization of sociotechnical imaginaries. We conclude by summarizing how different contexts shape expectation management and suggest implications for the governance of emerging technologies.

2. Literature review

The role of shared sociotechnical imaginaries in technological innovation has been highlighted by multiple, partly unconnected literatures. Most relevant to our argument are three strands of research: the literature on sociotechnical imaginaries, on mission-oriented innovation policies, and on strategic niche management. While all three literatures acknowledge the crucial importance of shared sociotechnical imaginaries for innovation policy, they have rarely specified how the expectations of heterogeneous sets of stakeholders are aligned over time.

2.1. The sociology of expectations and sociotechnical imaginaries

Scholars in the tradition of science and technology studies have emphasized the importance of shared sociotechnical imaginaries for technological development since the

1990s [5,6]. The central tenet of what has been called the sociology of expectations is that sociotechnical imaginaries about future technological pathways can become reified and constrain agency in science and technology. Rip and van Lente [12] capture this idea with the notion of *prospective structures*. In a significant number of innovation processes, new business ventures, conferences, labels, educational programs, government frameworks, research institutes, and scientific professions exist *before* the underlying technologies are developed and commercialized. Hence, entrepreneurial actors and groups – often with diverse expectations [12,15] – compete to influence predominant imaginaries about the future in order to channel investment flows into emerging technological fields [5]. Explanations of the emergence of new technologies in this perspective are based on the emergence of shared expectational structures drawing relevant actors into technological paths [15,6]. For example, in van Lente's analysis of the emergence of membrane technology, commitment to the emerging promissory label preceded tangible investment by the state, research, and industry [13]. A major focus of the sociology of expectations has been on the very early stages of technological innovation, characterized by high degrees of technological openness. A major issue in the field has been the question of practices and possibilities of "anticipatory governance," the problem of stimulating and regulating technologies and expectations reflexively [17,18]. Recent extensions have tried to trace the dynamics of technological expectations into later stages of policy-making and technological development [19].

Two theoretical extensions of this perspective are particularly relevant for our argument as they expand upon the role of collective governance in the dynamics of expectations. First, in a series of publications, Sheila Jasanoff and colleagues have demonstrated that states effectively "model" technological pathways based on predominant sociotechnical imaginaries [19]. For example, they document "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific … technological projects" in nuclear energy programs [4]. This article aims to explore and specify the power of governance institutions to – willingly or unwillingly – shape technological development by supporting shared imaginaries.

Second, in economic sociology, Jens Beckert has connected the argument about the power of shared imaginaries to general social theory and political economy [2]. Important for our analysis, he suggests that the coordination and alignment of imaginaries over time is not a spontaneous process, even if actors share an underlying interest in pursuing joint projects. To the contrary, as expectations structure investment flows, they become the subject of distributional conflicts. Beckert terms this problem the *politics of expectations* and emphasized the crucial role of the state in settling conflicts and aligning the expectations of contending parties [2]. Our analysis contributes to these arguments on sociotechnical imaginaries and the sociology of expectations by explicating the institutions and instruments at play in the governance of imagined futures in innovation policy.

2.2. Developmentalism and mission-oriented innovation policies

A second strand of literature our paper builds on is the recently revived interest in the state-led articulation of missions and visions to structure private innovative activity [20]. As argued prominently by Marianna Mazzucato and collaborators, private industry typically lacks the long-term perspective and collective action resources required to develop technological solutions to big societal problems [10,22]. While much of the recent work on mission-oriented technology policies revolves around the problem of how to reconcile the different risk preferences of private industry and government, it includes an argument about the role of the state in structuring sociotechnical imaginaries. Empirically, present day mission-oriented technology policies – such as American energy independence, European sustainability or Chinese digital sovereignty initiatives – are not tightly knit hierarchical programs to bring about pre-defined technologies. Rather, they take the form of continuously nurtured frameworks articulating overarching goals, bringing together stakeholders, and guiding experimentation by state, business and civic actors [22, p. 1564]. In our conceptual language, mission-oriented innovation policies can articulate, align, and reformulate sociotechnical imaginaries.

Historical analyses of developmentalist policies in the energy arena and beyond show that guiding sociotechnical imaginaries can be highly contested in society. The assumption of benevolent public institutions, carrying out public purpose-missions, may be a working starting point for rethinking 21st century innovation policies, but it is a weak guide to analyzing the historical determinants of sociotechnical change. Particularly in the energy arena during the last 50 years, initiatives for technological change and a rethinking of how to structure energy provision have emerged with social movements and those outside the elite networks dominating energy policy in state and industry [23]. The development of innovation policies in favor of renewables has been described as a full-fledged “battle over institutions” [25]. At least since the late 1960s, political contestation must be considered a major force in shaping innovation policies in the energy arena [26].

Our analysis contributes to the debate about the developmental state in the energy arena by highlighting that the development, alignment and reworking of sociotechnical imaginaries are distinct governance problems. Moreover, we demonstrate that there are discernably different problems for coordination at different stages of technological development. While our analysis focuses on collective governance, instead of contestation, it is complementary to conflict-theoretical depictions of the politics of energy. As fragmentation and infighting is among the major causes of ineffective social movements [27], the coordination of guiding visions must be understood as a challenge for collective governance at multiple levels of sociotechnical systems [28].

2.3. Strategic niche management

A third important basis for our argument is the literature on *strategic niche management* [29,30]. Developed in the context of empirical research on the barriers to sustainable technologies, research in this tradition argues that firms, intermediary organizations and governments can evoke protected niches as developmental grounds for the nurturing of new technologies. The inertia of large technological systems is a long-standing theme in the analysis of technological development [31,32]. Established technologies typically capture existing resources, personnel, government attention, regulatory approaches, and the public imagination.

Crucial for our purposes, approaches in strategic niche management emphasize the necessity of an early "coupling of expectations" to stimulate activity and cooperation [17,33]. Only on the basis of sufficiently developed promises about the future benefits of a new technology will actors commit resources to high-risk ventures and render the respective niche stable. State agencies and state representatives take center stage in the niche-stabilizing articulation and dissemination of expectations [17,34]. Our paper adds to the literature on expectations in strategic niche formation in two ways. First, we demonstrate the conceptual usefulness of a typology of how states and intermediary organizations can influence the alignment of expectations among stakeholders depending on the stage of the innovation process. Second, we show how internal conflicts among stakeholders – rather than external system-level inertia – can endanger the stability of developmental niches.

