HAND IN HAND TO NOWHERELAND? HOW THE RESOURCE DEPENDENCE OF RESEARCH INSTITUTES INFLUENCES THEIR CO-EVOLUTION WITH INDUSTRY

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Published in *Research Policy*

Please cite this article as: Hoppmann, J. 2021. Hand in hand to Nowhereland? How the resource dependence of research institutes influences their co-evolution with industry. *Research Policy*, 50(2): 104145.

ABSTRACT

The linkages between science and industry have long been of interest to scholars studying technological change. Recent studies demonstrate that resource exchange between science and industry may lead to patterns of co-evolution, with major implications for the rate and direction of innovation. However, we currently know very little about how the dynamics of co-evolution between research institutes and industry are influenced by organizational characteristics. To address this shortcoming, in this paper we draw on a comparative case study of the world's two largest research institutes for solar photovoltaic power and study how differences in their financial resource dependence influence patterns of co-evolution. We demonstrate that when a research institute is heavily reliant on industry funding, it leads to close co-evolution of science and industry, thereby raising the risk of a mutual lock-in into specific technologies. A heavy reliance on public funding, on the other hand, contributes to the decoupling of science and industry evolution, which entails the risk of research having limited impact on practice. By developing a framework that shows how co-evolution between science and industry is affected by resource dependence, our study contributes to the literature on science-industry collaboration, co-evolution, and technological paradigms. Moreover, our study bears important implications for policy makers and managers of research institutes interested in spurring technological change.

Keywords: Science-industry linkages, co-evolution, resource dependence, lock-in, solar power

1. INTRODUCTION

Recent years have seen a steady increase in policies that aim to improve the interface between science and industry to raise the level of innovative output and address pressing societal issues like climate change (Anadon, 2012; Goldstein and Narayanamurti, 2018; Perkmann et al., 2013). Based on the idea that developing closer relationships between industry and science can speed up the process of innovation, policy makers in many countries have introduced measures that aim to encourage the transfer of knowledge from scientific research to practice, e.g., by promoting the establishment of science parks or innovative organizational designs for research programs (Bruneel et al., 2010; Phan et al., 2005). This trend has been supported by academic research that analyzes the channels used to transfer knowledge from science to industry, as well as different modes of science-industry collaborations that can be used to facilitate this transfer (Perkmann et al., 2013).

Whereas early academic research studying the science-industry interface focused on a unidirectional link from science to industry, more recent research stresses the interconnected nature of science and industry and sees them as co-evolutionary, i.e., mutually influencing each other's evolution (Blankenberg and Buenstorf, 2016; Murmann, 2003). Murmann (2013), for example, demonstrates that in the case of synthetic dyes, academic research and industry have co-developed in a way that has led certain countries to develop a comparative advantage over others. As reasons for this co-evolution, he identifies several mechanisms, such as the exchange of human and knowledge resources, that resulted in mutually reinforcing effects between science and industry.

Studies taking a co-evolutionary perspective offer new insights into the dynamics of technological change, since the reinforcing effects between science and industry may lead to technological lock-ins and path dependencies within individual organizations and entire industries. However, despite these potential important consequences of co-evolution, we currently lack insights into how its dynamics are influenced by organizational characteristics. In particular, while it seems obvious that not all organizations co-evolve with all others, we know little about whether and when a specific research institute might co-evolve with industry. Yet this knowledge is important to accurately predict patterns of co-evolution and their impact on the emergence and decline of technological trajectories. Studies on science-industry linkages shed light on specific organizational characteristics that affect the knowledge exchange between science and industry (Bozeman et al., 2015; Perkmann et al., 2013). However, this literature primarily focuses on a unidirectional exchange, rather than studying co-evolution and related long-term consequences, such as lock-ins. One stream of literature that has studied the drivers and dynamics of lock-ins is the one dealing with technological trajectories and paradigms (Dosi, 1982; Malerba, 2009). Yet this literature has concentrated on the role of industrial firms and provides limited insights into the role that research institutes play in the emergence of technological paradigms and the risks they face as lock-ins form.

To shed more light on the role that organizational characteristics play in moderating the process of co-evolution, in this paper we develop theory on *how the resource dependence of research institutes, specifically with regard to financial funds, influences their co-evolution with industry*. Among alternative organizational factors that might influence co-evolution, we focus on research institutes' dependence on external financing since previous studies indicate that the sources of funding and the demands of funders decisively influence the technological foci and collaborations of research organizations (D'Este and Patel, 2007; Schartinger et al., 2002). While the primary goal of this paper is not to extend resource dependence theory, this perspective, as we will show, is very well suited to generating novel insights into science-industry interactions and co-evolution.

To investigate the impact of resource dependence on the co-evolution of science and industry, we draw on a comparative, longitudinal case study of the two largest research institutes for solar photovoltaic (PV) power in the world, the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) in Germany and the National Renewable Energy Laboratory (NREL) in the United States. These cases are particularly well suited to investigating our research question since (a) the research institutes pursue similar missions while differing in their financial resource dependence, and (b) science-industry collaborations in the context of renewable energy play a critical role in addressing pressing societal issues, such as climate change (Anadon, 2012). In the energy sector, lock-ins hinder the transition toward sustainability and have been shown to occur within specific clean energy technologies, such as PV, wind, or battery technologies, which may slow down technological change (Hoppmann et al., 2013; Unruh, 2000). Therefore, it seems critical to shed more light on how the funding structure of research institutes affects their co-evolution with industry.

We find that differences in resource dependence are connected to significant differences in how the two research institutes interact with industry. Fraunhofer ISE is required to procure a large share of its funding from industry, which has led to a close co-evolution between the research institute and industry. NREL, on the other hand, is almost exclusively funded through public funding, which is why it has focused on technologies removed from the market and has shown a much lower degree of co-evolution. We also show that both types of resource dependencies, and their resultant impacts on co-evolution, have specific risks. Strong co-evolution raises the risk of a collective lock-in into specific technologies in the long run, while weak co-evolution may lead to a decoupling of science and industry that could reduce the output of the innovation system as a whole.

Our study makes several contributions to the literature. Our research adds a dynamic, lock-in perspective to the discussion of science-industry linkages. For example, we show that research institutes and industry may become mutually locked into specific technologies, which poses the risk that both types of organizations wander hand in hand to Nowhereland. We draw attention to the importance of financial resource dependence as an antecedent of knowledge transfer, thereby complementing existing work that has sought to understand the drivers behind the use of specific transfer channels. We provide a dynamic, longer-term perspective on science-industry interaction, which helps connect this stream of literature to the work on technological paradigms and lock-ins. Moreover, we contribute to the literature on co-evolution by showing how resource dependence helps understand the heterogeneous patterns of strong and weak co-evolution observed in practice.

2. THEORETICAL BACKGROUND

In the following, we provide a more in-depth account of the literature on science-industry linkages, co-evolution between science and industry, and resource dependence theory. We do so to (1) highlight the channels of knowledge transfer between science and industry, as well as the specific consequences resulting from closer and more distant links; (2) explain how taking a co-evolutionary perspective instead of investigating a unidirectional link between science and industry can help explain innovation dynamics and the emergence of technological trajectories; and (3) demonstrate how financial resource dependence, in turn, may shape patterns of co-evolution. In addition, this section introduces the most important concepts and motivates the research question of this paper.

2.1 The Impact of Science-Industry Linkages on Technological Change

The interface between science and industry plays a crucial role for technological change, industrial competitiveness, and economic growth (Hall, 2004; Narin et al., 1997; Salter and Martin, 2001). For example, recent research points to the important role of science-industry linkages for the emergence of innovation clusters (such as Silicon Valley) and to address pressing societal issues, such as innovation in clean energy technologies (Anadon et al., 2016). In fact, several studies suggest that a lack of interaction between science and industry is one of the key factors that reduces the effectiveness of national research institutes and hinders the commercialization of critical new energy technologies (Bonvillian and Van Atta, 2011; Chan et al., 2017; Goldstein and Narayanamurti, 2018).

Given the importance that the links between industry and science play for the process of technological change, it is not surprising that the literature has long been interested in how to most effectively design the interfaces between the two groups of actors. A long line of research has dealt with the different channels through which knowledge can flow from science to industry and back again, such as publications, patents, licenses, meetings and conferences, collaborations, contract research and consulting, personnel transfer, and information exchange (Cohen et al., 2002). A core finding in this literature is that there are a many barriers that can inhibit the transfer of knowledge between science and industry, such as differences in time horizons, a lack of knowledge of the recipient's needs, or a lack of incentives and rewards (Bozeman et al., 2015; Bruneel et al., 2010; Carayol, 2003; Perkmann et al., 2013). At the same time, scholars have also pointed to potential downsides of forging strong linkages between industry and science (Martin, 2012). For example, Cohen et al. (1994) argue that strong industry involvement may induce research institutes to delay or completely forego the publication of research results (see also Blumenthal et al., 1986; Carayol, 2003). Other authors point out that pressure to develop marketable results may reduce researchers' productivity or lead research institutes to shift their focus from more basic research toward applied research (Meyer-Krahmer and Schmoch, 1998; Perkmann et al., 2013; Rosenberg and Nelson, 1994).

2.2 Co-Evolution of Science and Industry

While the literature provides important insights into the mechanisms and effects of science-industry linkages, much of the earlier work assumes a unidirectional flow of knowledge from science to industry rather than studying how industry and science may dynamically influence each other over time. Scholars have only recently started to acknowledge the interconnected nature of science and industry (Kaufmann and Tödtling, 2001) and have begun taking a co-evolutionary perspective to study how collaborations between scientific bodies and industry may shape an organization's focus over time (Blankenberg and Buenstorf, 2016; Murmann, 2003, 2013; Murray, 2002; Petersen et al., 2016). Rooted in evolutionary economics, co-evolutionary theory proposes that entities, such as organizations, evolve through a process that entails variety creation, selection, and retention (Lewin and Volberda, 1999; McKelvey, 1997). In contrast to evolutionary theory, however, co-evolutionary theory suggests that entities do not evolve in isolation as they are not only influenced by but also influence their environment (Murmann, 2003). For example, Nelson (1994) pointed out that universities make important contributions to technology development while simultaneously choosing research topics that they perceive will be easily marketable through industry at a later stage (see also Garud and Rappa, 1994). Building upon this, in his study of the evolution of the synthetic dye industry, Murmann (2013) demonstrates how the exchange of personnel, commercial ties, and lobbying can lead to a convergence between the technological foci of research institutes and firms over time. Blankenberg and Buenstorf (2016) finally show a mutually reinforcing effect between the number of producers, patents, publications, and PhD dissertations in the West German laser industry.

By revealing the patterns and mechanisms of co-evolution, studies such as the ones by Murmann (2013) and Blankenberg and Buenstorf (2016) help explain patterns in the emergence of technological trajectories within specific countries or industries over time. Specifically, co-evolution between research and industry may lead to the emergence of technological lock-ins and path dependencies that result from an increasing convergence of foci. Lock-ins may be highly undesirable from a societal perspective, since they can lead to a situation where technological progress becomes more incremental and technologies with better performance characteristics (e.g., with regard to their ecological footprint) do not find their way into the market (Hoppmann et al., 2013; Nemet, 2009; Unruh, 2000). However, while co-evolutionary patterns might therefore have important ramifications for technology dynamics, we currently know little about the conditions that determine whether two entities co-evolve or not. Existing studies on the co-evolution of science and industry are predominantly focused on the industry or country level rather than on the organization level. As a result, while it seems obvious that not all firms co-evolve with all scientific institutes at the same time in the same way, we know little about how differences in the characteristics of scientific institutes and firms influence patterns of co-evolution. Such an understanding, however, seems critical if we want to draw a complete picture of co-evolution and its impact on technological change. For example, knowledge about which entities co-evolve can help predict the convergence or divergence of technological foci in specific firms or research institutes, which would complement knowledge about co-evolution at country and industry levels.

