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A framework and methodology for analyzing technology spillover processes with an application in solar photovoltaics

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ABSTRACT

Technology spillovers, understood as knowledge flows across technology domains, are an important mechanism for innovation, as progress in one technology area can lead to unexpected benefits in other technology areas. Despite the importance of technology spillovers in theories of recombinant innovation, significant gaps remain in our understanding of how spillovers across knowledge domains occur, what factors enable or affect spillovers, or how much consideration should be given to technology spillovers in research and innovation policy and management. In this paper, we develop and demonstrate novel conceptual and methodological tools to address these knowledge gaps. Specifically, we introduce a conceptual framework that views technology spillovers as a dynamic process of micro-level knowledge transfer across technological domains that drives recombinant innovation in a knowledge-receiving domain. We use this framework to develop a process-tracing methodology for identifying and analyzing individual micro-level technology spillovers. We demonstrate the application of our framework and methodology in a case of three important innovations in crystalline silicon solar photovoltaics by reconstructing a detailed history of how technology spillovers have played a critical role in enabling and driving these three innovations over time. We show how our approach generates important insights relevant to public policy and R&D management that aim to harness spillovers for accelerating innovation.

1. Introduction

A knowledge spillover occurs when knowledge developed for one purpose or in one socio-technical context is applied for a new purpose or in a new context. Theories of innovation point to the critical role of knowledge spillovers in driving technological change and economic growth (Romer, 1986; Griliches, 1991; Weitzman, 1998). Reflecting this role, knowledge spillovers between firms or geographical locations have been extensively studied in the literature (see, for example, notable reviews by Griliches, 1991; Feldman, 1999; Breschy and Lissoni, 2001; Cerver-Romero et al., 2020).

In contrast, knowledge spillovers across technology areas, which we refer to as “technology spillovers” in this paper, have received relatively less scholarly attention. Prominent historical examples of technology spillovers include advances in aircraft technology driven by postwar progress in electronics in the mid-20th century (Mowery and Rosenberg, 1998), or the development of commercial TV technology by radio manufacturers (Klepper and Simons, 2000). More recently, the development of wind energy has significantly benefitted from knowledge and expertise in shipbuilding, marine propulsion, and micro-meteorology (Nemet, 2012), composite materials (International Energy Agency, 2020), and offshore oil and gas extraction (Steen and Hansen, 2014; Mäkitie et al., 2018), while knowledge on phosphor chemical compounds developed for color TV sets enabled the first practical white solid-state lighting sources (Weinold et al., 2021).

Overall, existing theories of recombinant innovation, as well as empirical research, show that breakthrough innovations often come from novel combinations of technologically distant prior knowledge (Rosenberg, 1994; Ahuja and Lampert, 2001; Fleming, 2001; Rosenkopf and Nerkar, 2001). However, reliance on external knowledge does not

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always yield fruitful innovation and can even be counterproductive to the success of innovation process (Levinthal and March 1993; Ahuja and Lampert, 2001; Kaplan and Vakili, 2015). For organizations involved in conducting or funding research and development (R&D), this can create a trade-off between supporting R&D in their core competence areas and supporting interdisciplinary work that encompasses multiple domains (Rothaermel and Alexandre, 2009; Nemet and Johnson, 2012; Wang et al., 2018; Choi and Lee, 2021). Therefore, understanding how technology spillovers drive innovation is essential to inform the development of policies, strategies, and R&D management practices that aim to support and accelerate innovation and technological change. This is especially important in domains such as clean energy, where technology spillovers are expected to play a major role in the development of next-generation technologies, and where accelerating innovation is crucial for meeting global climate goals (International Energy Agency, 2020).

Existing studies on technology spillovers have mostly leveraged patent citations and trade data to understand the aggregate dynamics of knowledge flows between different sectors, industries, or technology domains. However, due to the aggregate nature of data used, these methodological approaches are typically limited in their ability to develop insights into the micro-level processes of external knowledge search, transfer, and recombination that drive innovation and technological change, according to existing theories. As a result, there is limited systematic empirical evidence and understanding of the micro-level mechanisms by which spillovers across technology domains (rather than firms or geographies) occur, the factors that enable or hinder these spillovers, or the ways in which they have contributed to innovation in particular technologies.

New conceptual and methodological tools are needed to address these knowledge gaps. The main aim of this paper is to develop such tools, which would enable the systematic analysis of the mechanisms, determinants, and impact of technology spillovers on innovation, and demonstrate how these tools can be applied in practice to develop actionable insights for R&D and innovation policy and management.

To achieve this aim, our study makes three important contributions to research and practice. First, we contribute to innovation theory by developing a novel conceptual framework that defines technology spillovers as a dynamic process of knowledge transfer between technology domains that drives innovation in the knowledge-receiving domain. Our second contribution is to research methodology. Using our conceptual framework, we develop a process-tracing methodology to inductively identify individual micro-level technology spillovers into a particular technology domain and analyze their sources, mechanisms, determinants, and impact on innovation. Our methodology is based on a process tracing approach (Collier, 2011; Mahoney, 2012) that seeks to offer a mechanistic account of spillover outcomes through an iterative, pragmatic research design (Beach and Pedersen, 2019). Specifically, our approach combines literature surveys, in-depth expert interviews, analysis of citations in publications and patents, and a machine learning-based algorithm for patent text analytics that tracks the integration of knowledge characterized in the text of patents into a technology domain. Third, we contribute to the literature on clean energy innovation and a growing body of empirical evidence on the impact of energy innovation policies by applying our framework and methodology in an illustrative case study of three important innovations in crystalline silicon-based (c-Si) solar photovoltaic (PV) technology. Using these conceptual and methodological tools, we reconstruct a detailed history of these c-Si PV innovations over the span of almost six decades. From this case study, we identify important insights about the role, mechanisms, and determinants of technology spillovers in solar photovoltaics and show how these insights can inform public policy and technology management practices that aim to advance clean energy innovation.