3. Data and Methodological Challenges

This article's aims are twofold, each involving distinct methodological challenges. Empirically, we document that measures to align sociotechnical imaginaries were a crucial component of innovation policies for solar photovoltaics technologies in three nations. The crucial methodological problem here is the problem of analyzing expectations retrospectively. Conceptually, we exploit historical case studies to develop types of collective governance. The major issues for our attempt at theory-building involve problems of case selection and representativity.

3.1 Data sources and analysis

The methodological challenges of analyzing "futures past" [34] have been debated in multiple fields for decades [36,37]. Analyzing past expectations from today's vantage point risks bias in multiple dimensions. To name just a few, as archives select material based on a particular representation of "importance," they are chronically biased in terms of data retention and cataloguing. Knowledge of later events may lead to ex-post rationalizations of decisions in favor of history's "winners" in comparison with unfulfilled alternative tracks. Researchers can hence be expected to significantly underestimate uncertainty and contingency when dealing with historical decision-making through what has recently been called "explanation bias" [38]. Given the inherent dangers, our historical analysis should be understood as a provisional interpretation of historic photovoltaics policies, even if we rely on and quote rather definitive-sounding sources.

Through our selection of data sources we tried to minimize the risk of systematic biases and increase the chances of recognizing perspectives deviant from our major lines of interpretation. For all three historical episodes, we analyzed archival documents from government, parliament, research organizations and industry, complemented with contemporary news coverage and the available secondary literature (Table 1 gives an overview of primary sources). This article's historical reconstruction relies on document analysis to reconstruct evolving imaginaries [39]. As compared to more focused qualitative methods relying on firsthand accounts or direct observation, document analyses try to leverage large amounts of preserved materials to weigh competing understandings of the past against each other and get at the perspectives of multiple actors.

Table 1 about here

For the case of the United States, we took as a research starting point the numerous extensive parliamentary hearings on solar energy held throughout the 1970s. These helped us gain an overview of relevant actors in research, industry and government and to identify the major issues for the development of the nascent industry. During the 1970s, most commercialization initiatives were coordinated through NASA's Jet Propulsion Laboratory in Pasadena, the Solar Energy Research Institute in Golden (today's NREL), and the solar energy division of the Department of Energy. We searched for available documents from the period under study in major American university libraries and in the Department of Commerce's National Technical Information Service. A major source for reconstructing technological expectations was status reports prepared by firms in the context of project-specific government funding. We complemented these documents with newspapers and primary material from the Carter Presidential Library in Atlanta and the Reagan Presidential Library in Simi Valley.

For Japan, to gain insight into the thinking of policymakers in different time periods, we consulted the proceedings of the Diet (Japan's federal legislature) and Science and Technology White Papers. For example, we identified relevant Diet proceedings through keyword searches on photovoltaics (太陽光発電, taiyōkōhatsuden) in the electronic records of Diet proceedings, which are available since the first proceeding in May 1947. We also consulted references to energy in the Science and Technology White Papers. Since 1958, these annual reports have discussed Japanese science and technology policy; the changing context of science and technology; update of key R&D areas; and policy initiatives to support the development science and technology in Japan. To further understand the expectations of technical experts, we examined a range of documents including papers in scientific journals.

We also consulted a uniquely Japanese data source, the Delphi surveys contained within the G*ijutsu Yosoku Hōkoku*, which took place roughly every four to five years (1971, 1977, 1982, 1987, 1992, 1997, 2001, 2005, and 2010). The G*ijutsu Yosoku Hōkoku* were translated as "Technology Forecast Reports" until 1997, then as "Technology Foresight Reports" since 2001. Whereas papers in scientific journals typically present the opinions of a single or a few authors, the Delphi surveys are designed to capture and average out the opinions of many individuals with expertise in a particular area. From 1971 to 1987, the Delphi surveys were conducted by Japan's Science and Technology Agency. From 1992 to 2010, the surveys were administered by the National Institute for Science and Technology Policy (NISTEP). As NISTEP ceased using the Delphi method in 2015, we consulted the 2015 G*ijutsu Yosoku Hōkoku*, which was based on scenario planning by priority fields. To gain a better insight into the expectations of technical experts in the fifth phase after 2011, we supplemented the scientific articles and 2015 G*ijutsu Yosoku Hōkoku* with JPEA PV Outlook documents (2012, 2013, 2015, 2017) released by the

Japan Photovoltaic Energy Association (JPEA).

To reconstruct the more recent case of Germany, we began with secondary reconstructions of the policy process to identify relevant actors and organizations. We complemented these with expert interviews with actors from industry, government and interest groups, many of which provided us with hints at crucial documents, events, and meetings. To reconstruct expectations about the technology more systematically, we collected parliamentary debates and hearings about solar energy support since the early 1990s. We also assembled the seven *Energieforschungsprogramme* (energy research programs) of the German government. The energy research programs were initiated in 1977 and have since been used to coordinate federal programs to support the development of non-nuclear energy technologies in Germany. As most German photovoltaics producers went public during the 2000s, we made use of corporate reports published during the 2000s to understand the evolution of the industry. As in the United States, intermediary and final reports prepared by firms for public funding agencies – some of which can be accessed through technical universities' libraries – proved a major source of information about the coordination of expectations. As the industry took off during the 2000s, generating substantial public interest, we were able to complement these documents with continuous reporting in dedicated industry journals, especially *Photon* and *PV Magazine.*

While we try to provide comparative insights throughout our historical reconstruction, the comparability of our three cases is impaired by three factors. First, similar institutions in the different countries do not necessarily have similar functions within the broader national innovation system. While we analyze parliamentary proceedings in all three countries, the role of parliament in the cases differs in terms of political influence in technology policy and the tendency to function as a public arena for rival social groups. Second, the cross-national heterogeneity of institutions' functions interacts with the innovation process, undermining comparability even further. Pushing the technology into the market made parliament crucial in Germany, while it arguably played second fiddle in the United States throughout the 21st century. As we focus different historical episodes in the three countries, we deal with highly idiosyncratic innovation systems across our cases. Third, like any historical study, there are data access issues in all three cases. As mentioned above, the idea of a "complete" historical record waiting to be discovered and discerned should be treated as a fiction. Notwithstanding, our data access is skewed across cases, as, for example, we do not have access to cabinet-level communication records from 21st century governments.