2.3 Resource Dependence as a Factor Influencing Co-Evolution

To address the lack of research on how organization-level factors influence patterns of co-evolution, we draw on resource dependence theory to study how research institutes' dependence on external resources affects the co-evolution between scientific bodies and industrial firms. We chose this theory as it is well suited to explaining the phenomena we observed when studying our focal organizations.

Resource dependence theory posits that the survival of organizations depends on their ability to access resources in their external environment (Pfeffer and Salancik, 1978). No organization is an island, and each one depends on external resource providers that provide the organization with monetary or physical resources, information, or social legitimacy. The more operationally critical, hard to substitute, or unavailable from alternative sources a resource is, the more an organization depends on the resource provider and the more power the provider has over the organization (Davis and Cobb, 2010). This power manifests itself in demands made on the dependent organization. For example, in return for providing critical financial resources to research institutes, funders of research projects usually expect some sort of outcome, such as publications, patents, or products.

The literature emphasizes that organizations can employ different strategies—such as mergers and acquisitions (M&A), joint ventures, or board interlocks—to alleviate the risks of resource dependence and secure supply (Boyd, 1990; Hillman and Dalziel, 2003; Hillman et al., 2009; Pfeffer, 1987). However, organizations cannot always devise strategies that reduce external control (Casciaro and Piskorski, 2005). For example, Casciaro and Piskorski (2005) draw on a sample of more than 10,000 public U.S. companies to show that, if an organization depends on another in a one-sided manner, the organization is less likely to be able to use mergers and acquisitions as a means to reducing its external resource dependence. This is because an organization will find it hard to convince the resource provider, which it depends upon in a unilateral way, to agree to a restructuring of the resource dependence relationship and to give up its power. If an organization cannot break free from resource dependence, its only option may be to comply with providers' demands.

For research institutes, one of the most critical resources is research funding. While research institutes also depend on other types of resources, such as human resources, legitimacy, or know-how, financial resources are particularly critical, since (a) non-profit research institutes cannot build financial resources internally, and (b) financials resources can be used to purchase other types of resources. Previous studies show that research institutes can fund their operations in different ways, most notably through public or industry funding. Differences in funding structures have been shown to have an important impact on the technological foci of research institutes (Carayol, 2003; Meyer-Krahmer and Schmoch, 1998; Perkmann et al., 2013), as well as influencing how they interact with industry (Colyvas et al., 2002; D'Este and Patel, 2007; Lee, 1996; Schartinger et al., 2002). However, we currently lack systematic evidence of how different funding structures for research institutes influence patterns of co-evolution between science and industry. As we will show, combining resource dependence and co-evolutionary theory has the potential to significantly enhance our understanding of the science-industry link and the resulting dynamics of technological change.

3. METHODS

3.1 Research Setting

To study how the resource dependence of research institutes influences their co-evolution with industry, we used a comparative, longitudinal case study of the two largest research institutes working on solar photovoltaic (PV) technologies: the Fraunhofer Institute for Solar Energy Systems (Fraunhfoer ISE) in Freiburg, Germany, and the National Renewable Energy Laboratory (NREL) in Golden, United States.[1] Previous studies stress that the first step toward studying co-evolution is to specify the variable on which organizations are expected to co-evolve. Since the focus of this study is technological change, we decided to track the technological co-evolution of the two research institutes with the solar PV industry. As the temporal boundaries, we chose the time from the founding of each research institute (1981 for Fraunhofer ISE and 1977 for NREL) to the end of 2013. We select this time frame since (a) it covers a time when PV was not competitive with alternative power generation technologies, thereby requiring ongoing research efforts by research institutes, and (b) during this time the U.S. and Germany were hotspots in the PV industry. Since 2013, the PV industry has been dominated by Chinese PV manufacturers, which has shifted the focus from research toward technology deployment and has led to a geographic shift toward Asia.

Solar PV as a case is particularly well suited to investigating the technological co-evolution between science and industry since (a) there are several distinct PV technologies, which allows for an analysis of the technological foci of research institutes and industry over time, and (b) this technology plays an important role in addressing pressing societal challenges, such as climate change (Hoppmann et al., 2020). Compared to alternative energy generation technologies (e.g., coal, gas, or nuclear), PV technologies generate electricity with very limited CO_2 emissions over the technology's

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[1] There are several other research institutes that have played an important role in advancing PV technologies, such as the Australian Research Council (ARC) Photovoltaics Centre of Excellence at the University of New South Wales (Australia), the Centre for Solar Energy and Hydrogen Research (ZSW) in Stuttgart (Germany), the Sandia National Laboratories in the U.S., or the Energy Research Center of the Netherlands (ECN). However, our analysis showed that NREL and Fraunhofer ISE are larger than the other institutes (in terms of budget, publications, and staff). According to the International Energy Agency, public funding for RD&D in PV technologies in Germany, the U.S., and globally amounted to USD 61 M, 150 M, and 545 M respectively (IEA, 2019). In this sense, Fraunhofer ISE's budget (USD 97 M) and NREL's budget (USD 550 M, of which about 25%, i.e., USD 137 M, are dedicated to PV) make up quite a significant percentage of global R&D on PV. However, when comparing public budgets and the budgets of the two research institutes, one has to keep in mind that Fraunhofer ISE is only partially funded through public funds.

life-cycle. At the same time, however, despite strong cost reductions, during the time frame of this analysis PV technologies were still not fully competitive with alternatives in all locations, requiring ongoing research efforts and accelerated commercialization (Nemet, 2019).

Currently, the dominant technology is crystalline silicon (c-Si) PV, which was invented in 1954. Modules based on c-Si PV are manufactured in a multi-stage process by drawing or casting ingots from high-purity silicon, cutting the ingots into wafers, processing the wafers into cells, and assembling the cells into PV modules. Because the process of manufacturing c-Si PV is relatively time- and material-intensive, since the 1970s two alternative groups of PV technologies have emerged that might replace c-Si PV as the dominant PV technology in the future: thin-film and third-generation PV technologies (Bagnall and Boreland, 2008). Thin-film modules are manufactured through a highly automated process as part of which a thin film of semiconductor material is deposited onto a carrier material (e.g., glass). Compared to the manufacturing of c-Si PV, this process uses much less material and therefore has the potential to considerably reduce the cost of solar PV in the future. At the same time, however, commercial thin-film modules currently offer lower electricity conversion rates than c-Si modules, making them less attractive for space-constrained applications. Third-generation PV technologies, such as organic, nano, or dye-sensitized PV, are the least mature, not currently manufactured at large scale, and used in niche applications, such as building-integrated PV. Because third-generation PV is not expected to replace c-Si PV in the foreseeable future in this study we only focus on c-Si PV and thin-film PV, since the competition between the two technologies for market share has meant that research institutes have had to make strategic technology choices and could draw on alternative funding sources (public vs. industry). Thus, the focus on c-Si and thin-film PV allowed us to study in detail how differences in the financial resource dependence of research institutes affect their strategic technology choices and co-evolution with industry.

Within the solar PV setting, we selected Fraunhofer ISE and NREL as cases since they differ significantly with regard to their resource dependence. While Fraunhofer ISE was established in 1981, NREL was founded as the Solar Energy Research Institute (SERI) four years earlier and declared a U.S. national laboratory in 1991. The mission of both NREL and Fraunhofer ISE is to promote renewable energy and energy efficiency by engaging in both applied and basic research, developing technologies, and transferring related knowledge to industry.[2] While the institutes have a very similar mission, they differ considerably regarding where they source their most critical resource research funding (see findings section). The strong difference between the funding structures for the two research institutes provides an ideal setting to generate insights into how such differences in resource dependence influence research institutes' co-evolution with industry.

3.2 Data Collection and Analysis

To investigate the impact of resource dependence on co-evolution, we proceeded in four major steps. First, to investigate the technological co-evolution, we obtained data on the technological foci of the two research institutes and the global PV industry over time. To this end, we collected all the scientific articles published by the two research institutes in the years between when they were founded (1981 for Fraunhofer ISE and 1977 for NREL) and the end of 2013 from the ISI Web of Knowledge.[3] This effort resulted in 9,263 and 1,646 scientific publications by NREL and Fraunhofer ISE respectively. In addition, we collected all the patents published by NREL and Fraunhofer ISE

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[2] It should be noted that Fraunhofer ISE focuses on a narrower set of technologies—specifically solar PV, energy efficiency in buildings, solar thermal technologies, fuel cells, electricity grids, sustainable mobility, battery storage, and energy system analysis—whereas NREL covers a broader range of renewable energy technologies, including biomass, wind, hydropower, and geothermal technologies. As pointed out in footnote 5, however, the share of c-Si and thin-film PV publications and patents in the overall research portfolio is quite similar for both research institutes. Research on PV represents one of the focal areas for both research institutes.

[3] The ISI Web of Knowledge only covers a limited range of journals. Given that the majority of journals in which the two organizations have published are contained in the database, however, it serves as a reliable source to compare the technological foci of the two organizations over time. To obtain all scientific articles by researchers at NREL, we searched for articles containing the address "Golden AND ((Solar* En* Res*) OR SERI OR NREL OR (Nat* Ren* En*))". Using these search terms ensured that we were also able to find articles by NREL published under its former name "Solar Energy Research Institute" as well as different abbreviations used for its current name "National Renewable Energy Laboratory". To obtain scientific articles by researchers at Fraunhofer ISE, we altered the address to "((Fraunhofer AND Solar*) OR (Fraunhofer AND ISE)) AND Freiburg". This search string for Fraunhofer ISE excluded all publications made by Fraunhofer Institutes other than Fraunhofer ISE in Freiburg, Germany.

between 1977 and 2013 from the NREL and Fraunhofer publication databases respectively.[4] The total number of patents we obtained was 367 patents for NREL and 384 patents for Fraunhofer ISE.

Using quantitative content analysis of the titles and abstracts, we then categorized the publications and patents according to which PV technologies they referred to in order to generate insights into each research institute's technological focus each year (for a detailed description of the process used to classify the articles and patents, including the keywords used, please see Appendix A of this paper).[5] In addition, we measured the technological focus of the PV industry by retrieving data on the share of different technologies in the global PV market and firm entries from the industry magazine *Photon*, as well as data on firm patents from the Thomson Reuters Derwent Innovations Index database.[6] Complementing this data with historical information on the PV industry allowed us to draw a picture of the technological evolution and market applications of PV technologies. In addition, to investigate whether the trends we observe are specific to our two sample organizations, we collected data on the technological foci of other large research institutes working on solar PV technologies, such as the ARC Photovoltaics Centre of Excellence at the University of New South Wales (Australia), the Centre for Solar Energy and Hydrogen Research (ZSW) in Stuttgart (Germany), the Helmholtz Zentrum Berlin (Germany), the Sandia National Laboratories in the U.S., and the Energy Research Center of the Netherlands (ECN). We complemented this data with data on PV cell efficiency records published by NREL to identify which firms and research institutes had

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[4] In the case of our two sample organizations, patents are often filed under the name of the umbrella organization ("Fraunhofer Society" for Fraunhofer ISE and the "Alliance for Sustainable Energy" for NREL). To obtain the organizations' patents, we therefore drew on the publication databases provided by the Fraunhofer Society (Fraunhofer, 2020) and NREL (NREL, 2019), which allow identifying the patents published by Fraunhofer ISE and NREL. A challenge when working with these publication databases is that they treat similar patents filed in multiple jurisdictions as separate patents, which may result in double-counting of patents that refer to the same innovation. To resolve this issue, we imported the patent numbers contained in the filings into the Derwent Innovations Index database to identify the patent families to which the patents belonged. This process resulted in 367 unique patent families for NREL and 384 unique patent families for Fraunhofer ISE.