The rest of the paper is structured as follows. Sections 1.1-1.3 discuss existing technology spillover concepts, review prior literature, and identify major knowledge gaps in this field. Section 2 introduces our conceptual framework of technology spillover processes and describes the process-tracing methodology based on our framework. Section 3 demonstrates the results of applying our methodology in a case study of three c-Si PV innovations. Section 4 concludes with a discussion of the research and policy implications of our work.

1.1. *Two perspectives on technology spillovers*

Knowledge spillovers are typically viewed in economics as an externality by which "*creation of new knowledge by one firm is assumed to have a positive external effect on the production possibilities of other firms*" (Romer, 1986). This perspective has been instrumental in a wide range of findings, from explaining endogenous economic growth (Arrow, 1962; Romer, 1986) and geographical concentration of innovation (Jaffe et al., 1993; Audretsch and Feldman, 1996; Feldman, 1999), to estimating the social returns on R&D investment (Nelson, 1959; Griliches, 1991; Hall et al., 2010; Bloom et al., 2013), measuring the impact of foreign direct investment on domestic innovation and productivity (Kokko, 1994; Coe and Helpman, 1995; Perez, 1997), and tracking cross-country knowledge diffusion (e.g., Conti et al., 2018). In this perspective, spillovers at the firm level are typically operationalized as the change in R&D activities, patenting, productivity, human capital, or market value of one firm as the result of R&D in other firms (Jaffe, 1986; Kokko, 1994; Garcia-Vega, 2006; Bloom et al., 2013; Byun et al., 2021; Nemet et al., 2020). In this context, the term "technology spillovers" (cf. Bloom et al., 2013) is often used synonymously with "R&D spillovers" (cf. Griliches, 1991; Audretsch and Feldman, 1996) or, simply, "knowledge spillovers" (cf. Feldman, 1999) and typically does not exclusively mean spillovers between different technologies.

Another perspective on spillovers comes from evolutionary economics, science and innovation studies, and knowledge management research. In this literature, innovation and technological change are often considered to be a result of the recombination of existing "building blocks" of knowledge coming from different scientific disciplines and technology domains (Usher, 1954; Nelson and Winter 1982; Rosenberg, 1994; Grupp, 1996; Mowery and Rosenberg, 1998; Weitzman, 1998; Fleming, 2001; Arthur, 2007). These "building blocks" can be either "local" or "external" relative to a particular technological area. Correspondingly, a spillover in this perspective is simply an external knowledge input into the innovation process in a particular technology domain. Following this logic, the transfer of knowledge between different disciplines, technologies, industries, or sectors for the purpose of innovation is often called "inter-sectoral knowledge spillovers" (Verspagen, 1997; Stephan et al., 2019), "external knowledge spillovers" (Battke et al., 2016; Noailly and Shestalova, 2017), "inter-technology spillovers" (Nemet, 2012; Noailly and Shestalova, 2017), or, simply, "technology spillovers" (Grupp, 1996; Mowery and Rosenberg, 1998; Verspagen and De Loo, 1999). Accordingly, we adopt "technology spillovers" as our preferred terminology in this paper. Importantly, viewing technology spillovers as knowledge input into innovation does not negate or contradict the view on spillovers as knowledge externalities. Instead, the "knowledge input perspective" builds on the "knowledge externality perspective" by suggesting a particular mechanism by which knowledge externalities contribute to innovation.

Empirical evidence from individual historical cases and quantitative research supports the knowledge input perspective on spillovers by showing that breakthrough innovations often rely on a "boundary-spanning search" for external knowledge beyond the technological specialization of an organization (Ahuja and Lampert, 2001; Rosenkopf and Nerkar, 2001; Phene et al., 2006). However, the search for knowledge beyond domain boundaries can be less fruitful than local knowledge search (Jung and Lee, 2016) or even counter-productive (Levinthal and March 1993; Ahuja and Lampert, 2001; Messeni Petruzzelli et al., 2015) due to the lack of capacity to absorb and use cognitively distant external knowledge (Cohen and Levinthal, 1990; Messeni Petruzzelli et al., 2009). Similarly, Kaplan and Vakili (2015) find that the recombination of distant or diverse knowledge is a “double-edged sword:” it is necessary for breakthrough innovation but fruitless without a deep understanding of the local knowledge domain. Overall, the extent of reliance on external knowledge input has been observed to have an inverted U-shaped relationship with the likelihood of individual breakthrough innovations in particular domains (Phene et al., 2006) and the overall innovative performance of a firm (Rothaermel and Alexandre, 2009). However, research also indicates that the extent to which external knowledge from different technologies or sectors contributes to important innovations in a particular technology or sector is highly contextual, domain-specific, and relies on many factors such as knowledge maturity or technology distance between domains (Nemet, 2012; Nemet and Johnson, 2012; Noailly and Shestalova, 2017; Capaldo et al., 2017).