3.2 Case selection and range of theoretical claims

We leverage our historical analysis for theory development, implying a range of methodological problems commonly associated with theoretically ambitious *small-n* analyses [40,41,42]. Crucial for the positioning of our conceptual claims is the relationship of our empirical cases to the larger universe of cases on two levels: the universe of cases of public support of photovoltaics and the universe of cases of innovation policies more generally.

Within the universe of support policies for photovoltaics we selected our historical cases following a logic of negative [43] or exceptional [44] case selection. In all three episodes, initiatives involving activism, industry, and government went beyond the system-level inertia commonly associated with large technological systems and tried to lay the groundwork for sociotechnical change. Moreover, we exploit historical variation between the cases to theorize approaches to coordinate expectations across the innovation process. We explicitly do not focus our analysis on institutional differences between national innovation systems, not least due to the fact that photovoltaics policies were in our view untypical for common categorizations of the three countries (such as expansive federal subsidies in neo-corporatist Germany and extensive coordination in the market-based U.S.). Selecting our cases as exceptional cases implies distinct dangers and limitations of our results. Selecting cases "on the dependent variable" has been criticized as a recipe for cherry-picking evidence [45]. While we agree with the basic tenet of such warnings, our research design is decidedly not meant to discriminate between rival explanations for a specific outcome. It rather develops conceptual suggestions meant to be challenged in future explanatory accounts.

In the wider universe of cases of innovation policies – and particularly in the realm of contemporary energy innovation policies – photovoltaics support in the three countries can be understood as a representative or typical case. However, we do not want to belittle the range of idiosyncratic features of the technology and its political economic environment. Compared to many other energy technologies, photovoltaics breakthrough was strongly contingent on mass production and economies of scale and scope as opposed to breakthrough inventions in laboratories [46]. What is more, in all three countries photovoltaic technology became the subject of substantial social movement and small firm activities. Both idiosyncrasies may suggest that the technology was untypically reliant on wider popular sociotechnical imaginaries as compared to convictions of small circles of sociotechnical elites. Particularly for the energy field since the 1960s, we conceive of such differences between technological fields as differences of degree, rather than of type. The development of highly laboratory-reliant, complex, and elite-driven technologies – such as nuclear fission – has been shown to similarly rely on wider societal beliefs and coalitions [19]. Notwithstanding, transfers of our conceptual argument to other fields should be made with a sense of proportion regarding sociotechnical characteristics.

4. The management of sociotechnical imaginaries in three countries

With niche precursors since the late 19th century, photovoltaic technologies have been under active development since the early 1950s, when AT&T's *Bell Labs* presented the first stable crystalline silicon photovoltaic cell to the public. Too expensive for large-scale electricity production, the technology found uses in niche-applications, such as the powering of satellites, the lighting of buoys, or the electrical supply to certain pipelines' anti-corrosion devices. Proper private and public programs to adapt the technology for mainstream electricity production only began in the late 1960s [47,48]. While there have been scattered contributions to the development of solar photovoltaic technologies in many countries – much of the activity after 2008 has occurred in mainland China, for example [49] – the major continuous programs for the commercialization of the emerging technology were for 40 years anchored in the United States, Japan, and Germany. Between the 1970s and 1990s, the countries implemented innovation policies, as industry and government took advances in foreign innovation systems as reasons for propping up domestic capabilities [50] – engaging in a kind of virtuous arms race [51].

While this paper does not provide a full account of photovoltaics policies in the three countries, our selection of historical episodes in the three settings covers a significant share of crucial initiatives driving the technology towards mass-market maturity between 1970 and 2008. For example, in the early 1970s, American programs brought together relevant groups to commercialize the technology and created path-breaking technological foundations for the first time. Between the early 1980s and mid-1990s, the Japanese innovation system advanced photovoltaic technologies as many Western systems lost interest in accelerated commercialization. After 1998, the German system brought about the first large-scale attempt to propel the technology into mass-market electricity provision.

We argue that a crucial condition for the success of these contributions to the commercialization of photovoltaics was the management of the sociotechnical imaginaries of stakeholders by intermediary organizations and state agencies [34,52,53]. By tracing the management of imaginaries across three episodes, we seek to illustrate the three types of roles that collective governance can play in aligning expectations in innovation policy. There are challenges in the alignment of expectations in the *emergence*, *adaptation*, and *materialization* of imaginaries in innovation processes.

4.1 The creation of shared sociotechnical imaginaries – United States, 1973–1985

In the United States, the state cultivated the imaginary of a viable scale-up of crystalline silicon photovoltaics as the field developed. As the following section illustrates, actors pushed the idea that the technology was "sufficiently ready" to green the country's energy system. In particular, the U.S. managed the *emergence* of a shared imaginary by bringing together disparate actors, by sponsoring early-stage experiments, and by providing institutionalized protected spaces for a specific technological path.

At the beginning of the 1970s, the American photovoltaic industry was a highly fragmented set of small firms developing photovoltaic technology for niche markets; mostly for the space programs [47]. While there were regular field-configuring events [54], such as the so-called annual "Photovoltaic Specialist Conferences," the development of the photovoltaic technology for space programs meant the industry was embedded in government programs. Indeed, there was limited progress in developing the technology for terrestrial use until the early 1970s [55]. Industry dynamics were tailored to the space programs, as evidenced by a focus on development for extreme longevity, weight reduction and failure-resistance.