[5] Overall, of the scientific articles published by Fraunhofer ISE and NREL, 24.4% and 17.2% deal with c-Si PV and thin-film PV respectively. Of the patents published by Fraunhofer ISE and NREL, 16.1% and 28.6% were categorized as pertaining to the two PV technologies.

[6] To retrieve company patents, we first downloaded all patents for PV, drawing on the search string listed in Table B.1 in Appendix B. The patents were then filtered to identify those patents filed by companies and classified into different PV technologies using the same search string we used to classify the research institutes' publications. To categorize the patents, we did an analysis similar to our analysis of publications.

been leading in specific PV technologies over time. In addition, we collected data on the number of employees for our two sample organizations to track their size over time.

Second, to better understand the connections between the evolution of Fraunhofer ISE's and NREL's technological foci with those of the industry, we obtained data on the resource exchange between the research institutes and industry. For this purpose, we used Factiva to search for press articles announcing partnerships, collaborations, and licensing agreements between the research institutes and firms.[7] In total, we obtained over 3,000 press articles which were manually reviewed to identify links between the research institutes and industry, such as alliances, contract work, and licensing. In addition, we used patent citation analysis to identify those organizations that most frequently cited Fraunhofer ISE's and NREL's inventions.

Third, to investigate resource dependence, we collected archival data on research funding. We focused on financial resources, since both the previous literature and informal interviews with executives from other research institutes suggested that funding constitutes the most critical resource (Hodge and Piccolo, 2005).[8] To understand the sources and amounts of funding for NREL and Fraunhofer ISE, we collected annual reports issued by the two organizations[9] as well as their public sponsoring bodies[10] and developed a detailed overview of the two research institutes' budgets over time. To obtain insights into the demands of funders, we searched for statements in documents issued by the policy bodies and industry organizations that we had identified as the main providers of

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[7] We used the search strings _(NREL or "National Renewable Energy Lab*") AND (partner* or cooper* or alliance or collabor* or licens*) AND (solar or photovoltaic*)_ for NREL and _Fraunhofer ISE" OR "Fraunhofer Institut für Solar*" or "Fraunhofer Institute for Solar*") AND (partner* or kooper* or cooper* or allianz or alliance or kollabor* or collabor* or licens* or Lizenz*) AND solar_ for Fraunhofer. The search yielded 2,709 press articles for NREL and 644 press articles for Fraunhofer ISE.

[8] The assumption that financial resources constitute the most critical resource for NREL and Fraunhofer ISE was later confirmed in personal interviews with the executives.

[9] Through online research and by directly contacting the research institutes, we were able to obtain 24 annual and program reports describing NREL's research activities dating back as far as 1991, as well as all 33 annual reports issued by Fraunhofer ISE between 1981 and 2013.

[10] To shed more light on NREL's funding sources, we obtained 50 documents containing information on the U.S. Department of Energy's Solar Photovoltaics Program dating back as far as 1981. To identify the effect of German R&D funding on Fraunhofer ISE, we gathered reports describing the German R&D program for PV from the German Ministry of the Environment and the German Ministry for Economic Affairs.

financial resources. Moreover, we used Factiva to identify 337 press articles that contained additional information on the resource dependence of Fraunhofer ISE and NREL.[11] Based on this information, we assembled a table of more than 100 pages containing detailed information for both research institutes on the history of funding, the demands of funders, and financial dependence.

Fourth, to examine the mechanisms through which research institutes' resource dependence is linked to their co-evolution with industry, we conducted interviews with 16 current and former members of NREL and Fraunhofer ISE.[12] Interviewees were selected such that they possessed in-depth insights into the institutes' technological foci, had played an important role in funding decisions, and were involved in setting the institutes' research agendas. At Fraunhofer ISE, we interviewed all three former directors of the institute (including its founder), the heads of the research departments for solar cells and technologies and solar cell development and characterization, and the coordinator of PV research, as well as four directors of two subsidiaries of Fraunhofer ISE, the Fraunhofer Center for Silicon Photovoltaics and the Fraunhofer Center for Sustainable Energy Systems in Cambridge, United States. Interviewees at NREL included the current director, both the current and a former director of NREL's National Center for Photovoltaics, the Deputy Lab Director of Strategic Programs and Partnerships, and the Director of the Center for Chemical and Materials Science. Interviews were semi-structured and typically lasted an hour. A key objective of the interviews was to shed light on the drivers behind the institutes' technological foci, their links with industry, and the funding sources. For this purpose, we showed our interviewees the results of our publication and patent analysis and asked them to explain the differences in the technological foci across Fraunhofer ISE and NREL and within each institute over time. We inquired about whether and how the research institutes collaborated with and shaped industry. Moreover, we asked our

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[11] To obtain the articles from Factiva, we used the search string "NREL" or "Fraunhofer AND ISE" in combination with "budget* OR fund* OR financ* OR finanz* OR *mittel OR *förderung". The articles were then manually screened to select those that contained relevant information.

[12] We conducted these interviews as part of a larger study on the role of research institutes in technological change in the PV industry.

interviewees to elaborate on the research institute's funding sources and on how both links to industry and funding affected the technological focus (an exemplary interview guide is available from the authors upon request). All interviews were transcribed and saved in a central case study database (Gibbert et al., 2008; Yin, 2017). Table 1 summarizes the data sources used in this study.

TABLE 1: Data sources

Construct	Data	Number	Source
Techno-logical co-evolution	Scientific publications by NREL and Fraunhofer ISE	10,909	ISI Web of Science
	Patents published by NREL and Fraunhofer ISE	751	Derwent Innovations Index
	Documents on market share of different PV technologies	12	Photon
	Documents on firm entries	12	Photon
	Firm patents	100,168	Derwent Innovations Index
Science-industry linkage	Patent citations for NREL and Fraunhofer ISE patents	10,762	Derwent Innovations Index
	Press announcement of collaborations	3,012	Factiva
Financial resource dependence	Annual reports	57	Archives & websites
	Budget reports of political sponsoring bodies	61	Archives & websites
	Press articles on resource dependence	337	Factiva
General	Interviews with current and former executives	22	Personal interviews

To develop a theoretical framework showing the impact of resource dependence on co-evolution, we first developed timelines for the technological foci of the research institutes and the PV industry, as well as timelines for the funding and funders' demands over time. We then analyzed the data on patent citations, collaborations, and record cell efficiencies, and also conducted first explorative quantitative analyses to provide additional insights into the link between the research institutes' funding structure and their technological foci. The insights on collaborations and patent citations were used to draw qualitative inferences about which firms drew upon the knowledge developed by Fraunhofer ISE and NREL. In addition, to reveal in detail the mechanisms at play, we coded the qualitative interview data that describes the role that each institute's funding structure played for its technological focus and how the institutes were both shaping and shaped by industry (Yin, 2017). In the first step, following the suggestions by Gioia et al. (2013), we used open coding procedures to identify the mechanisms linking the research institutes with industry. In later stages, we then transitioned to more closed and axial coding procedures to draw comparisons between the two research institutes and link our findings to constructs derived from the literature, such as resource dependence, co-evolution, and lock-ins (Strauss and Corbin, 1998). To ensure a systematic process, during the data analysis stage we used the qualitative data analysis software ATLAS.ti. Going back and forth between the empirical data and theory, we then developed a theoretical framework that captured the dynamics we observed (Gibbert et al., 2008). We stopped this process as soon as we felt that the framework accurately described the dynamics we observed (Eisenhardt, 1989).

4. FINDINGS

In the following, we describe how the resource dependence of Fraunhofer ISE and NREL affects their technological co-evolution with industry. To this end, we first separately describe the technological evolution for the PV industry as well as for the two research institutes. Then, we provide detailed information on the funding structure of the two research institutes over time and describe how their dependence on financial resources affected their technological foci as well as their interaction with industry. To conclude the presentation of our results, we show that the different ways that the two research institutes are funded are associated with distinct patterns of co-evolution, each entailing specific risks for the research institutes and their funders. Throughout the section, we reference the most important data sources using the abbreviations D1 to D29 for document sources (see Table B.2 in Appendix B for a list) and I1 to I16 for our interviewees.

4.1 Technology Evolution in the PV industry

Figure 1 shows the evolution of the technological focus of the PV industry over time as indicated by firm entries, industry patents, and the global market size and share of c-Si and thin-film PV. Throughout the period of investigation, the PV market was dominated by c-Si PV and since the late 1990s experienced particularly strong growth. Until the early 1980s, PV modules were primarily used in space applications, such as satellites and remote terrestrial applications, e.g., battery charging for navigational aids, telecommunications equipment, and offshore oil rigs. Although these markets were very small, they provided the first commercial opportunity for manufacturers to produce modules from c-Si PV, which were very expensive but the only viable PV technology.

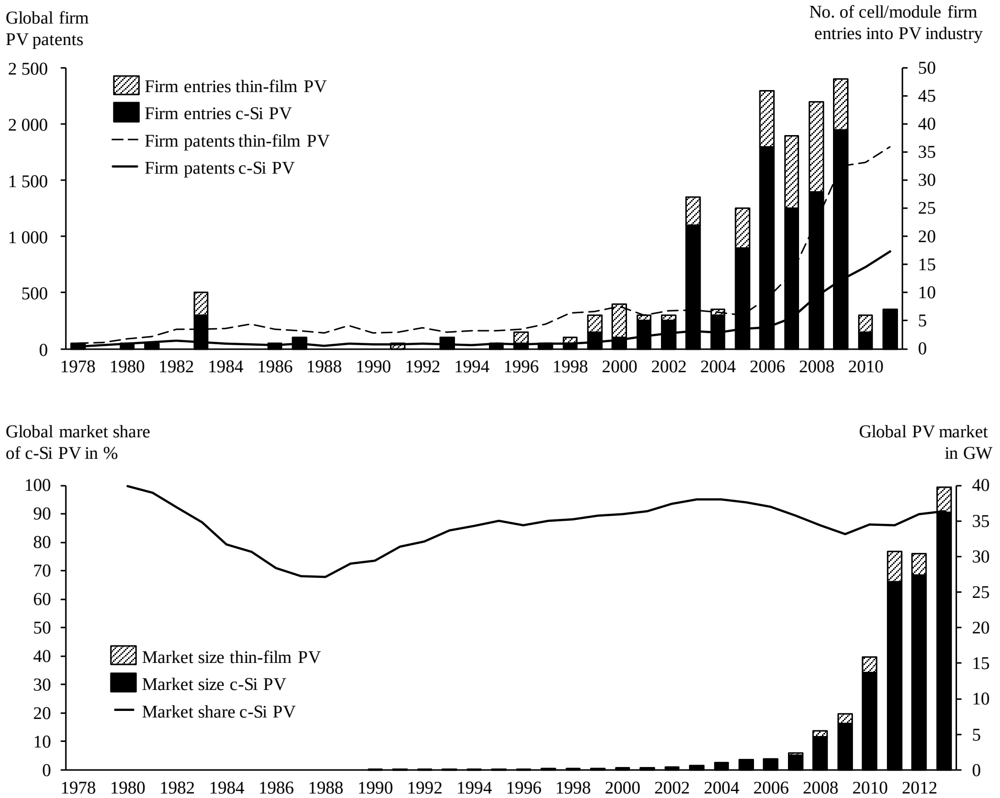

FIGURE 1: Technological focus of the PV industry as indicated by firm entries, patents, and market share of the PV technologies over time[13]