These findings suggest that balancing local and external knowledge search in the process of innovation can be important for R&D and innovation management, strategy, and policy, as there can be both complementarity and tradeoffs in pursuing progress in core areas of technological expertise or expanding these efforts into external domains through interdisciplinary R&D and learning (Rothaermel and Alexandre, 2009; Nemet, 2012; Nemet and Johnson, 2012). Finding and actively managing such balance for the advancement of technological innovation requires the systematic understanding of answers to the following research questions: 1) How technology spillovers occur? 2) What factors enable or affect spillovers? and 3) How and in which way technology spillovers contribute to innovation?

1.2. Mechanisms, determinants, and contributions of technology spillovers to innovation

The literature on knowledge management and knowledge exchange together with historical case studies of individual technological innovations provide useful insights into the mechanisms of cross-domain knowledge transfer. We group disparate empirical observations made in these studies into four potential spillover mechanisms: 1) independent *learning and researching* activities, which involve finding external knowledge either in existing sources of codified knowledge (e.g., publications, patents, technical reports) or through the process of independently conducted R&D (Malerba, 1992); 2) knowledge sharing between individuals or organizations in the process of *communication and collaboration* (Malerba, 1992; Appleyard, 1996; Watanabe et al., 2004; Fershtman and Gandal, 2011; Al-Laham et al., 2011; Tzabbar et al., 2013; Steen and Hansen, 2014; Wang et al., 2017; Stephan et al., 2021; Gao et al., 2022); 3) *human mobility* across industries or disciplines (Feldman, 1999; Song et al. 2003; Görg and Strobl, 2005; Liu et al., 2010; Al-Laham et al., 2011; Tzabbar et al., 2013; Mäkitie et al., 2018; Stephan et al., 2021); and 4) *mediation by physical objects* (Coe and Helpman, 1995; Feldman, 1999), wherein materials, components, infrastructure or manufacturing equipment originating in external domains, industries or sectors find use in the recipient technology domain (Han and Park, 2006; Hoppmann, 2018; Mäkitie et al., 2018; Stephan et al., 2021).

Notably, while these observations suggest potential technology spillover mechanisms, there is insufficient systematic evidence about the prevalence of different mechanisms, how technology-specific they are, and what contextual factors and in what way affect these mechanisms and spillovers in general. Some studies, relying on patent citations or interviews, consider the extent to which the source and characteristics of external knowledge shape individual technologies over time, based on factors such as the complexity of the knowledge base and position in the supply chain (Malhotra et al., 2019), product architecture and centrality of the relevant knowledge to the technology (Battke et al., 2016), or stage of technology development (Stephan et al., 2017). Historical case studies of particular technologies also indicate other factors that may enable technology spillovers, such as the availability of relevant technical and marketing expertise within a firm (Klepper and Simons, 2000), public R&D expenditures in dual-purpose technologies (Mowery and Rosenberg, 1998), or strategic efforts of firms to seek new market opportunities in sectors with a similar resource base (Steen and Hansen, 2014). More recently, Stephan et al. (2021) found that several key technological breakthroughs and manufacturing process improvements in lithium-ion batteries were driven by technology spillovers that differed by their source and mechanism and were enabled by factors such as the structure and availability of public and private funding for interdisciplinary research, freedom of search, established channels of knowledge exchange between industry and academia, and public interest in a problem.

Although these disparate studies offer a glimpse into a variety and complexity of factors that can affect technology spillovers, they are insufficient to generate a systematic understanding of the relationship between recombinant innovation processes, spillover mechanisms, technology characteristics, and broader institutional, policy, and organizational environments that determine how technology spillovers occur and contribute to technological innovation. To the best of our knowledge, no study has systematically and empirically analyzed the mechanisms of technology spillovers or evaluated the extent to which spillovers have contributed to innovations in a particular technology over time, nor what policies, knowledge exchange practices, or organizational factors made those spillovers possible.

1.3. Limitations of existing spillover concepts and research methodologies

The identified gap in evidence and understanding can be attributed to the limitations of existing technology spillover concepts and underlying research methodologies. The knowledge externality perspective on technology spillovers focuses on the aggregate effect of external knowledge, as discussed in section 1.1, with limited capacity for identifying and analyzing the micro-level causal mechanisms that drive this external effect. The knowledge input perspective addresses this limitation by explicitly focusing on one such mechanism: the contribution of external knowledge “building blocks” provided by technology spillovers into the recombinant innovation process. This perspective enables the analysis of spillovers at the micro-level of individual innovations. Still, there are substantial methodological obstacles that make the systematic analysis of micro-level spillover mechanisms and determinants difficult.

Specifically, quantitative studies based on the knowledge input perspective commonly represent technology spillovers and associated macro-level inter-technology and inter-sectoral knowledge flows by patent citations between technology domains (cf. Trajtenberg et al., 1997; Phene et al., 2006; Han and Park, 2006; Nemet, 2012; Nemet and Johnson, 2012; Messeni Petruzzelli et al., 2015; Battke et al., 2016; Noailly and Shestalova, 2017; Capaldo et al., 2017; Stephan et al., 2017; Stephan et al., 2019). In this approach, backward citations in patents indicate connections to prior knowledge “building blocks”, whereas forward citations indicate knowledge contributions of the patents to future inventions. A citation can potentially represent an individual spillover if the citing and cited documents connected by it belong to different knowledge domains. However, patent citations typically provide little information about the context in which individual spillovers occur. Moreover, citations are known to be an imperfect and very noisy proxy of knowledge flows, as not all inventions and innovations are patented, not all knowledge sources are cited, and not all citations represent an actual transfer of knowledge, as citations are often added by patent examiners rather than inventors (Jaffe et al., 2000; Alcácer and Gittelman, 2006). In addition, this proxy is even less reliable in longitudinal contexts as citation practices have evolved over time (Kuhn et al., 2020). As a result, quantitative methods based on analyzing patent citations can produce some relevant insights into the high-level structural or institutional factors, such as technology or sectoral characteristics, that affect spillovers, but otherwise provide limited information about the context, mechanisms, determinants, or dynamics of individual spillovers.