A change to this path occurred briefly after the proclamation of the Arab Oil Embargo leading into the First Oil Crisis. The Jet Propulsion Laboratory (JPL) of the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF), under its Research Applied to National Needs (RANN) program, brought together a wide array of actors relevant to the development of the industry in late 1973. In addition to representatives from the American solar industry, conference participants included representatives of the military, major utilities, and chemical firms involved in silicon processing, among others [56].

The event's express purpose was to re-configure the field to focus technological development for use in mass electricity production. It did so more through stimulating the emergence of a shared set of scenarios for the commercialization of the technology than through mere information sharing. Participants *foretalked* [57] the future, at times in an aspirational euphoria. Such excitement was due to a change in the parameters of how the industry thought about how to influence the future of photovoltaics. Contrary to the structure of earlier debates concerning mass-market application, which centered around the question of whether the technology was "ready" on a laboratory stage, participants developed – or "realized" – the imaginary of stimulating technological development by expanding production. NASA and NSF agents concerned with photovoltaics admitted that production costs would have to come down by a factor of 100 to come close to the price levels required for non-niche terrestrial energy applications. At the same time, they reasoned that a "significant part of this is expected to be gained through the required million-fold expansion of production rates and attendant automation" [58].

At the October 1973 conference, various manufacturers claimed to be able to meet cost-goals for crystalline photovoltaic modules that had been considered illusionary just a few years earlier. For example, Solarex's Lindmayer claimed that he would be able to produce modules for $10 per watt-peak immediately, given sufficient demand. In the meanwhile, Heliotek's Ralph presented prospective milestones of $2.50 until 1978 and $0.30 until 1983 [59]. When pressed by participants how he came up with possible module costs of $5 at the research-intensive Radio Corporation of America (RCA), Paul Rappaport explained the anticipatory logic of this quasi-tournament of promised cost savings. "I don't care if it is $20 a watt at the present time," he argued: "We feel that prices now are artificial because demand is too limited" [56]. The NASA's William Cherry pointed to the obvious role governmental support should play in this situation and reminded participants of the prime example of the virtues of state-support to get industrial upscaling going: "Definitely the government has got to do some pump priming ... The semi-conductor industry got started the same way" [56].

The mostly manual production techniques inherited from the space programs were to be replaced by what program participants called a fully automated "sand in, cells out" approach [56]. Based on several new concepts for the production of cells, supporters hoped that sufficient demand would kick-start investment in dedicated advanced production facilities. Amidst the various projections, the conference participants eventually agreed on the feasibility of a realistic pathway to commercialization. Until 1985, they imagined that a dedicated state-led initiative would allow the industry to build 50 MWp of annual cell production capacity (up from 0.37 MWp in 1975) to lower the costs of the technology to 50 cents per watt peak (down from around 30 dollars in 1975) [56].

Outside of the NSF and NASA community, assessments of photovoltaics in the aftermath of the oil crisis were mixed at best. Plans from the federal government in line with earlier recommendations by the Atomic Energy Commission were rather skeptical of near-term commercialization of the “solar-electric approach” and focused their renewables recommendations on much simpler devices for solar heating and cooling [60]. The transfer of the imaginary of “cheap semiconductors” in the energy arena to broader circles was not instantaneous. *Popular Science*, for example, devoted its December 1974 title page to the new photovoltaics industry, summarizing: “Dramatic technical developments can bring free energy into our big power” [61]. While citing problems of cost and storage, the *New York Times* in 1975 echoed solar energy supporters’ claims that there were essentially two ways available to modern society to escape energy problems for good: “fuel to power nuclear fusion is nothing more exotic than ordinary sea water, but the technology of conversion requires massive reactor complexes. The second ‘ultimate’ power source is the oldest source of energy known to man, the rays of the sun; the device for converting solar rays into electricity is small and harmless enough to fit into a baby’s fist” [62]. The first comprehensive planning report for renewables by the newly created Energy Research and Development Administration (ERDA, later part of the Department of Energy, DOE) already adapted most of the scenarios developed at the 1973 conference. They became the basis of a series of ERDA-led commercialization programs – against continued critique and contestation by non-solar planners at the R&D administration [63].

Over the 1970s, the ERDA, NSF, and NASA photovoltaics programs were extremely successful in enlisting domestic producers in a collective industrial scale-up dynamic. Crucial instruments for this were block buys of significant inventory of the American industry by the JPL. Experts at the JPL evaluated and tested the industry’s solar panels to disseminate best practice knowledge in the industry. Between 1975 and 1977, JPL suppliers had cut the cost of their solar panels from around 30 to 15 dollars per watt peak. American panel production tripled in the same time to around 1.2 MW peak [64,65]. The intermediary successes of the programs made the imaginary of a rapid concerted industrialization of the technology able to travel through wider policy circles. In 1978, Congress – vowing for issue leadership in green energy support during the 1970s – jumped on the bandwagon and passed a dedicated law prescribing the immediate commercialization of the technology, suggesting $1.5 billion for dedicated support.

The American commercialization effort began to stagnate in the late 1970s. Contrary to popular explanations [47], the photovoltaic programs ran into problems years before Ronald Reagan's cuts to American green energy policies [23]. A crucial reason for industrial stagnation was that sociotechnical imaginaries about the future of the technology began to fragment among crucial stakeholders. The administration actively worked against the 1978 bill and cut funding for commercialization due to fears that "large purchases of photovoltaic systems at this stage in the development of production methodology may tend to 'freeze' the technology before it is sufficiently mature and would hinder further R & D" [66]. Manufacturers were hesitant to invest in production capacity as the technology was rapidly evolving, undercutting the initial scale-up logic of the policies [67,68]. Research institutes and R&D-intensive manufacturers began to go back to researching new potential materials for cells, promising basic research "breakthroughs" [69].

In the public sphere, environmental activists, industry, and utilities began to diverge in the projections of how to get photovoltaics to market [70]. The guiding imaginary of many activists envisioned a future energy system relying on decentralized technologies disconnected from the grid. Such visions of local autonomy crashed with the industrial and systemic thinking of state agents and industry representatives. Surveying values underlying support for solar energy in the late 1970s, planners needed 49 categories to systematize reasons for support in politics and industry and 81 in civil society, ranging from national defense through to individual self-realization [71]. The dissolution of federal programs gave way to the geographical fracturing of green energy policies still characteristic for the United States today. Local initiatives across the states have been important breeding grounds for experimentation with the operation of renewable technologies, but also for communities' appreciation of future opportunities and challenges of renewable energy [72,73]. However, the American states have also been a major site for organized opposition to renewable energy to systematically dismantle transition initiatives and shift public opinion [74,].