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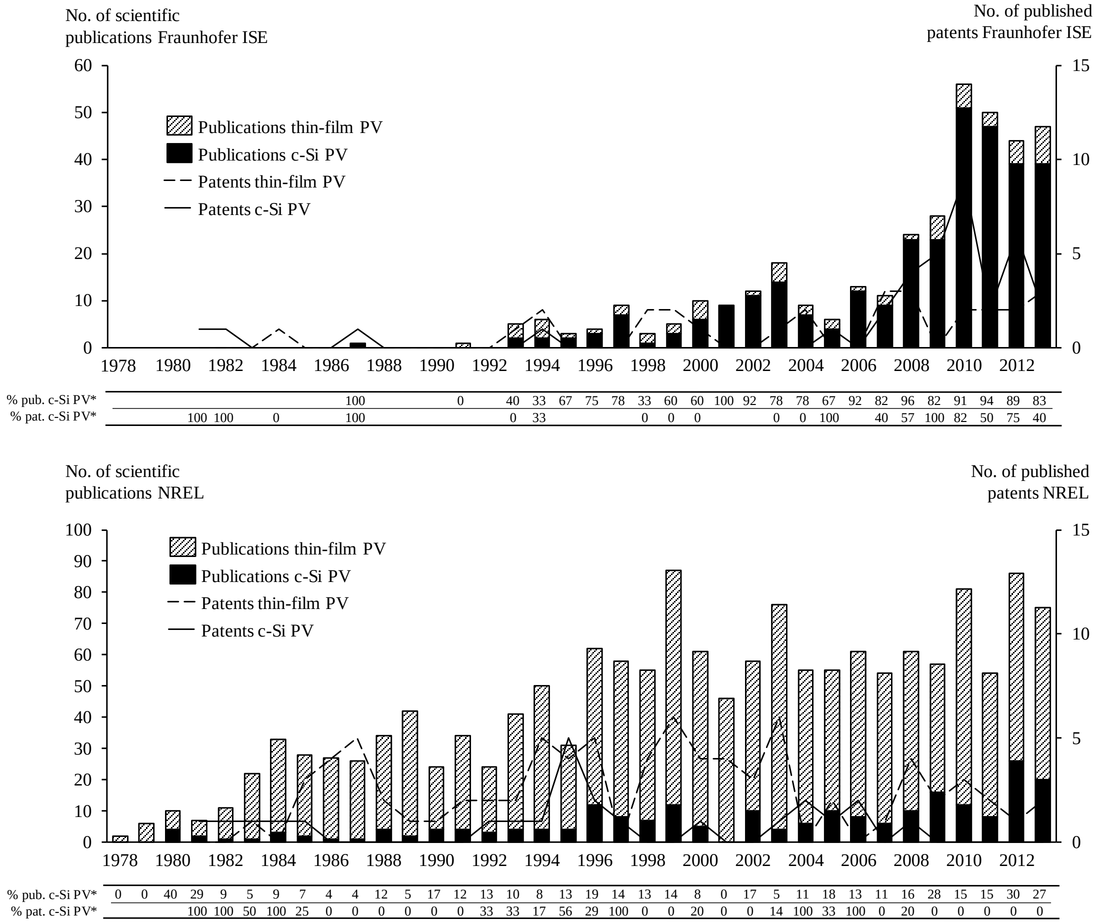
[13] The fact that the number of thin-film patents exceeds the number of c-Si patents in the PV industry is partly due to the use of PV in consumer applications, such as calculators. At the same time, firms invested in thin-film PV since, similar to NREL and the DOE, they believed that c-Si PV would be replaced by thin-film PV in the future.

At the end of the 1970s, thin-film PV made from amorphous silicon entered the market, primarily being used in consumer electronics, such as solar powered calculators, watches, or radios. Since the market for consumer electronics grew very quickly, the market share of thin-film PV rose to 32% by 1988 and also led to a surge in thin-film patents, which already outnumbered industrial c-Si patents by the late 1970s. In the early 1990s, however, Japan and Germany implemented comprehensive demonstration programs, such as the "1,000 Roofs Program", which for the first time created an incentive to use PV in large-scale electricity generation. At that time there were "20 years of experience in crystalline silicon" (I14), thin-film modules "were not very reliable" (I14), c-Si PV had higher conversion efficiencies, and c-Si was "the easiest and the most rapidly scalable technology and the easiest to move into mass production" (I4). Therefore, it was a "logical step" for the PV industry to "specialize on crystalline silicon" (I14), such that in the 1990s c-Si PV regained significant market share until, in 2004, thin-film only made up around 4% of the market.

Starting in the early 2000s, governments in a growing number of countries implemented deployment programs, which led to strong growth in the market for PV modules. In 2004, for example, the German government amended its Renewable Energy Sources Act, leading to a surge in installed capacity by almost 300 percent in that year. In the wake of rising demand for PV modules, several firms entered the market and developed and produced thin-film modules from novel materials, such as cadmium telluride (CdTe) or copper indium gallium selenide (CIGS). The success of some of these firms, like First Solar, in combination with a shortage of industrial-grade silicon, contributed to a rise in the market share of thin-film PV to more than 17% in 2010. However, after the silicon bottleneck was resolved and producers of c-Si PV significantly expanded their production capacity, the market share of thin-film fell back to 9% in 2013. Overall, therefore, despite the high hopes of firms producing thin-film PV, "c-Si PV has been able to maintain its position as the dominant technology” (I11) in the PV industry, although the industry also saw great promise in thin-film technologies, as indicated by a sharp rise in the number of patents since the early 2000s.

4.2 Technology Evolution at Fraunhofer ISE and NREL

Figure 2 shows the evolution of the technological focus of Fraunhofer ISE and NREL respectively.



* Number of annual c-Si PV publications or patents divided by sum of annual c-Si and thin-film PV publications or patents

FIGURE 2: Technological focus of Fraunhofer ISE and NREL over time

While both institutes pursued a variety of technologies, Fraunhofer ISE’s technological focus greatly resembles the focus of the PV industry described in the previous section. Throughout its history, Fraunhofer ISE “strongly focused on c-Si PV” (I14) and has published a relatively limited number of publications on thin-film PV. At the same time, its research activity increased greatly in the early 2000s and reached a peak in 2010. Compared to this, NREL's technological focus puts a much stronger emphasis on thin-film PV. Throughout the period of investigation, publications and patents on thin-film PV strongly exceed those about c-Si PV. Only in the early years 1997, 2004, and 2006 did c-Si PV assume a more significant share of NREL's patents. Moreover, the increase in publications is far less pronounced for NREL than for Fraunhofer ISE. How can we explain these striking differences in the technology evolution between the two research institutes?

4.3 Resource Dependence of Fraunhofer ISE and NREL as a Factor Influencing their Co-Evolution with Industry

Our analysis suggests that differences in the technological foci and evolution of Fraunhofer ISE and NREL can be explained by taking a closer look at the institutes' resource dependence, i.e., the sources of their funding and the funders' demands. Reliance on different funding sources induced the institutes to focus on different technologies and led to different modes of interaction with industry.

4.3.1 Fraunhofer ISE: Impact of resource dependence on the technological focus of the research institute

Fraunhofer ISE is a subsidiary organization of the Fraunhofer Society, which has important implications for its funding profile and research portfolio (see Figure 3 and Table 2). The central mission of the Fraunhofer Society is to foster applied research of direct value to the private sector. Therefore, it provides its institutes with a base funding of only around 10% of their total budgets and requires them to obtain at least 25% of their budgets directly from industry. Meeting this share of industry funding is "a strict requirement" (I10) and, as executives pointed out, failure to meet the requirement "is dangerous" (I6) and will get the institute "into serious trouble" (I8).

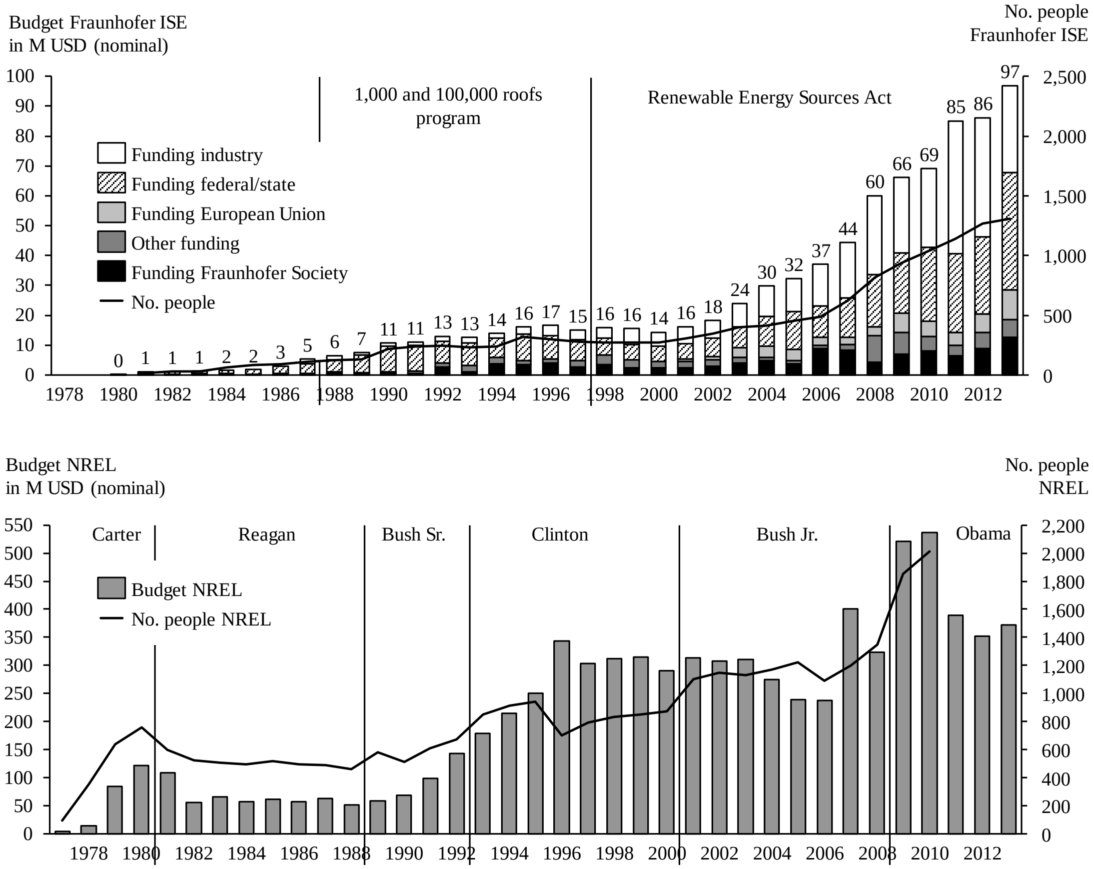


FIGURE 3: Budget and employees of Fraunhofer ISE and NREL over time

To meet the requirement of 25% industry funding, from the start Fraunhofer ISE strategically positioned itself close to industry and focused on research in c-Si PV. The first director of Fraunhofer ISE, Adolf Goetzberger, knew that in order to meet the quota he would have to focus on a mature technology, for which "there is a direct interest of the industry" (I18). Although the choice of c-Si was also driven by Goetzberger's background in silicon research and a strong belief in the material, focusing on c-Si PV was a "strategic choice" (I1) to maximize the likelihood of industry funding.

Yet until the mid-1990s "the PV industry was basically non-existent" (I6), so Fraunhofer ISE "predominantly relied on public funding" (I12), almost entirely from the German Ministry for Research and Education, which "laid its focus on [funding] basic research" (I3). The projects funded by the Ministry for Research and Education involved collaborations with large, individual firms, e.g., Siemens and AEG. At the same time, however, the nature of funding required Fraunhofer ISE to focus on more basic research with the goal of developing high-efficiency solar cells. The dependence on public funding was so strong that cuts in public funding in 1992 and 1997 significantly threatened the existence of the institute (D19-D23, I6).