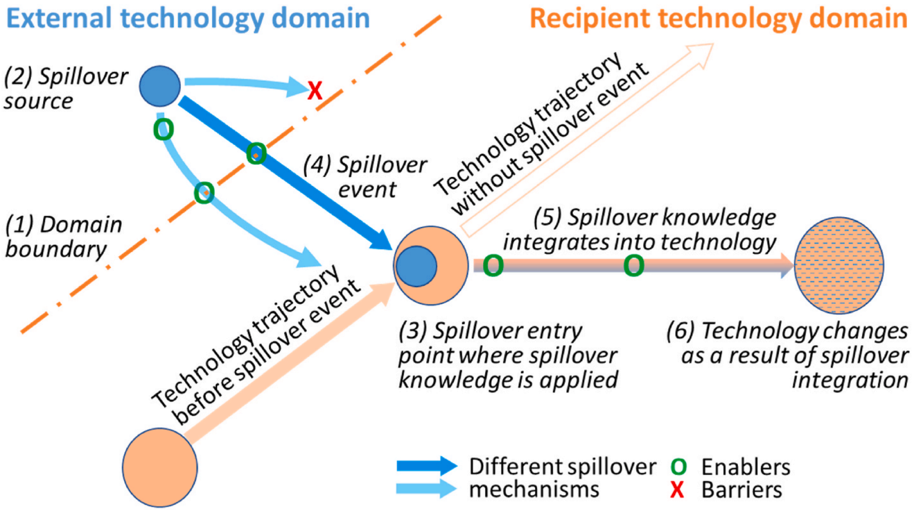

Fig. 1. Schematic representation of a technology spillover process. The blue color represents external spillover knowledge, with arrows of different shades of blue representing different spillover mechanisms. The orange color represents the recipient technology, with orange arrows representing its trajectory over time. Small green circles and a red cross correspondingly represent enablers and barriers of the spillover.

This missing information can be obtained for individual spillovers with qualitative research methods, such as elite interviews with inventors and industry experts (Tansey, 2007) or reviews of written records of inventions contained in historical documents or published in scholarly literature. These methods can offer deep insights into the role and mechanisms of spillovers in particular innovations as they happened (cf. Steen and Hansen, 2014; Stephan et al., 2021). However, these qualitative methods are hard to generalize beyond individual cases and biased towards major technological breakthroughs that are already familiar to experts, potentially overlooking some important but lesser-known cases of technology spillovers.

Overall, we find that on their own, knowledge externality and knowledge input perspectives on technology spillovers, as well as existing quantitative and qualitative research methods are limited in their capability to build the level of understanding of the mechanisms, determinants, and contributions of technology spillovers to innovation necessary for generating actionable insights for policy and management. New conceptual approaches and methodological tools are needed to overcome these limitations. The main aim of this paper is thus to develop such a conceptual framework and methodology that jointly enable the systematic analysis of the mechanisms, determinants, and impact of technology spillovers at the micro-level of individual innovations and spillovers, and then demonstrate how this framework and methodology can be applied in practice.

2. Conceptual framework and methodology

We address the identified conceptual and methodological limitations in the extant literature by proposing a novel process-based perspective on technology spillovers. This approach builds on both the knowledge externality and knowledge input perspectives by viewing technology spillovers as *a process of knowledge transfer between technology domains that drives technological change in the recipient domain* by contributing external knowledge to the recombinant innovation process in this domain. Conceptualizing spillovers as a process builds on prior literature that has adopted process-based research frames (Langley et al., 2013) in innovation studies (Ellwood et al., 2022; Geels, 2020; Hekkert et al., 2007; Garud et al., 2013; Van de Ven and Poole, 2000; Van de Ven et al., 1999). As Hekkert et al. (2007) observe in the context of analyzing functions of innovation systems, "*[t]he process approach conceptualizes development and change processes as sequences of events. It explains outcomes as the result of the order of events. It encompasses continuous and discontinuous causation, critical incidents, contextual effects and effects of formative patterns.*" In our case, viewing innovation as the process of knowledge recombination allows us to consider technology spillovers as the part of this process that introduces and integrates external knowledge inputs into the recombinant innovation process in a sequence of individual "events" of cross-domain knowledge transfer. This process-based perspective enables the analysis of such "spillover events" individually at the micro-level and in the context of particular innovations, which is necessary for answering the research questions about technology spillover mechanisms, determinants, and contributions to innovation formulated in section 1.1.

2.1. Conceptual framework

To characterize spillovers in this perspective, we introduce a conceptual framework that identifies six key elements of technology spillovers understood as a process, represented schematically in Fig. 1. The first four elements in our framework describe the cross-domain knowledge transfer process itself. These elements are: 1) a *domain boundary*, which simultaneously defines the recipient technology domain and separates it from all other external domains; 2) a particular *source* of external knowledge belonging to an external domain; 3) a *spillover entry point* in the recipient technology domain, which is a particular invention or technology improvement where external knowledge is applied toward a certain technology-related purpose; and 4) a *spillover event*, in which external knowledge is transferred from its source to its entry point across the domain boundary.