Aligning expectations around photovoltaics was no harmonious or linear process. Rather, it has to be understood as a deeply conflictual and experimentalist undertaking. Resumption of the earlier imaginary around concerted upscaling only reemerged in the mid-1990s, then in the face of widespread fears that Japanese manufacturers would dominate the technology in the future [76,77]. Notwithstanding the decline during the 1980s, U.S. program administrators helped give birth to a shared imaginary for the concerted commercialization of the technology that has driven the industry until the present day. Where administrators failed was in the adaptation of that imaginary in the face of challenges, interruptions, and conflicts.

4.2. The adaptation of shared sociotechnical imaginaries, Japan, 1973–2005

In Japan, intermediary organizations coordinated the imaginary of a solar powered energy future, accompanied by a world leading photovoltaics industry. In the following paragraphs, we focus on the period between 1973 and 2005. In particular, we illustrate how Japanese intermediary organizations managed the *adaptation* of shared sociotechnical imaginaries by coordinating information and knowledge exchange, as well as supporting novel technological paths (such as with amorphous silicon), despite numerous frustrations from technological experiments.

As in the United States and in Germany, the First Oil Crisis intensified earlier concerns by industry and government with regard to Japan's energy scarcity, and accelerated the search for alternative, domestic energy sources [78]. In this context, the Japanese government launched the *Sunshine Project* in 1974, which was designed to promote R&D in new energy technology; and later, with a view to eventually making photovoltaics a suitable source of electricity for Japan's grid [79]. Compared to the United States, movement-driven imaginaries pushing for off-grid structures in future energy systems were much less prominent in Japan. Diet discussions at the time revealed modest sector-level expectations that photovoltaics would produce 100 MW of electricity in Japan by 1985, and 1 GW by 2000 [80]. The low conversion efficiency and small-scale production of solar cells also meant that the cost per kilowatt-hour was prohibitively high. Mirroring the American discussion a decade earlier, Diet discussions in 1981 noted that the cost per kilowatt-hour would have to be reduced to a hundredth of its existing level for photovoltaics to gain widespread acceptance as a source of electricity for the Japanese grid [80]. At the same time, policymakers noted that rapid technological advances over the previous decade had reduced the cost of generating electricity with photovoltaics from 30,000 yen/watt to approximately 2,000 yen/watt in 1984 [82,83].

As in other countries, debates about energy security receded in Japan during the 1980s. Unlike Germany and the United States, however, which largely relegated the technology to research-intensive work when the initial hype toward photovoltaics weakened, Japanese actors were dedicated to developing new niche markets for the technology and to pushing industrial automation. Furthermore, Japan brought about the world's first large-scale demand-pull program in the early 1990s, laying the grounds for today's mass energy provision advances of the technology.

In terms of its organizational stakeholders, much of Japan's industrial development in photovoltaics has been coordinated by a dedicated government agency, the New Energy and Industrial Technology Development Organization (NEDO). NEDO was founded in 1980 and was controlled by the Ministry of International Trade and Industry (MITI) – later the Ministry of Economy Trade and Industry (METI) – until the early 2000s. Similar to the United States and Germany, technology policy efforts consisted of a blend of research funding, coordinating activities, and the creation of shared visions for the development of the technology [84]. Japan's Science and Technology Agency organized Delphi forecasting surveys about the technology roughly every four to five years (1971, 1977, 1982, 1987, 1992, 1997, 2001, 2005 and 2010), while NEDO managed multiple consortia around specific photovoltaic technologies as well as problems of mass manufacturing [85].

Throughout the 1970s, most of the solar-related funding of the Sunshine Project went into a concerted effort to develop solar-thermal plants, concentrating on devices utilizing the sun's rays to produce electricity via steam power. When these programs failed at the end of the decade, administrators repurposed their budget for a program developing photovoltaics [86]. Unlike the United States, but rather similar to Germany at the time, photovoltaics production and research in Japan was by electronics and conglomerate firms, rather than small specialist firms or the subsidiaries of oil concerns. Key industrial actors, like the 1950s' pioneer Sharp or electronics conglomerates Hitachi, Kyocera, NEC, Sanyo and Toshiba, developed photovoltaics technology with a background of capabilities in mass manufacturing, chemical processing, and semiconductors. Contrary to the United States, where stakeholders were mostly limited to the energy arena, the Japanese sector developed a specific imaginary of technological spill-over and industrial cross-fertilization [87]. Beginning in the late 1970s, important Japanese producers moved their foci towards the development of amorphous silicon photovoltaics, a less efficient but much cheaper basis for photovoltaic devices. Amorphous silicon photovoltaic devices were light and cheap enough to effectively power small electronic devices like calculators and watches. The small electronic device space was photovoltaics' first true mass market, which made the manufacturer Sanyo temporarily the largest photovoltaics manufacturer in the world [47]. Unlike the United States and Germany, R&D budgets for photovoltaics remained stable throughout the 1980s [88]. Also unlike the other two settings, private expenditure for photovoltaics R&D in Japan rose markedly throughout the 1980s and overtook public funding as early as in 1981, signaling to the public sector credible commitments regarding the technology's potential [87].

Even though amorphous silicon applications provided an important lifeline for the industry throughout the 1980s, the technology has not, with a few exceptions (such as in tandem-constructions), proven effective in large-scale electricity generation. Along the lines of ideas about industrial cross-fertilization in technological development, MITI and NEDO in the early 1990s pushed for a renewed attempt at commercialization for Japanese photovoltaics industry. The major lever for administrators was a newly founded consortium called the Photovoltaic Power Generation Technology Research Association (PVTEC) created in 1990. PVTEC brought together leading firms from, among others, the fields of electronics, machine tools, metals processing, chemical engineering and ceramics for collaborative research and development projects. By 1996, MITI had engaged 65 firms in its photovoltaics programs [87].