TABLE 2: Demands of resource providers to Fraunhofer ISE

Year	Main Resource Provider	Main Demands	Exemplary Quotes	Source
1981–1998	Fraunhofer Society	Applied research	"The idea of the Fraunhofer Society from the beginning was to focus on applied research."	I8
	German Ministry of Research and Education	Basic research in c-Si and thin-film PV	"The pure basic research projects lie with the German Ministry of Research and Education."	I1
Since 1998	Fraunhofer Society	Applied research	"Fraunhofer is a non-profit research society that has the task to help industry."	I5
	German Ministry of Economic Affairs & Ministry of the Environment	Applied research in c-Si PV	"Research projects are directly aimed toward a concrete need and the results are used immediately. […] [Approved research projects] can be categorized as follows: silicon wafer technology: 73% of the PV budget, silicon thin-film 6%, CIS thin-film 13% […]."	D26
	German PV industry	Applied research in c-Si PV	"The domestic industry has invested less in revolutionary cell concepts but puts a strong emphasis on the evolution of existing [c-Si] concepts."	D27

The financial resource dependence of Fraunhofer ISE changed with the emergence of a PV industry at the end of the 1990s. With a growing market, the industry started to fund research at Fraunhofer ISE that was "mostly focused on crystalline silicon" (I12). Yet as two of the directors noted, when the industry emerged "what we did sometimes wasn't the problem industry was working on" (I6) and "often we developed radical ideas that industry wasn't interested in" (I12). To be closer to industry, Fraunhofer ISE hence deliberately shifted its focus to more applied research. Executives engaged in "convincing the more basic-science oriented researchers in the institute that the race for high efficiency isn't beneficial since we don't get money then" (I6), which "took several years" (I6).

As a result of this positioning close to industry, Fraunhofer ISE strongly increased its financial resources, from less than USD 15M in 2000 to over USD 97M in 2013. In 1999, "funding from industry constituted the largest budget position of the institute" for the first time (I13, D24, D25).

Besides directly raising the funding available to Fraunhofer ISE, the emergence of a PV industry also indirectly affected the nature of financial resource dependence by altering the research sponsored by German ministries. With the strong growth of the German PV industry, the German government decided in 1998 to shift the main responsibility for renewable energy research funding from the Ministry of Research and Education to the Ministry of Economic Affairs, and later to the Ministry for the Environment. Funding by the latter ministries was guided by the principle of supporting projects "for which there is an economic interest and a willingness of companies to financially partake" (D26) and which "have a direct impact on industry and the energy sector" (I15). Since the industry strongly focused on c-Si PV, public funding in the 1990s also began to increasingly support it. As one Fraunhofer representative pointed out "roughly speaking about 70 percent of the funding went to c-Si PV, 30 percent to thin-film" (I5). Moreover, although the majority of funding in 2011 and 2012 already went to c-Si PV, in 2013 the Ministry for the Environment announced that it would "more strongly focus research funding on c-Si technologies" (I5).

4.3.2 Fraunhofer ISE: Impact of resource dependence on the technological focus of industry

Together, the increase in industry funding and the shift in public funds toward more applied research led to a strong increase in applied research projects on c-Si PV at Fraunhofer ISE. At the same time, the possibility of conducting research with industry also significantly raised the knowledge transfer from Fraunhofer ISE to industry, thereby reinforcing the industry's technological focus. As several representatives of the research institute confirmed, with the rise of a PV industry, Fraunhofer ISE started to closely collaborate with firms (particularly in Germany) to help them develop commercial products and machinery (I1, I6, I8, I9, I14, I9). For example, between 2008 and 2013 Fraunhofer ISE partnered with several leading firms producing PV modules, such as Solarworld and Q-Cells. Eicke Weber, the director of Fraunhofer ISE, even took on a position in the board of directors in the latter firm. In some cases, Fraunhofer worked with companies “for 20, 30 years and even when they were sold, the contacts remained. If you look for example at Siemens […]. Or if you look at Solarworld or Bayer, Wacker, then Bayer Solar, then Solarworld. […] There are technology lines in c-Si PV where Fraunhofer ISE played an important role, was an important player in their history” (I9). Moreover, Fraunhofer was actively involved in furthering the equipment produced by German equipment manufacturers, such as Centrotherm and Manz. These companies greatly benefited from Fraunhofer ISE’s expertise, and played an important role in shaping the industry’s technological focus as they developed standardized manufacturing equipment, which was later sold to China and thereby enabled the rapid growth of a PV industry focused on c-Si PV.

The projects that resulted from Fraunhofer ISE’s dependence on industry funding usually involved joint product development where “companies […] used the know-how that was developed in the research institute” (I14) and “the commercialization was done by the firm” (I14). Several of the collaborations included the (temporary) transfer of personnel from Fraunhofer ISE to the firms. Employees from Fraunhofer “went into industry and back” (I6) and German PV firms even asked Fraunhofer ISE “to take on more doctoral students, so they can hire them as experts later” (I15). As a result, as one Fraunhofer representative stressed, “a large number of our alumni work in these [German PV] firms” (I10), implying a strong transfer of knowledge from the institute to industry. Moreover, if industry showed little interest in the technologies it had developed, in several cases Fraunhofer ISE directly spun out the technologies. For this purpose, the Fraunhofer Society “directly got engaged as a venture capital investor, which initially holds shares in the ventures and later retracts” (I12). By engaging in the direct development of commercial products, transferring employees, and spinning out technologies, Fraunhofer ISE had a direct influence on the competitive position of companies in the PV industry and also cemented the focus of these companies on c-Si PV. In the words of one Fraunhofer executive: “The results we obtained were reassuring to the industry, so they could further grow and make profits” (I6).

4.3.3 NREL: Impact of resource dependence on the technological focus of the research institute

In contrast to Fraunhofer ISE, in the period of investigation, NREL was predominantly dependent on public funding from a single source: the U.S. Department of Energy (DOE). As one director of NREL points out, throughout its history NREL has “almost exclusively been funded by the DOE” (I11), which in turn is allocated an annual budget through the U.S. Congress (D1-D10). While NREL also seeks “some industrial partnerships maybe as an add-on” (I13), it “relies heavily on DOE financing” (I1). NREL has a “heavy administrative overhead,” such that “working with NREL is very expensive” (I4). Hence, the organization receives almost no direct income from industry, and cooperates with firms primarily through “special programs that are often initiated by the DOE” (I3).

Both the amount of funding provided by the DOE and its demands have fluctuated considerably over the years (see Figure 3 and Table 3).[14] However, since the DOE is a government organization, it is generally “much more reluctant to get so far into funding technology development that they determine winners and losers” (I13). In order to avoid distorting competition between firms, Congress and the DOE thus “tend to be much more interested in long-term research. In this country getting too close to the marketplace makes some people in the Congress quite nervous. They would like it to be a little bit earlier stage” (I11). Moreover, when the DOE funds more applied research, it “intends to provide value to a lot of different companies” (I11). In fact, as one NREL representative pointed out, “if one company believes that another company is benefitting from the money that is provided by NREL they could sue. They could cause a big thing. And that has happened” (I4).

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[14] In recent years, about 25% of the overall funding for NREL went into PV research.

Despite the general mandate to not interfere with the market, in the early years of the institute under the Carter administration, the DOE still promoted a “broad program of basic and applied R&D on a variety of different photovoltaic devices and cells” (D11). Besides supporting basic research in thin-film technologies, the DOE funded “six to ten approaches at each step of the manufacture of silicon-based modules” (D11) and invested in demonstration programs, such as the Solar Homebuilder Program, to gain insights into the performance of more advanced technologies in the marketplace. During the early years, therefore, NREL (then still called the Solar Energy Research Institute) focused on more than basic research in thin-film technologies. The directors believed that the institute should “refine solar cells to the point where they could power an individual home or even part of an electric utility” (D12) and NREL did “quite a bit of [crystalline] silicon work” (I4).

TABLE 3: Demands of resource providers to NREL

Year	Main Resource Provider	Main Demands	Exemplary Quotes	Source
1977–1981	Department of Energy (Carter)	Basic and applied research in c-Si and thin-film PV	“The photovoltaic program has established a broad program of basic and applied R&D on a variety of different photovoltaic devices and cells.”	D11
1981–1989	Department of Energy (Reagan)	Basic research in thin-film PV	“We are going to concentrate funding on long-term, high-risk, high-potential-payoff research and development.”	D13
Since 1989	Department of Energy (Bush Sr., Clinton, Bush Jr., Obama)	Basic and applied research in thin-film PV	“The truth is that we don’t do very well in applying science to a practical use.”	D14

The demands of the DOE changed significantly when Ronald Reagan took office in 1980. Funding for research programs in PV was cut by some 90%, and the remainder was dedicated to “long-term, high-risk, high-potential-payoff research and development” (D13). This was done because the Reagan administration felt that it was “sound economics to put all forms of energy on an equal footing in the marketplace” (D15), which implied “eliminating Federal involvement in near-term [PV] technology” as this “retards the pace of the research program, freezing technological development by the private sector and creating pressure for further subsidy of uneconomic or immature technology" (D16). NREL reacted to these new demands by replacing its director. Under the new director, activities relating to the commercialization of mature technologies were considerably reduced and work shifted to "conducting and coordinating long-term, high-risk research and development 'which private industry cannot reasonably be expected to undertake'" (D17).

As a result of the reduced policy focus on the commercialization and deployment of technologies in the U.S., PV firms in other countries, such as Japan, were able to catch up and overtake U.S. PV firms in the 1980s. Moreover, it became increasingly clear that much of the basic knowledge developed in the research institutes in the U.S. was not applied in practice. In response to this, the administrations under George H.W. Bush, Bill Clinton, George W. Bush, and Barack Obama, started to focus federal PV R&D more on applied research and commercialization activities. For example, as early as 1984 the DOE established the Amorphous Silicon Research Project, which was later transformed into the Thin-Film PV Partnership Project. As part of these projects, NREL closely collaborated with competitively selected firms, which carried part of the costs through cost-sharing mechanisms beginning in the late 1980s. Moreover, NREL played an important role in the Photovoltaic Manufacturing Technology Project (PVMaT), which was designed to "[help] the U.S. PV industry improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for a substantial scale-up in the capacity of U.S.-based PV manufacturing plants" (D18).

By engaging in these efforts, NREL helped significantly advance PV technology. Still, the overriding paradigm within the U.S. DOE remained avoiding distortions in the market. Therefore, the DOE shied away from supporting c-Si PV as the dominant technology, which was generally "considered mature" (I6). Moreover, given that the U.S. had lost its leadership role in c-Si PV, focusing on thin-film PV as a potential breakthrough technology was seen as a promising way for the U.S. to regain PV market share. As a result, NREL's work beginning in the 1980s "put […] much emphasis on thin-film" (I11). To avoid producing research for the benefit of individual companies, much of the work of NREL remained focused on investigating more basic physical principles underlying PV technologies. As one of our interviewees points out "they specialize on one semiconductor system, for example, and have never built a [PV] module. Therefore, they are quite detached from the actual application" (I1). An NREL executive agrees that "we typically have worked on projects that have more like a ten year horizon. And these are the kinds of things that industry really is reluctant to or might never fund" (I13).