Importantly, not every spillover event results in a useful knowledge input into the recombinant innovation process. The application of any novel or external knowledge to an existing technology inevitably involves experimenting with this knowledge to adapt it and make it work for the intended technology-related purpose (Arthur, 2007). It requires time and effort, as well as capacity to absorb and assimilate unfamiliar knowledge (Cohen and Levinthal, 1990; Tzabbar et al., 2013; Hoppmann, 2018). Only if this process of gradual adaptation and absorption of initially unfamiliar knowledge, which we call "knowledge integration," is successful, we can consider this knowledge to have provided useful input into the recombinant innovation in this technology. In such cases, if unfamiliar knowledge was initially external to the recipient domain, it not only gradually becomes a part of this domain—i.e., integrates into it—but also changes the domain itself by expanding its boundary and shifting the trajectory of technology affected by this knowledge input (Dosi, 1982; Funk and Owen-Smith, 2017).[1] In other words, successful integration of external knowledge transferred by a technology spillover into the recipient domain results in technological change in this domain.

Thus, we identify two further key elements in our conceptual framework of technology spillovers: 5) the process of *spillover integration* into the technology domain, and 6) *technological change* that results from spillover integration. By including these elements in the framework, we ensure that we do not consider every possible attempt to bring external knowledge into the recipient domain in our analysis, but instead focus only on the cases of technology spillovers that have contributed to technological change in the domain.

Fig. 1 provides a schematic representation of a technology spillover process in our framework that can be understood through an analogy of an "inelastic collision".[2] Consider a technology developing along a certain trajectory in the domain of interest. It is shown as an orange circle in the bottom left corner of the figure progressing along the orange arrow that represents its initial technological trajectory. If on this trajectory there is an appropriate entry point into the domain (3)—a specific improvement that can be achieved or a technical problem that can be solved by applying knowledge from an external source (2), represented by a smaller blue circle at the top left corner—then external knowledge may transfer across the recipient domain boundary (1) in a spillover event (4, shown as a straight blue arrow) and enter ("collide with") the technology at this entry point. If the spillover event is successful, the external knowledge is absorbed by the technology and gradually integrates into it (5). In turn, this spillover knowledge changes the recipient technology and its trajectory (6), indicated by the horizontal arrow leading to the orange-blue circle.[3]

Notably, there are different pathways, schematically represented by curved blue arrows in Fig. 1, by which spillover knowledge can potentially transfer from its external source to the spillover entry point in the recipient domain in a spillover event. These pathways correspond to different *spillover mechanisms*, i.e., different ways by which spillover events can occur (see section 1.2).

Technology spillover processes can also be affected by various contextual factors, such as the presence or absence of specific types of policy support, favorable or unfavorable market dynamics, knowledge proximity, sectoral connections between domains, or disciplinary composition of R&D teams. These factors can enable or prevent particular spillover events and mechanisms or influence the way spillovers integrate (or not) into the recipient domain and contribute to technological change. We call such factors the *determinants of spillovers* and distinguish between the factors that enable or support the spillover process at any stage (or '*enablers*', schematically represented by small green circles in Fig. 1), and constraining factors (or '*barriers*') that obstruct spillover events or integration or even prevent them from happening (red "X" symbol in Fig. 1).

2.2. Process-tracing methodology for analyzing technology spillovers

Our conceptual framework allows us to systematize the analysis of individual technology spillovers by disaggregating a complex cross-domain knowledge transfer process into six key elements which can be separately identified and analyzed with research methods appropriate for each element. We can synthesize the empirical evidence gained about these elements to reconstruct individual spillover processes and identify their mechanisms, determinants, and contributions to innovation and technological change.

In section SI1.1 of the Supplementary Information 1 (SI1) document we operationalize this approach and our conceptual framework by showing how different elements of the framework are grounded in the existing literature and identifying the types of research methods that can be used to obtain empirical evidence about each individual element. We draw on a wide variety of potential sources of information (summarized in SI1, Table SI1.1), including technical content in relevant patents and publications, inventors' tacit knowledge and subjective personal reflections, historical records, changes in technical language and terminology, and the structure of citation and collaboration networks. Crucially, we find that no single method can individually identify and analyze all six elements of the framework. Each method has its strengths and limitations, but only by combining the outputs from multiple methods can we overcome the limitations of individual methods and reconstruct a detailed micro-level picture of the spillover process in its context.

We adopt process tracing (Collier, 2011; Mahoney, 2012; Beach and Pedersen, 2019) as a methodological approach for synthesizing empirical evidence about spillover elements obtained by multiple research methods. The outcome of such synthesis is a detail-rich narrative description of a sequence of events that comprise a technology spillover process, which we call a "spillover history." The power of process tracing in this context is in its ability to generate, support, and mutually reinforce causal claims about the relationship between spillovers, their elements, mechanisms, determinants, and impact on innovation and technological change.[4] As David Collier (2011) vividly demonstrates, even in the absence of strong direct evidence of causality, it is still possible to "pile up" multiple independently weak inferences of potential causality in a mutually reinforcing and cross-validating way, resulting in a cumulatively strong causal claim. We demonstrate how this approach to making causal inference about technology spillover

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[1] Following Dosi (1982), we consider technological trajectory as a representation of the evolution of technology as a sequence of technology designs and corresponding problem-solving activities. We further discuss our approach to operationalizing technological trajectories and integration of knowledge into technology domains in Sun et al. (2021).