While NEDO – similar to the American program – had organized limited block buys of modules during the 1980s, the administration launched the world's first large-scale demand support program for photovoltaics in 1994. The early 1990s' initiatives to accelerate technological development seem in large part motivated by the growing consensus about the need for policies against man-made climate change at the time [89,90]. After a "voluntary" agreement between the government and the utility sector to institute country-wide net-metering for household photovoltaics systems had little effect, MITI began subsidizing solar installations with up to 50 percent of upfront costs in what was called the "New Sunshine Program." Until 2005, the government subsidized an estimated 200,000 photovoltaic installations [86]. A major innovation of the program was the administrators' degressive design of subsidies [86,85]. Subsidies were reduced in successive steps to spur and mirror savings in production and installation costs, effectively institutionalizing the imaginary of commercialization driven by mass production. By the early 2000s, Japan's domestic market was the largest in the world, whereas Japanese solar manufacturers dominated world markets [91].

The government removed the generous demand-pull support in 2005, causing a grave decline in both domestic installations and producers' capacity expansion [92]. The sudden stop of aid to the technology was legitimated on the basis of the belief that subsidies were superfluous for an already maturing industry [93,94]. While the Japanese government reintroduced a generous demand-pull policy after the Fukushima disaster with the introduction of a feed-in tariff in 2012, the Japanese innovation initiative for photovoltaics lost much of its dynamism after 2005.

A comparison of policy-makers' and technical experts' beliefs shows that expectations about the future of the technology began to grow apart in the mid-2000s. Policy-makers tended towards over-optimistic estimates of the state of the technology, while sectoral experts grew increasingly cautious of such optimism. Importantly, utilities became increasingly hostile towards solar support. For example, policymakers argued that photovoltaic technology should now be able to "stand on its own feet" (i.e., should be able to compete with conventional sources of power without subsidies) [93,94]. They argued that technological advances had led to a fall in the prices of photovoltaic systems, which cost 3.7 million yen/kW before 1994, and had fallen to 660,000 yen/kW by 2005 [94]. In the meanwhile, the Japanese Business Federation (Keidanren), which is dominated by the interests of large Japanese corporations, including utilities, issued public advertisements in major broadsheets, which informed readers that government environmental policies would "lower GDP," "increase unemployment," "lower family income" and "raise household energy bills" [95].

Like in the other two countries, adoption of photovoltaic technology has been uneven across different regions. Prefectures in southern Japan (e.g. Saga, Nagasaki, Miyagi), often less populated and featuring longer daylight hours, have high proliferation rates. In the meanwhile, high installation rates are observed in metropolitan areas – but not in city centers – where more residents live in single-family homes [96]. Aside from reasons of climate and population density, existing scholarship has elaborated on the importance of regional politics – particularly additional regional subsidies – in shaping the adoption of photovoltaic technology [97]. At the same time, it may be worth noting that the efforts of local initiatives faced considerable contestation, both from regional utilities refusing to carry solar-generated power and from residents citing a deteriorating scenery [98].

The Japanese episode of managing photovoltaic technology in concert with industry and academic stakeholders from the 1970s to the early 2000s has been heralded as a success story in innovation management [99]. In this section, we have argued that the Japanese actors successfully managed the adaptation of shared sociotechnical imaginaries through extensive knowledge exchange. At the same time, it is important to note that – as in the United States – expectations in Japan were neither monolithic nor linear. Organized backlash fractured the shared imaginary of energy prosperity and independence raising fears about technological mis-direction and lock-in [100,101].

4.3. The materialization of shared sociotechnical imaginaries, Germany, 1998–2005

As in the United States, in Germany the driving sociotechnical imaginary concerning photovoltaics involved the promise of industrial scale-up of known photovoltaic technologies to promote a more environmentally-friendly energy transitions. As compared to Japan, activists and movement ideas played a much more prominent role, pushing for decentralization and democratization of the energy system. In this section, we show how collective governance in Germany *materialized* – or “locked-in” – technological paths by encouraging resource flows into particular fields and by sponsoring institutional landscapes around those paths.

Like Japan and the United States, the German innovation system had engaged with the development of photovoltaic technology since the 1960s, and the government introduced support programs after the First Oil Crisis. One of the features of the German system [102] was that innovation policies were in large parts driven by large integrated enterprises, mostly AEG Telefunken, Siemens, and a number of chemical firms, in collaboration with government-funded research institutes (*Projektträger*). While there was a steady stream of successful R&D collaborations and continuous small-batch production between 1973 and the early 1990s (particularly in polycrystalline silicon technologies), the German industry lagged far behind its Japanese and U.S. counterparts at the time [91]. This early laggard position was over-thrown only when the German government forced the technology into a scale-up dynamic with the help of previously unheard-of demand support programs.

It is worth noting that the motif of the *Energiewende* of “growth and prosperity without petroleum and uranium” [103] emerged out of the anti-nuclear movements of the 1970s and 1980s [104,105], highlighting the importance of social movements – and multiple publics – in shaping sociotechnical change [23]. Yet, many of the actual technology policies emerged out of the neo-corporatist politics characteristic for the country [106]. The country’s transformation into one of the global leaders of photovoltaic development was due to a confluence of industrial policy and climate change concerns during the 1990s. After giving in to activists and industry supporters in 1990, the Ministry for Research (BMBF) together with the German states ran a program of demand-side subsidies of up to 70 percent of the upfront costs for roughly 2,000 small-scale installations between

1991 and 1995. Siemens provided 50 percent of the 5.28 MWp installed capacity, AEG's successor ASE roughly 30 [107].

In addition to these dedicated programs, a conjunctural factors led to the institutionalization of a country-wide feed-in tariff system in 1991, forcing utilities to allow independent power producers in their grids (the law emerged in reaction to quarrels between large utilities and independent water power producers seized upon by proponents of wind energy). While neither of these developments had a direct significant impact on the growth of the photovoltaic industry, they consolidated societal support for the technology over the 1990s. The German research ministry had launched the program with the express purpose to "demonstrate to the public the possibilities of decentralized production of solar electricity" [108]. Throughout the decade, countless solar installations were co-funded by enthusiasts, municipalities, municipal utilities, church communities, and civic associations, leading to the creation of a broad political constituency for the imaginary of decentralized operation and rushed deployment of solar technologies. Importantly, these demand-side programs led to highly influential local experiments with owning and operating independent solar systems, which may explain much of the geographically variegated technology adoption in later years [109].