4.3.4 NREL: Impact of resource dependence on the technological focus of industry

While, similar to Fraunhofer ISE, NREL's resource dependence strongly shaped its technological focus, NREL's positioning farther from the market led to a situation where its direct impact on industry was more limited. In several cases, the technologies developed by NREL were adopted by start-ups pursuing innovative thin-film technologies based on cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) PV. For example, as one interviewee pointed out, "NREL played an essential role in starting First Solar" (I4), which later became the largest thin-film PV producer in the world. Also, as an NREL representative noted, "the interactions between NREL and all the U.S. players in CIGS are quite intense and have been for quite a number of years" (I13). This statement was confirmed by our patent citation analysis, which showed that many firms working on CIGS PV, such as Nanosolar, Stion, or Heliovolt strongly built upon NREL's knowledge. Still, given the large number and size of companies working on c-Si PV, many of the thin-film PV firms struggled to find a hold in the fast-growing PV market. Overall, therefore, considering NREL's leading role in PV research, its large number of patents, and its active efforts to transfer technologies through licensing and partnership agreements, relatively little of the institute's research is reflected in the technologies used in the PV industry. As one of our interviewees stressed, "I am sure that [NREL's research] has resulted in a lot of know-how. But if you look at what has been used in industry, it's a bit sobering" (I1). In the words of one NREL executive: "It's a different kind of agreement that Fraunhofer has where they have to partner with an industry on an industrially meaningful kind of process or product development activity. We have never been funded to do that" (I11).

4.4 Patterns of Co-Evolution with Industry for Fraunhofer ISE and NREL

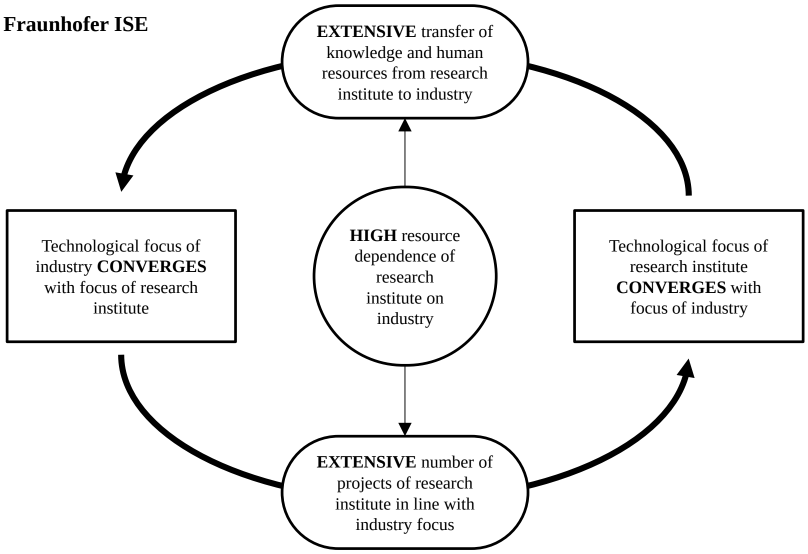
Figure 4 shows the co-evolutionary patterns observed for Fraunhofer ISE and NREL in a stylized way. As described in the previous section, Fraunhofer ISE is highly dependent on funding from the industry, which has led to many industry projects and a deliberate alignment of its technological focus with that of industry (i.e., applied research in c-Si). The reliance on industry funding has meant a robust transfer of knowledge and human resources from the research institute to industry, thereby cementing the industry's focus on c-Si PV. Overall, therefore, for Fraunhofer ISE one can observe a close co-evolution between its technological focus and that of industry. As one of our interviewees stressed, "it's a wonderful feedback mechanism. They deliver, the company is successful, […] that will give them new and interesting things to work on and funding to do so" (I4). A Fraunhofer executive concurred that "we try to shape industry, and we are also part of the industry" (I15).

In contrast to Fraunhofer ISE, NREL shows a low dependence on industry funding, which has led to a limited number of projects with industry and a focus on more basic research on thin-film PV. Moreover, by relying on public funding, NREL has had little incentive to transfer knowledge and human resources from the research institute to industry. In fact, the DOE and Congress have historically been very worried that, publicly funded industry collaborations would replace private investments and distort the market. Thus, although NREL has fostered the emergence of start-ups in thin-film PV, the technological focus of the industry (on c-Si PV) has broadly evolved independently of NREL's work. As a result, NREL is "a little bit more detached from the actual market" (I4) and "Fraunhofer has historically been much more tightly coupled with industry" (I11).[15]

4.5 Risks Resulting for Fraunhofer ISE and NREL

While both patterns represent viable ways of operating research institutes, our analysis shows that each strategy bears risks for both the research institute and its funders. In the case of Fraunhofer ISE, two key risks are its heavy dependence on industry funding and the risk that the research institute and industry would become mutually locked into a specific technology.

First, strong coupling with industry makes Fraunhofer ISE vulnerable to shocks in industry funding. Beginning in 2010, the German PV industry faced a lack of demand and increasing competition from China. As a result, Fraunhofer ISE "lost many of [its] important customers through insolvency" (D28) and "those firms that are still there don't have money" to spend on research. This development "hit the institute very hard. That so many firms went bankrupt, that's brutal for us" (I8).



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[15] Our exploratory correlation analysis confirmed that the more research institutes draw on industry funding, the more they focus on c-Si technology as the more mature technology. Specifically, when correlating the two institutes' annual share of industry funding with the annual share of publications that focus on c-Si PV, the resulting Pearson correlation coefficient is 0.73, indicating strong correlation.

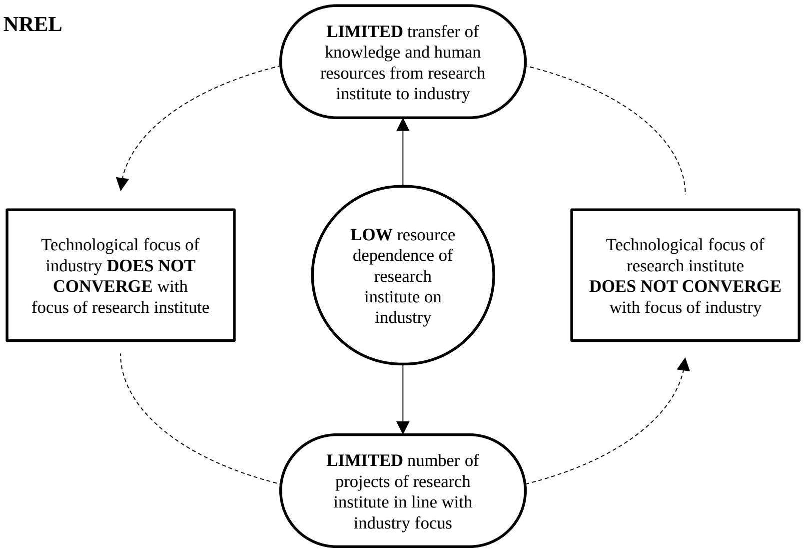

FIGURE 4: Co-evolution between the technological focus of the PV industry and (a) Fraunhofer ISE and (b) NREL

Second, by collaborating so closely, Fraunhofer ISE and its industrial partners reinforce each other's technological focus, which might lead to a mutual technological lock-in. While the proximity to industry is an advantage when trying to generate a practical impact, it could lead to a situation where the contribution of a research institute becomes "kind of incremental, […] more like an engineering job as opposed to pushing back the frontiers of the field" (I4). Indeed, previous literature has shown that, due to public demand-side policies, in recent years firms focusing on thin-film technologies have had difficulty entering and surviving in the PV market (Hoppmann et al., 2013). By conducting research on c-Si PV, research institutes funded by firms working on c-Si PV have contributed to this lock-in, as they have added to the advantageous position of c-Si compared to thin-film in the form of self-reinforcing cycles. In addition, the strong coupling of science and industry could pose a major challenge to both the research institute and firms if, as the DOE expects, thin-film replaces c-Si PV as the dominant technology in the future. As a representative from Fraunhofer ISE pointed out, technology specialization of organizations makes switching to alternatives increasingly difficult: "You have your technology basis, your focus, and you have machinery and personnel that you have hired and built up. You can't just say that you want to do crystalline PV one day, thin-film the next. You'd need to buy new machinery and hire new personnel" (I14). Especially given that "there are other institutes that have long years of experience in a specific technology and you cannot easily make up for this" (I1), a heavy focus on the industry's current technology may turn out to be a disadvantage if that industry shifts its technological focus. As one Fraunhofer ISE director pointed out, he "did sometimes lose sleep when CIS [thin-film] cells with 18% or 20% efficiency were published by some laboratory. Those are the moments when you sit down and calculate what a large plant could look like, what the full costs of ownership are" (I6).

In the case of NREL, the risk of a mutual lock-in with industry is very small. At the same time, however, the institute's heavy dependence upon public funding comes with an increased vulnerability to public budget cuts and the risk that its research will have a limited impact on industry. First, the history of NREL shows that—despite its more diversified portfolio—its sole reliance on public funding has made the research institute very susceptible to changes in political constellations and corresponding budget cuts. For example, in 1995 (after Republications gained control of both houses of Congress) and again in 2005, Congress decided to cut funding for NREL, which meant the institute had to put several research projects on hold and lay off several hundred members of staff. As one NREL representative points out, "budget fluctuations and especially budget reductions in basic R&D funding can be particularly disruptive. It becomes very challenging to maintain our core capabilities and hire promising scientists and engineers for basic research […]" (D29).

Second, a key risk in the way NREL is funded and set up lies in its limited impact on industry. In fact, as pointed out in the previous section, NREL is doing world-class research on PV technologies and, by focusing on more radical technologies and partnering with small firms, has contributed to the emergence of start-ups. A risk of this approach, however, is that "many of the patents developed at NREL are not being commercialized" (I1) and that the institute is becoming decoupled from industry and locked into technologies that are not used in industry. Indeed, as one of our informants confirmed, similar to Fraunhofer ISE, NREL cannot easily change its focus, since it operates specialized equipment and relies on highly specialized researchers. In addition, the institute has developed a culture where "people are evaluated based on publications" (I1), which provides a strong incentive for researchers to focus on more basic research instead of transferring technologies to industry. By being mandated to not distort competition, the institute risks "daydreaming" (I9) and developing solutions that "cannot be implemented at an industrial scale" (I1).

5. DISCUSSION

5.1 Emergent Framework

Figure 5 presents the emergent theoretical framework that describes how the resource dependence of research institutes influences their co-evolution with industry. We suggest that resource dependence influences the technological co-evolution between industry and science through two main mechanisms. First, depending on its resource dependence, a research institute will adjust the number of projects in line with the focus of industry. In the case of a high resource dependence on industry, research institutes engage in more applied projects that aim to improve the technologies the industry is working on. As a result, resource dependence may lead a research institute to adjust its own technological focus to that of industry. Second, research dependence influences the flow of knowledge and human resources from the research institute to industry. When the resource dependence of a research institute on industry is high, the institute will usually design projects to create a direct value for industry, e.g., by helping industry develop products and processes. Moreover, by fostering science-industry collaboration, a high resource dependence on industry enhances the likelihood that researchers from the research institute will shift to working in industry. Together, these mechanisms lead to a situation where the industry adjusts its own technological focus to that of the research institute. Overall, a high resource dependence of research institutes on industry might therefore lead to patterns of co-evolution where the research institute and industry mutually influence each other such that the technological focus converges. If the resource dependence of a research institute on industry is low, however, this self-reinforcing cycle is less likely to emerge, such that no pattern of co-evolution—or only a weak one—can be observed.

5.2 Alternative Explanations

In the following we discuss several alternative factors that might serve as alternative explanations for the dynamics we observe, and we explain why they do not undermine the main findings of our study.