[2] In classical mechanics, inelastic collision between two objects is one in which objects stick together after the impact. Part of the initial kinetic energy in this system is absorbed by friction that keeps the objects joined after the collision event, similarly to the effort needed to absorb incoming spillover knowledge and integrate it into the recipient technology.

[3] We can illustrate how the framework presented in Fig. 1 describes real-world innovation by a prominent historical example of white light emitting diode (LED) lighting technology (Weinold et al., 2021). After blue LED was invented by Shuji Nakamura at Nichia Corporation in Japan in 1993, initial efforts to create white LED-based light source were aimed at mixing light from red, green, and blue LEDs in a single lighting device (initial technology trajectory on Fig. 1). However, a simpler solution was eventually found at Nichia, based on using phosphor chemical compounds to convert blue LED light directly into white light. As a chemical corporation, Nichia already had expertise in phosphors for various applications such as color TV (spillover source 2 in Fig. 1), but it was initially separate from their work on LEDs (domain boundary 1). When Nichia engineers successfully applied YAG phosphor to a blue LED in 1996 (spillover entry point 3), a spillover event 4 occurred. This approach to produce white LED light proved to be successful, forever changing the trajectory of white LED technology development towards better and more efficient LED phosphors (element 6 on Fig. 1) and making knowledge about LED phosphors an integral part of the LED technology domain (spillover integration 5 on Fig. 1).

[4] A closely related methodological approach is that of the "innovation journey" (Van de Ven et al., 1999) that traces a trajectory of individual innovation projects from initiation to adoption or termination within an organization. It has been applied directly or as a metaphor to analyze policy and governance innovation (Voss, 2007; Loft et al., 2020), social innovation (Oeij et al., 2019), and trajectories of innovation across niches, regimes, and socio-technical landscapes (Rip and Schot, 2002; Rip, 2012). The focus of these studies is on the internal characteristics of innovation dynamics and challenges of navigating the innovation journey for actors involved in it, which is relevant but distinct from our focus on tracing the origins and processes behind external knowledge inputs into the innovation process. We discuss potential complementary between the two approaches in section 4.

processes works in practice in an illustrative example provided in SI1, section SI1.2.

Using the process tracing approach to synthesize empirical evidence from multiple research methods, we formulate a methodology for identifying and analyzing individual technology spillovers consisting of the following five steps.

1. **Define a recipient technology domain** by its boundary (element 1 in the framework; see also section SI1.1.2 in SI1). First, we formulate a specific technology area of interest for the analysis of spillovers (e.g., "crystalline silicon photovoltaics", "lithium-ion batteries"). To analyze evidence available on spillovers in patents and publications, we define the domain boundary for the chosen area in the patent and publication record by using combinations of relevant keywords and (for patents) codes of patent classifications. In cases where it is hard to establish boundaries between a particular recipient technology domain and other closely related technologies (e.g., between different types of photovoltaic or battery technologies), the recipient domain can be nested within a higher-level "buffer" domain of related technologies, with spillovers considered coming only from beyond the buffer domain; see sections SI1.3 and SI1.4 in SI1 for details of this approach. We also use expert judgement to validate the resulting search strings for patent and publication databases, or directly establish if a non-patent-or-publication knowledge source belongs within or outside the recipient domain of interest.
2. **Assemble a list of important innovations** in the recipient domain. As noted in section 2.1, we are interested only in the cases of spillovers that successfully integrate into the domain, resulting in innovation and technological change (element 6). To find such cases, first, we need to identify what notable innovations occurred in the recipient technology over time. This can be done through a literature survey, expert judgement, and/or patent analytics. In this approach, the literature survey involves searching for evidence of important innovations in both the primary sources of scientific and technical information on the recipient technology, and secondary sources such as literature reviews, historical records, and studies in the history of technology. An output of this process is a list of innovations that are further probed for the involvement of spillovers in the next steps of the methodology. Further details about assembling the list of innovations, including which innovations we consider sufficiently important for the inclusion in this list, are discussed in SI1, section SI1.1.7.
3. **Trace spillover sources, events, and entry points** (elements 2–4). We start this process by analyzing backward citations in publications and patents that represent innovations in the list assembled in step 2 to find those citations that link to external sources located outside the core or buffer domains constructed in step 1. In such cases, citing documents may represent spillover entry points and cited documents may be spillover sources. We then analyze these documents as well as broader relevant evidence from a survey of the literature, documentary sources, expert interviews, and further iterative analysis of citations in the identified publications and patents. This allows us to validate the findings, identify associated spillover events, and reconstruct the context of these events to identify relevant spillover mechanisms, barriers, and enablers. If for any innovation in the list there remains insufficient evidence of spillover involvement after this iterative process, this innovation is discarded from the initial list and not considered further. See sections SI1.1.3-SI1.1.5 in SI1 for more detail.
4. **Trace spillover integration** (element 5; see also section SI1.1.6 in SI1). Where patent data is available, we trace integration quantitatively using the text mining-based method of patent analytics introduced in Sun et al. (2021). This method is based on tracking how the text of patents that represents spillover knowledge gradually becomes a part of the technical language of the recipient domain over time. See section SI1.5 in SI1 for a brief description of this method. If patent data is not available or relevant for the potential spillover, we can observe integration indirectly either by tracking the accumulation of citations to the spillover source in the recipient domain if the source is a publication or in the form of qualitative evidence of the uptake of the invention represented by the entry point in the recipient domain obtained from expert interviews.
5. **Synthesize the spillover history** of the recipient technology from empirical evidence gathered about the elements of multiple individual spillovers. We can represent it either as a detail-rich narrative description of the timeline of spillovers and their contributions to innovations in the recipient technology domain that emphasizes the mechanisms and determinants of spillovers, or as a "spillover map" that visually represents individual technology spillovers as a network of knowledge flows between the source and recipient technology domains mapped onto the timelines of innovation in these domains.