When the conservative government denied the 1990 program a successor in 1995, environmentalists and opposition parties began to campaign for a concerted state effort to push the technology to market. On display in these propositions was a strategy going beyond what happened in Japan and the United States. Instead of searching for means to stimulate industrial development, renewable energy proponents in Germany developed strategies meant to turn photovoltaics into an irreversible social reality. They aimed at *materializing* the imaginary of a solar-driven energy system.

When German industry reacted to the end of the 1990-program with a consolidation of production capacity, the opposition Social Democrats and Greens warned of a looming industrial "thread breakage" and that "German producers … will lose this future market … to American and Japanese producers" [110]. The European advocacy group Eurosolar began demanding a European 100,000-rooftop program in 1994 so as to not lose "the only semiconductor technology in which the EU has a world market share of a third" [111]. In 1996, the opposition presented a draft bill earmarking €500 million over five years for "the support of industrial solar cell technology" [112]. Greenpeace Germany started a campaign for industrial solar cell production in 1995. It disseminated a much-discussed study, positively evaluating the feasibility of a large-scale production plant for solar cells [113]. A similarly spectacular feasibility study was published in 1996 by European industry representatives, which positively evaluated a then extraordinary 500 MWp factory [114]. In addition, Greenpeace Germany began a widely talked about but eventually unsuccessful campaign to “crowdfund” the necessary demand for a German mass production plant. Illustrating continuous contestation of how to get solar to market, the Greenpeace campaign was heavily opposed by the German solar industry, which feared the unevenness of a one-time demand spike [115]. Like the Japanese and American authorities, German planners throughout the 1990s organized consortia-like projects between different sections of the industry – importantly with the broad involvement of the German machine tool industry [116] –, while legislators did not give in to demands for significant subsidies for installations.

The promissory societal dynamic around photovoltaic technologies was turned into government programs immediately after the Social Democratic and Green Parties came into power in 1998 [25]. Both parties had campaigned with promises to revitalize German industry by supporting the manufacturing of environmental technologies [117,118]. More ambitious yet, important factions in both parties understood the support of green technologies as a means to change society. Hermann Scheer, without question the most important institutional entrepreneur for photovoltaics in the Social Democratic Party, described the underlying imaginary as one of changing alliances: “As industrial companies come to recognize and capitalize on their opportunities, new alliances will be formed: between electronics and glass, between the building materials and electrical industries and manufacturers of solar collectors and PV, between motor manufacturers and suppliers of chemical equipment. New groupings will form as old alliances dissolve; as the fossil industrial web unravels, so too will the power structures it sustains” [119].

Materially, the government began a so-called 100,000-rooftop program in January 1999, offering subsidies of approximately 40 percent of upfront costs for small-scale installations through the German Development Bank (KfW). In anticipation of a soon-to-come revision of the feed-in tariff system, buyers held back from purchasing and there were only about 4,000 applications during the first year [120]. When the government revised the system of tariffs with an almost sevenfold increase in the remuneration of photovoltaic electricity, demand exploded. In a matter of months, about 10,000 applications were submitted to the KfW, of which a first batch of 3,400 for €368 million in loans exhausted the earmarked funds [120]. A majority of the rapid increase in demand of solar panels was delivered by American and Japanese producers as German firms had pushed back capacity expansion [120]. Under the condition of an explosive rise in demand, all German producers announced immediate capacity expansions, leading to a wave in green-field investments, particular in Germany's deindustrialized East [121]. Moreover, the extremely generous funding schemes led to a wave of new idealistic entrepreneurs trying to gain a foothold in the industry, which had traditionally been dominated by integrated concerns [122]. The wave of small firm investments differentiated the German initiative from the American and Japanese programs, where the technology was developed by large diversified firms. The creation of a window of opportunity for small firm founders can be ascribed to both the generosity of demand-side subsidies and the increasing involvement of Germany's advanced machine tool industry in the programs, lowering the bar for industry entry.

The combined funding through subsidized loans and a generous feed-in tariff shifted the balance in debates about the inherent "readiness" of the technology. The flood of new demand made the imaginary of industrial scale-up of photovoltaics a material reality and an unquestioned part of contemporary energy systems. The German administration managed to expand the generous support regime until 2008, when increasing political resistance began to threaten its structure. Notwithstanding repeated cuts and administrative back-pedaling, the feed-in tariff system provided an estimated €300 billion in aid between the years 2000 and 2013, providing crucial seed funding for industrial scale-up of worldwide production.

As in the other historical episodes discussed in this article, we do not intend to portray German support for photovoltaics as consensual. Government programs focusing on rapid scale-up of known technologies were heavily contested – both within the sector as well as from the outside. In line with the theoretical predictions by research on sustainability transitions [123], traditional industrial sectors as well as utilities repeatedly tried to block the program [124]. From the perspective of our paper such political resistance was not just materially motivated. It must be understood as a strategy to restrain the materialization of sociotechnical imaginaries, as accepting a rapid scale-up imaginary for solar energy implied recognition of a substantial share of "stranded assets" in current energy provision systems [74].

5. Discussion

The three episodes of photovoltaics policy considered here highlight the variegated role that collective governance plays in aligning sociotechnical imaginaries. While we have been careful not to suggest a linear or monolithic process, we have connected our conceptualization of expectation management to stages of the innovation process (see Table 2).