First, while we focus on financial resources to explain how resource dependence shapes the co-evolution of science and industry, it might be possible that other types of resources, such as human capital, equipment, or legitimacy, drive the dynamics we observe. Yet we are confident that financial resources actually played the most important role in shaping the co-evolution of research institutes for two main reasons. First, the critical importance of funding type and sources emerged inductively from our interviews. Interviewees stressed that, while other resources, such as human resources, could be built in-house, it was not easily possible for non-profit research institutes to find substitutes for external funds, which created a high dependency on external funding sources. Second, the finding that financial resources matter most was also confirmed in our archival analysis, which showed that both institutes went through phases of funding cuts that threatened the institutes' survival. These dynamics clearly show the strong dependence of the research institutes on financial resources. In contrast, human resources and equipment primarily serve as important *channels* through which knowledge is transferred, the use of which depends on the type of financial resource dependence.

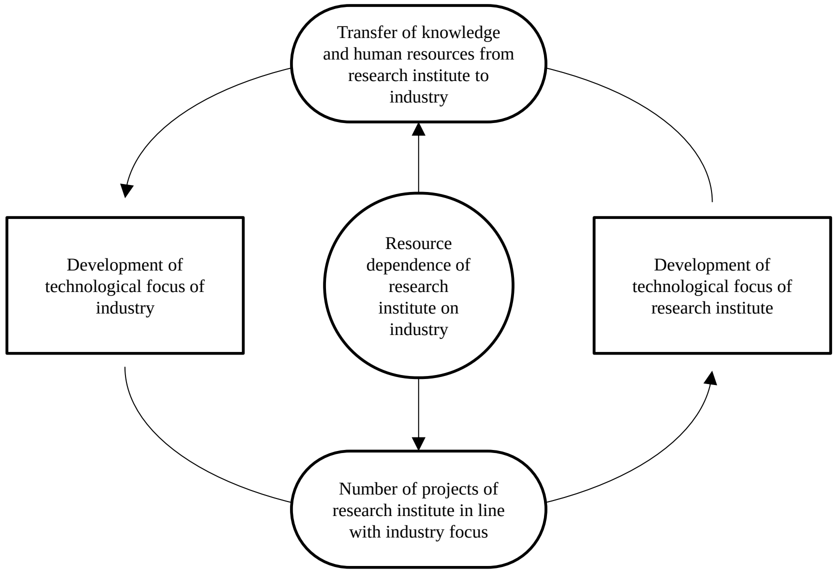

FIGURE 5: Theoretical Framework showing how the resource dependence of research institutes affects their co-evolution with industry

Second, we chose to investigate two large research institutes in two different countries because the differences in funding structure allowed us to investigate in detail how financial resource dependence shapes their co-evolution with industry. A potential problem with this choice, however, is that the patterns in technology evolution we observe may be driven, at least partly, by the culture of the two organizations' home countries, public policies, or other factors operating at the national level. In fact, previous studies have suggested that U.S. culture may favor more radical solutions, which could partly explain the different technological foci of NREL and Fraunhofer ISE (Garud and Karnøe, 2003; Hendry and Harborne, 2011). Yet, the technological focus of each research institute changed considerably over time and was not limited to radical technologies at NREL or incremental technologies at Fraunhofer ISE respectively. Similarly, throughout the period of investigation, there were many other research institutes working on both c-Si and thin-film PV in both countries. For example, in Germany (in addition to Fraunhofer ISE) the ZSW Stuttgart and the Helmholtz Zentrum Berlin have conducted research on PV technologies. The ZSW receives a larger share of its funding from the German government than Fraunhofer ISE. As a result, it has focused on both basic and applied research in thin-film PV and has shown a weaker co-evolution with industry. The Helmholtz Zentrum Berlin is fully government-funded, which has resulted in a strong focus on basic research in thin-film technologies and a very limited interaction with industry. Given these differences across research institutes within the same country, we can rule out that the patterns we observe are solely due to cultural or policy variables at the national level. Moreover, these examples show that the framework we develop holds for research institutes other than Fraunhofer ISE and NREL.

Third, it seems possible that the patterns we observe may be shaped by general trends in technology development. Specifically, previous work shows that deployment policies have contributed to a lock-in with c-Si PV (Hoppmann et al., 2013), which might explain why, despite engaging in commercialization and transfer, NREL has not had a stronger impact on industry. Indeed, broader technological developments have been important in shaping the dynamics we observe. For example, for Fraunhofer ISE, the strong dominance of c-Si PV meant that the institute was able to grow faster than would have been possible otherwise. However, despite this, the strong industry focus on c-Si PV does not undermine the general finding that only when drawing on the construct of resource dependence can we explain the institutes' differences in co-evolution with industry. Specifically, our interviews indicate that Fraunhofer ISE's focus on c-Si and its shift toward more applied research was a strategic choice that was taken even before the industry had been fully established. Moreover, NREL deliberately focused on breakthrough technologies far from industry and continued to do so even as it became clear that the PV industry was primarily focused on c-Si PV. In fact, even if thin-films had entered the market with more strength, NREL's reliance on the DOE would have required it to take a more hands-off approach, since U.S. policy makers wanted to avoid distortions. In contrast, even in the case of a breakthrough, Fraunhofer ISE would have had to closely collaborate with industry, since their funding structure requires them to do so.

5.3 Implications for the Literature

Our study makes several contributions to the literatures on science-industry linkages, technological paradigms, and co-evolution. First, we contribute to the literature on science-industry linkages by adding a dynamic, co-evolutionary perspective. Previous research provides detailed insights into the specific channels through which science and industry are linked, such as publications, licenses, spin-offs, and collaborations (Meyer-Krahmer and Schmoch, 1998; Perkmann et al., 2013; Schartinger et al., 2002). In this context, a number of studies have pointed out that a strong proximity between science and industry could have adverse effects on the mission and output of scientific institutes (Czarnitzki et al., 2012; Nelson, 1994). Yet, thus far, the large majority of studies has taken a unidirectional perspective, i.e., does not explicitly investigate how science and industry may mutually influence each other and what this implies for the overall dynamics in a sector. In contrast, we explicitly take a co-evolutionary perspective and show how knowledge transfer between industry and science, together with the adjustment of research foci, can lead to mutually reinforcing dynamics that are moderated by the resource dependence of research institutes. As a result, our work goes beyond the findings of studies that have taken unidirectional perspective as it shows that that the technological focus of research institutes and industry may converge over time, raising the risk of mutual lock-ins into specific technologies. At the same time, our work contributes to the literature by showing how a weak resource dependence of research institutes on industry may also lead research institutes to become locked into technologies that are not used in industry. These findings are important, since previous literature has highlighted the advantages and disadvantages of linkages between science and industry but, thus far, has not investigated the long-term consequences for scientific institutes that could result from a pronounced decoupling.

Second, we contribute to the literature on science-industry interaction by highlighting financial resource dependence as an important antecedent for the use of specific channels of science-industry interactions. While early work has focused on investigating the mechanisms and channels of science-industry interaction, recently researchers have become particularly interested in understanding what determines the use of individual channels in a specific context. In this context, first scholars have pointed to a potentially important role of funding as an antecedent of knowledge transfer (Carayol, 2003; Colyvas et al., 2002; Lee, 1996). Yet, thus far, little is known about how the funding structure of organizations affects the mechanisms and dynamics of knowledge transfer. We show that a greater financial resource dependence of research institutes on industry leads to the use of more direct channels of knowledge transfer, such as collaborations or personnel exchange (Carayol, 2003). More importantly, our findings show that resource dependence leads not only to a unidirectional transfer but also to mutual influence. In this sense, our work adds a new perspective to the study of channel antecedents, which, similar to studies on the channels themselves, has focused on factors that facilitate a unidirectional transfer of findings from science to industry.

Third, by providing a dynamic, longer-term perspective on science-industry interaction, our work helps connect this stream of literature to the work on technological paradigms and lock-ins (Arthur, 1989; Dosi, 1982). Work on technological paradigms and lock-ins has long investigated the different factors that may contribute to the emergence of specific technological trajectories and path dependencies. In this context, it has been pointed out that, over the course of a technology's life-cycle, the emergence of routines, standards, and economies of scale among scientific institutes, firms, and consumers may contribute to an increasing rate of incremental innovation (Arthur, 1989; Dosi, 1982; Malerba, 2009). To our knowledge, however, previous work has not studied how changes in the patterns of interaction between science and industry may contribute to such a development. Our findings suggest that, as an industry grows, so does the possibility of firms to fund external research, leading to a closer co-evolution between science and industry, and hence a more incremental approach to technology development. In this sense, our findings provide a new perspective on the emergence of technological paradigms that complements existing explanations in the literature.

Finally, we contribute to the literature on co-evolution by adding insights from the literature on resource dependence. Prior research on the co-evolution of science and industry has primarily studied co-evolution at the industry level (Blankenberg and Buenstorf, 2016; Murmann, 2013) and provides limited insights into how organizational characteristics may shape patterns of co-evolution. Specifically, the extant literature is relatively silent on why specific organizations might co-evolve with some entities but not with others. Murmann (2013, p. 58), for example, points out that "Although there is an emerging consensus that in high-tech sectors, firms, industries, technologies, and institutions like universities coevolve […], we lack a detailed account of how these coevolutionary processes take place […]." We identify a research institute's resource dependence as a critical factor determining the degree to which the technological focus of a research institute is coupled to that of industry. As a result, our study helps predict patterns of co-evolution between specific scientific bodies and industry. For example, based on our results, we would expect the focus of privately funded research institutes to converge much more strongly with industry than that of publicly funded bodies.

5.4 Implications for Practitioners

Our research also has important implications for policy makers and the managers of research institutes. In recent years, policy makers have tried to improve the interface between industry and science to advance technological change and address pressing societal and environmental issues, such as climate change, e.g., by investing public resources in developing clean energy technologies (Anadon, 2012; Mowery et al., 2010). Despite these efforts, studies have concluded that the impact of research on industry has often been limited (Bonvillian and Van Atta, 2011). For example, investigating the role of U.S. national labs in clean energy innovation, Anadon et al. (2016, p. 3) point out that there has been “an increasing disconnect between the Labs and the private sector”.

Our study suggests that one way to more closely couple science to industry and to speed up the commercialization of scientific findings could be to more strongly draw on private funding when financing public research projects. According to our study, complementing public funds with direct industry funding is likely to result in more relevant research projects as well as a more intensive and effective use of different transfer channels. An example for how such projects can be structured is a research program on battery storage, which the European Commission announced in December 2019 as part of its European Battery Alliance (European Commission, 2019). The program, a key goal of which is to spur “concerted action to accelerate lab-to-market innovation” will be jointly funded through public EU funding (EUR 3.2 B) and private funds (estimated EUR 5 B).

While private funding may help accelerate technology transfer, our research also indicates that a potential problem with using private funds to co-finance public research lies in distorting competition and a potential convergence of industry and science that could result in incremental innovation and technological lock-ins. To avoid competitive distortions, the results of research projects that are partly funded through public funds should be openly disseminated and/or projects be approved based on a competitive process. For example, the EU project on battery research requires that the results of the project “be widely shared by participating companies” (European Commission, 2019). Moreover, in the case of the EU project, “if the projects turn out to be successful, generating extra net revenues beyond projections, the companies will return part of the taxpayer money received to the respective Member States” (European Commission, 2019).