A key feature and benefit of our proposed process-tracing methodology is that it allows researchers to synthesize outputs from various sources of empirical evidence about spillovers and use it for the triangulation and cross-validation of cause-and-effect relationships between spillovers and innovation trajectories. Each constituent method that we bring together has its individual strengths and limitations, as well as different sources of potential errors, which limit their individual utility in the studies of technology spillovers. However, by combining the methods, we can overcome these limitations. For example, we improve on previous citation-based quantitative analyses of spillovers by gaining deep qualitative insights into the context and processes behind individual spillovers represented by citations. At the same time, we address the issues with the generalizability of findings from qualitative studies of single specific cases by systematically identifying and analyzing multiple cases of individual spillovers in a technology and enabling their comparison across multiple technologies in the same conceptual framework. The synergy between different methods contributes to the robustness of the results, provides strength to causal claims, and enables deep and systematic insight into spillover processes.

3. Results

In this section, we demonstrate how our framework and methodology can be applied in practice in an illustrative case study of technology spillovers in three historically important innovations in a key technology for solar energy generation, crystalline silicon solar photovoltaics (c-Si PV): ion implantation, pulse annealing, and laser doping.

We select c-Si PV as the main domain of interest for our case study for several reasons. First, it is a well-developed technological area with a long history of R&D, market development and policy support dating back to the 1950s (Nemet, 2019). The history and evolution of c-Si PV technology are extensively documented and analyzed, and this provides us with important information sources for our research. Second, its location within the general PV domain and relationships with other types of PV and semiconductor technology allow us to demonstrate the advantages and features of our multi-method approach to identifying spillovers. Third, PV is one of the clean energy technologies expected to play a key role in the global transition to net zero carbon emissions (International Energy Agency, 2020). Its future progress over time could still be shaped by R&D and integration of knowledge from different sectors and domains, including digitalization, new materials, and manufacturing processes, which makes insights gained from the study not only relevant to innovation theory but also valuable for policy and management practice. Fourth, there is still a gap in the literature and understanding of the extent to which spillovers contributed to innovations and technology improvements in PV.

For the case study, we choose three distinct but related innovations concerned with creating semiconductor junctions in solar cells: ion implantation, pulse annealing, and laser doping. We choose these innovations for the illustrative value of the resulting case study, which clearly demonstrates both the limitations of individual conventional methods of analyzing technology spillovers and the benefits (along with challenges) of our analytical framework and methodology based on process tracing. With our methodology, we reconstruct in detail a complex network of innovation trajectories and technology spillovers spanning two domains, semiconductors and photovoltaics, and almost 60 years of solar cell innovation, from the early 1960s to the present day. We identify at least seven notable spillover events that had a major impact on the three studied c-Si PV innovations. The earliest of these spillovers occurred in 1964, while the most recent took place in the early 2010s.

We describe the case study and implementation of our methodology in detail in section SI2.1 in Supplementary Information 2 (SI2) document. The resulting reconstructed spillover history of the chosen three innovations in the form of a detailed narrative description is provided in SI2, section SI2.2. Below, we present the summary of this spillover history in the form of a spillover network map in Fig. 2. In Table 1, we also summarize what we learned about the seven spillovers we identified (denoted as *SP1* to *SP7* in chronological order) by listing the elements of technology spillovers in the framework presented in section 2.1, along with spillover mechanisms, and enabling factors (split by policy-related and non-policy factors). Domain boundaries are represented in Table 1 by the separately listed source and recipient technology domains. We also indicate the stages of the innovation process affected by spillovers using the classification of innovation stages in energy technologies adapted from Grubler et al. (2012). Specifically, we distinguish between the stages of research R, technology development T, demonstration D, and market deployment M, with the latter designation used to indicate both market formation and diffusion stages of innovation.

For the identified spillovers into c-Si PV, general semiconductor technology is the main source domain, which is not surprising given the historical origins of PV in semiconductor science and technology (Nemet, 2019). Other technology domains that originated external knowledge that contributed to c-Si PV innovations in our case, either directly or by way of general semiconductors, are lasers, optics, particle accelerators, ion beam sources, and nuclear physics (see Table 1, ‘Source domain’ column).

We find that spillovers may occur multiple times between the same technologies and at any stage of the innovation process. For example, there were at least three distinct spillovers that brought knowledge about ion implantation from semiconductors to c-Si PV: *SP1* in 1964 contributed to early technology development in PV ion implantation, *SP6* in 1979–80 transferred manufacturing knowledge and equipment from semiconductors to the demonstration stage in c-Si PV, and *SP7* adapted semiconductor ion implanters for PV mass manufacturing in the early 2010s.

In terms of impact on innovation and technological change, three spillovers (*SP1*, *SP2,* and *SP5*) played the key role in enabling all three c-Si PV innovations considered in the case study; two (*SP3* and *SP4*) contributed to major breakthroughs that advanced innovation in pulse annealing; and the remaining two (*SP6* and *SP7*) helped advance PV ion implantation to a later innovation stage.