Table 2 about here

It should be noted that our case studies were selective and involved three countries that experienced episodes of exceptional historical success in the photovoltaic sector. The three cases also developed in the context of growing environmental concerns and shared substantial, albeit temporal, government support for the sector, which was subsequently withdrawn. Such support was often characterized by the persistence of conflicting and competing expectations between different stakeholders both within and outside the sector. Yet, given some of the differences across the cases, variation in imaginaries should be expected. For instance, solar energy matured in the United States as an alternative to coal and fossil fuels, whereas in Germany and Japan it emerged as an alternative to nuclear power. Industry structure differed as well, for example in the prominence of diversified producers in the United States and Japan, compared to the dispersed presence of small specialized firms in Germany. The relative influence of activists also differed; for instance social movements played an important role in shaping expectations in Germany and the United States, whereas they had a limited role in Japan. Further, technology scale-up in the U.S. and Germany focused on crystalline silicon whereas, in Japan, the initial focus lay on amorphous silicon.

5.1. Theoretical implications

Based on three historical case studies of the United States, Japan and Germany, we documented how stakeholders, intermediary organizations, and state agencies can foster the alignment of sociotechnical imaginaries in three ways. First, in the early stages of the innovation process, they can contribute to the *emergence* of shared sociotechnical imaginaries by bringing together disparate actors, by sponsoring early-stage experiments, and by providing institutionalized protected spaces for specific technological paths. Second, alongside technological advances, actors can coordinate the *adaptation* of shared sociotechnical imaginaries and expectations by coordinating information sharing and knowledge exchange, by funding experiments deviating from established paths, and by keeping fields afloat in the face of technological dead ends. Third, in later phases of the innovation process, collective governance can contribute to the *materialization* – or "locking-in" – of technological paths by steering resource flows into particular fields or by sponsoring institutional landscapes around specific paths.

5.2. Policy implications

Recognizing the crucial role of state and intermediary governance institutions in the formation of expectations may have wider implications for public policy. Literatures on industrial and technology policy [20,22,125] as well as on sustainability transitions [126,10] emphasize that traditional thinking about the role of the state in innovation may lead to systematic underinvestment in innovation and technology policy. The stabilization of collective imaginations of the future may warrant public investment into innovation policies even beyond straightforward economic, environmental, social, and technological rationales. Shared sociotechnical imaginaries are arguably crucial prerequisites to technological innovation, while their spontaneous emergence may be inefficiently difficult and slow. Especially in cases of urgently required technological development, as for example in the field of climate change mitigation, a "hands off-approach" to coordinating expectations implies potentially significant social costs.

5.3. Limitations and future research

To conclude, we would like to highlight two limitations of our article and three natural extensions. Throughout our discussion, we have only alluded to the issue of political power and of the capture of collective governance institutions by specific actors. Due to the high levels of uncertainty involved in technological innovation, we expect capture dynamics in innovation policy as the norm rather than the exception. This is the basic argument underlying Beckert's [2] notion of an endemic politics of expectations. Accordingly, we expect political economic capture to have direct effects on the collective sponsoring of share sociotechnical imaginaries.

We also acknowledge that regional approaches to energy adoption could vary widely as the governance of innovation in energy systems is shaped by the governance of sociotechnical imaginaries and expectations at multiple geographical levels [127], which is true for the United States, Japan and Germany [128,129]. For the purpose of federal comparison, we have overlooked the influence of subnational variations of imagined futures, which may require dedicated research designs accounting for varieties of federalism in energy and beyond. We believe future research may conduct deeper investigations on how collective governance may align sociotechnical imaginaries across space and time.

We suggest three directions for future research. First, we have not engaged with the question of how the type of institution managing collective expectations matters. Based on our historical material, we would certainly expect systematic differences in the managing capabilities of different types of institutions. Much of the later chaos in the American innovation programs may be explained by the fact that institutions at quite remote positions vis-à-vis research and industry tried to force their visions for the development of the technology onto industry. By contrast, Japanese reliance on broad industry participation and consortia may have repeatedly retarded the ambitiousness of government programs, while possibly safeguarding broad commitment. Questions like these would nicely link up to the literature on international comparative innovation policy, which has demonstrated that national regimes differ in their reliance on types of institutions [130,131,102].

Second, we have neglected the question of how the "instruments" through which sociotechnical imaginaries are managed matter. Systematic differences should be expected between the government-sponsored dissemination of narratives, the organization of field-defining events, or the "creation of hard facts" through generous subsidies. Besides questions of comparative efficacy, different "instruments" of alignment may also be differentially available to different types of actors and institutions. Interestingly, elite networks in the United States resorted to "cheap" strategies of sponsoring conferences, while movement actors in Germany pushed for expansive state aid. Exploring the differential access as well as the differential goals of actors with regard to governing imaginaries should be worth exploring empirically.

Third, our focus on the slow-moving, incremental maturing of industry support has underappreciated the effects of exogenous shocks on sociotechnical imaginaries. Our historical reconstruction did not cover the recent period after the Fukushima Daiichi nuclear accident. The repercussions of such exogenous shocks to the collective governance of expectations across settings are an important topic. Shocks seem to be both very relevant for the public imagination as well as variegated in their effects on national sociotechnical imaginaries, as can be seen in the differential effect of the Fukushima accident on Germany, Japan and the U.S [104]. Future research might develop models of how exogenous shocks re-shape the trajectories of sociotechnical imaginaries across settings.

6 References

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7 Tables

Table 1: Overview of document sources

Germany	Japan	United States of America
Listed Firm Annual Reports	Asahi Shimbun	Academic Search Complete
Deutscher Bundestag	Gijutsu Yo-soku Hōkoku	Carter Presidential Library
Frankfurter Allgemeine Zeitung	Japanese Parliamentary Committee Reports	Reagan Presidential Library
Financial Times Deutschland	National Diet Library	National Technical Information Service
Karlsruher Virtueller Katalog	Science and Technology White Papers	New York Times
Ministry for the Environment		US Congress
Ministry for Research		Washington Post
(variously renamed over the years)		
Photon magazine		
PV Magazine		

Table 2: Evolving patterns of collective governance of sociotechnical imaginaries

Stage	Emergent	Development	Commercialization
Mode	Creating	Adapting	Materializing
Instruments	Sponsoring early stage experiments; providing protected spaces to pursue a technological path	Launching national projects; issuing forecasting reports; introducing demand pull programmes	Steering resource flows into specific fields; sponsoring institutional landscapes around specific paths