To ensure that an increased share of private funding does not lead to research institutes becoming the puppets of industry, public bodies need to distribute funding in a way that reflects a portfolio of alternative technologies (including those not currently used in industry). In this sense, setting up research programs involves a delicate balance between building on prior industry knowledge (to ensure a smooth transfer) and funding research that leads to the emergence of radically new technological alternatives (to avoid technological lock-ins). In fact, although NREL has had a limited impact on the PV industry, a core strength of the approach taken by the DOE is that it has the potential of leading to the creation of new technological paradigms and start-ups beyond the existing industry (Doblinger et al., 2019). Given that many firms draw upon the knowledge of research institutes, the failure to foster the emergence of new technologies may quickly lead to lock-ins or a lack of innovativeness for entire industries within a country. For example, in the automotive sector, a large number of research institutes have specialized on combustion engines, which hinders progress on alternatives and contributes to the sector being locked into fossil fuels. Therefore, determining the right funding portfolio for research institutes is of major importance for both the research institutes (to secure their survival) as well as from a societal perspective. Whereas private funds are likely to primarily spur research that builds upon the existing knowledge of industry, public funds can be used to foster more explorative research. To foster both explorative and exploitative research, policy makers should thus use a mix of private and public sources. In this context, the ideal mix of funding sources is likely to depend on a large number of factors, e.g., the industry's maturity and barriers to entry, the availability, technological potential, and merits of technological alternatives, as well as the extent to which policy makers wish to support incumbent vs. start-up firms.

5.5 Limitations and Future Work

Our study has several limitations that offer promising avenues for future research. Specifically, the fact that our study is limited to the investigation of two research organizations for solar PV raises the question of the external validity of our findings. Broadly speaking, we would expect the general findings to hold for a wide range of industries, since the mechanism of private funding leading to more applied research and a stronger use of transfer channels appears to be applicable to research institutes in other sectors. At the same time, however, we acknowledge that PV possesses specific technology characteristics that could lead to differences in the specific dynamics and transfer channels compared to alternative technologies. For example, industries that rely on mass-manufactured, modular goods are usually characterized by steeper learning curves and a greater importance of economies of scale, which raises barriers to entry for novel technologies. We would therefore expect the risk of a mutual lock-in between science and industry to be more pronounced for mass-manufactured, modular technologies, such as PV, than for more complex, customized products, such as wind power or fuel cells. Future research should therefore investigate how technology characteristics might impact the patterns of co-evolution between industry and science, and the role of resource dependence in driving co-evolution. In addition, given the emerging character of our theory, we call for future research that explores in greater detail how research programs that include private funding can be designed to minimize the risk of distorting competition and to prevent institutes from being locked into specific technologies and wandering hand in hand to Nowhereland.

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APPENDIX A

We determined the technological focus (c-Si vs. thin-film PV) of the patents and publications from both research institutes by conducting a keyword search in the titles and abstracts (see Table A.1).

TABLE A.1: Keywords used in content analysis of publication and patent titles and abstracts

Category	Search String	Priority*
C-Si PV	“silicon solar cell*” OR “Si-solar cell*” OR “ribbon” OR “Si solar cell” OR “Si substrate” OR “silicon substrate” OR [(“ Si “ OR “silicon” OR “Si-solar”) AND (“single crystal” OR “single-crystal” OR “monocrystalline” OR “monocrystal” OR “ crystalline” OR “back surface passivation” OR “rear surface passivation” OR “wafer”)] OR [(“ Si “ OR “silicon” OR “Si-solar”) AND (“polycrystalline” OR “multicrystalline” OR “multi-crystalline” OR “multi crystalline” OR “poly-crystalline” OR “poly-crystalline” OR “polycrystal” OR “poly crystal” OR “multicrystal” OR “multi crystal” OR “Emitter wrap through” OR “Metal wrap through”)]	0
Thin-film PV	“steel substrate” OR “roll-to-roll” OR “roll to roll” OR “vacuum depos” OR “deposit” OR “vacuum chamber” OR “lamina” OR “epitaxially grown” OR “thin film” OR “thin-film” OR “ film “ OR “plastic substrate” OR “semiconductor film” OR “sputter” OR “glass substrate” OR “flexible substrate” OR “PECVD” OR “PVD” OR “solid phase crystallization” OR "laser crystallization” OR “a-Si” OR “amorphous” OR “microcrystal” OR “silicon-film” OR “Staebler” OR “Cadmium” OR “Telluride” OR “CdTe” OR “ CdS “ OR “Sulphide” OR “ Se “ OR “ Cd “ OR “ Te “ OR “ CIGS “ OR “CI(G)S” OR “indium” OR “selenide” OR “ CIS “ OR “CuInSe” OR “Copper indium gallium diselenide” OR “CuInGeSe” OR “Copper zinc tin sulfide” OR “CZTS” OR “chalcopyrite”	1
Third generation PV**	"lens" OR "CPV" OR "concentrator" OR "upconver" OR "up-conver" OR "downconver" OR "down-conver" OR "concentr*" OR "hot carrier" OR "hot-carrier" OR "GaAs " OR "Ga-Al-As" OR "gallium arsenide" OR "germanium" OR "crystalline thin-film" OR "crystalline thin film" OR "GaSb" OR "dye-sensitiz" OR "dye sensitiz" OR " organic" OR "dye" OR "nano" OR "tio2" OR "quantum dot" OR "droplet epitaxy" OR "polymer" OR “titanium dioxide” OR “titanium oxide” OR “Graetzel” OR “perovskite” OR [(“steel substrate” OR “roll-to-roll” OR “roll to roll” OR “vacuum depos” OR “deposit” OR “vacuum chamber” OR “lamina” OR “epitaxially grown” OR “thin film” OR “thin-film” OR “ film “ OR “plastic substrate” OR “semiconductor film” OR “sputter” OR “glass substrate” OR “flexible substrate” OR “PECVD” OR “PVD” OR “solid phase crystallization” OR "laser crystallization”) AND (Si “ OR “silicon” OR “Si-solar”] AND [“single crystal” OR “single-crystal” OR “monocrystalline” OR “monocrystal” OR “ crystalline “)	2
Generic	“storage” OR “mounting” OR “roof” OR “solar tracker” OR “fuel cell” OR “inverter” OR “absorber” OR “glazing” OR “antireflect” OR “anti-reflect” or “metal evaporation” OR “filter” OR “Gasochromic”	3

* In the case that an abstract contained keywords from several categories, it was assigned to the category with the highest priority since keywords in higher groups indicate work on more advanced technologies. The “generic” category captures publications on topics that are applicable to all PV technologies.

** Includes concentrating PV, dye-sensitized PV, organic PV, nano PV, c-Si PV, and thin-film PV

The categories of PV technologies were derived from prior literature, while the keywords used to assign patents and publications to the technology categories were developed in an iterative process drawing on prior PV publications. Specifically, to develop the keywords, we conducted a thorough review of the alternative PV technologies and developed a list of their differentiating criteria. Drawing on this list of keywords, we then classified the publications and patents of Fraunhofer ISE and NREL and checked a random set of publications and patents to determine whether our algorithm had correctly identified the underlying PV technology. We then added new and altered existing keywords until all publications and patents were correctly identified. To ensure that our categorization was correct, we discussed this classification with our interviewees and made final adjustments to the list of keywords.

In cases where the title or the abstract of a patent or publication contained keywords from several categories, it was assigned to the category with the highest priority, since keywords in higher groups indicate work on more advanced technologies. For example, if the abstract of a patent published by Fraunhofer ISE contained keywords pertaining to both c-Si PV and thin-film PV, it was assigned to thin-film PV, since keywords related to thin-film PV in addition to c-Si PV would indicate that the research organization is trying to advance older technologies (c-Si PV) by investigating newer concepts (thin-film PV).

Our classification approach works for both publications and patents since the list of keywords we used for classification was developed by looking at both patents and publications and extracting those signaling words that would allow us to differentiate them according to different PV technologies. Due to their different nature and purpose, patents and publications differ with regard to the prevalence of specific keywords. However, given that keywords clearly pertain to specific technologies, including keywords mostly found in patents to categorize publications and vice versa can be considered unproblematic. For the sake of consistency, we therefore did not develop two separate search strings but rather included all keywords in one search string that was suited to classifying both patents and publications with respect to the specific PV technologies.

APPENDIX B

TABLE B.1: Keywords used to extract solar PV patents

Patent search	Search String
Solar PV patents	IP=(B23K* OR B28D* OR C01B-033* OR C23C* OR C30B* OR E04D-013* OR H01L-031* OR H01L-021* OR H01L-025* OR H01L-051* OR H02M* OR H02J* OR H02N*-006* OR H01R* OR G01B* OR G01R* OR G05F-001*) AND (TI =("solar cell*" OR "solar power*" OR "solar module*" OR "photovoltaic*" OR "solar panel*" OR "solar grade" OR "solar electr*") OR (TS=("solar cell*" OR "solar power*" OR "solar module*" OR "photovoltaic*" OR "solar panel*" OR "solar grade" OR "solar electr*")))

TABLE B.2: List of referenced archival documents

ID	Document Title	Source	Date
D1	Washington Decrees a Solar Eclipse	The New York Times	08/12/1981
D2	Energy lab chief vows jump start	Denver Post	03/07/1995
D3	NREL director takes Galvin report to heart, plans to privatize research	R&D	05/01/1995
D4	Budget Reductions Prompt NREL to Weigh 10% Cut in Personnel	Federal Technology Report	10/09/1995
D5	Government Researchers Fear Budget Cuts Will Cool Solar Energy Work	The Washington Post	09/25/1996
D6	Between 150 and 160 NREL Employees Will Lose Their Jobs	Inside Energy	12/25/1996
D7	Energy lab facing worker layoffs as funds are shifted	Denver Post	12/20/2005
D8	US Renewable R&D Under Threat	Platts Commodity News	01/10/2006
D9	Budget Shortfall Forces Renewable Energy Laboratory to Lay Off 32 Staff	US Fed News	02/07/2006
D10	Bush Presses Energy Alternatives to Oil But Visits Lab With Layoffs Due to Federal Fund Cuts	Pittsburgh Post-Gazette	02/22/2006
D11	Photovoltaics Program Overview	U.S. Department of Energy	1981
D12	Energetic Questions and Answers Energy and Security	The New York Times	08/16/1981
D13	Revolutionary Changes for Solar Energy Field	The New York Times	08/18/1981
D14	Fed official stresses alternative energies Partnership with private industry pushed	Denver Post	04/14/1992
D15	U.N. Plans Parley on Energy Sources	The New York Times	07/26/1981
D16	Renewable Energy—DOE Opposes Bill to Expand Programs in Renewables, Conservation	Inside Energy	07/04/1988
D17	History and Overview of Solar Heat Technologies	Donald A Beattie, MIT Press	1997
D18	PVMaT Advances in the Photovoltaic Industry and the Focus of Future PV Manufacturing R&D	IEEE PV Specialists Conference New Orleans, Louisiana	05/20/2002
D19	Fraunhofer ISE Annual Report 1992	Fraunhofer ISE	1993
D20	Fraunhofer Solar Energy Research Institute Faces Lack of Funding	Frankfurter Allgemeine Zeitung	09/01/1993
D21	Sonnenenergie-Forschung geht düsteren Zeiten entgegen	Süddeutsche Zeitung	02/14/1997
D22	Solarprojekte ohne Lobby	taz - die tageszeitung	07/28/1997
D23	Fraunhofer ISE Annual Report 1996	Fraunhofer ISE	1997
D24	Fraunhofer ISE Annual Report 1998	Fraunhofer ISE	1999
D25	Fraunhofer ISE Annual Report 1999	Fraunhofer ISE	2000
D26	Innovation durch Forschung - Jahresbericht 2005 zur Forschungsförderung im Bereich der erneuerbaren Energien.	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, Berlin	2006
D27	Multikristalline Solarzellen bringen der Branche neue Hoffnung	MaschinenMarkt Online	05/07/2012
D28	Düstere Aussichten für deutsche Solarforschung	Deutsche Welle	08/09/2012
D29	Talking with Some Directors of the U.S. National Laboratories	The Journal of The Minerals, Metals & Materials Society (TMS)	06/2005