Identifying spillover sources in external domains was one of the more difficult tasks in the implementation of our methodology. In some cases, spillovers could not be tracked to specific sources of codified knowledge such as publications and patents. Instead, we found evidence of spillover sources of external tacit knowledge embedded in firms (*SP1*, *SP2*, *SP6*), research teams (*SP3*), or manufacturing equipment (*SP6*, *SP7*).

Among the spillover entry points, only three (*SP2*, *SP4,* and *SP5*) are codified in patents. Another three (*SP1*, *SP3*, and *SP6*) are represented by scientific publications and technical reports, and the last one (*SP7*) is identified through new product announcements. This observation clearly shows the limitations of any individual patent- or publication-based method of studying knowledge spillovers between disciplines

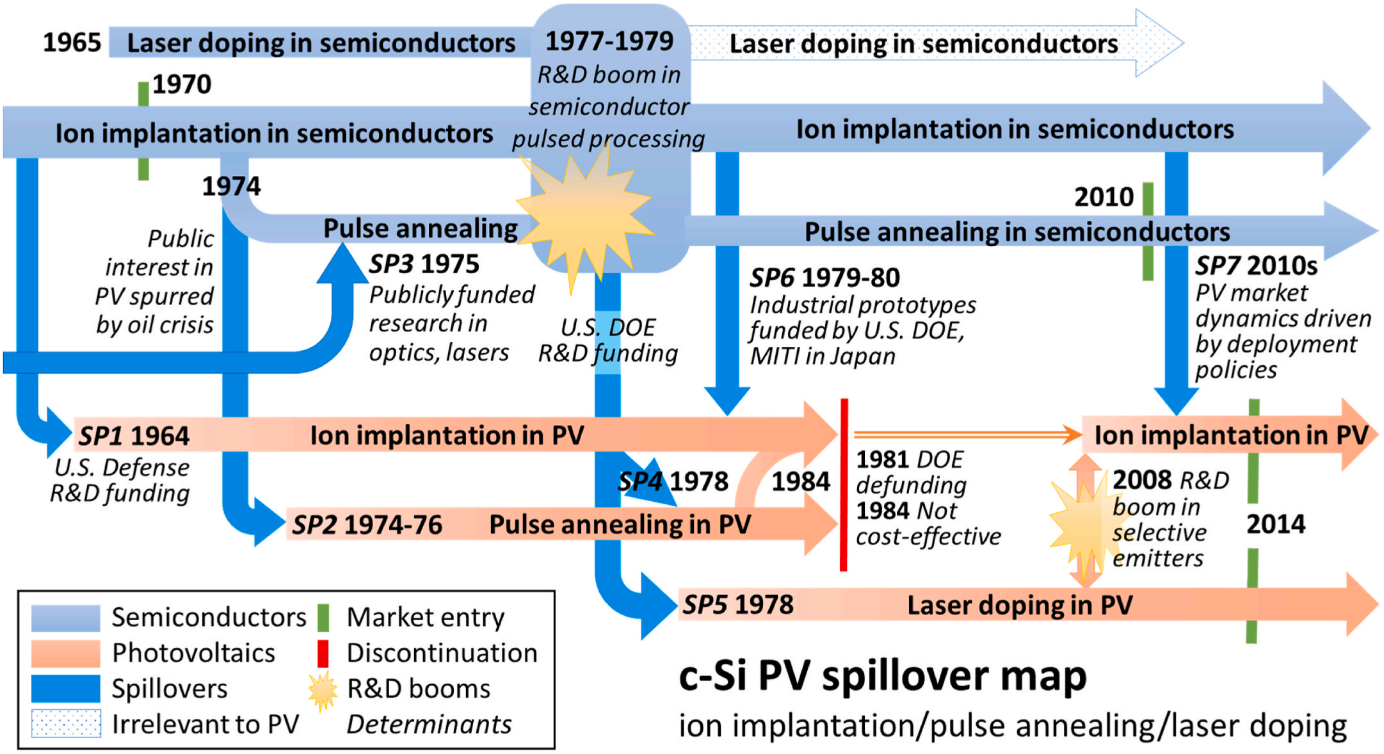

Fig. 2. Reconstructed network map of technology spillovers in ion implantation, pulse annealing, and laser doping in c-Si PV. Dark-blue and orange arrows represent technological trajectories of the three innovations in the source (semiconductors, dark-blue arrows) and recipient (c-Si PV, orange arrows) domains. The light blue arrows represent spillover events for spillovers *SP1-SP7*. Text in cursive represents determinants of spillovers, including spillover enablers (next to the light blue arrows) and barriers (next to the vertical red line). The full history of spillovers *SP1-SP7* is described in SI2, section SI2.2. DOE is the U.S. Department of Energy. MITI is the Ministry of International Trade and Industry, Japan.

Table 1
Analysis of seven identified technology spillovers contributing to three solar PV innovations.

Spillover/ Affected innovation	Source domain (stage)[a]	Recipient domain (stage)[a]	Spillover event	Spillover source	Spillover entry point	Impact on innovation	Evidence of spillover integration	Spillover mechanism	Enabling factors – policy	Enabling factors – other
SP1 **Ion implantation**	Semiconductors (T) Nuclear physics (R) Particle accelerators (T)	c-Si PV (T)	1964: Ion Physics demonstrates application of ion implantation in silicon solar PV	Internal firm knowledge on nuclear physics, accelerator technology and ion implantation of semiconductors	Publication: King and Burrill (1964) Contract reports to U.S. Air Force	Enabled ion implantation in PV	Evidence from citations that integration into c-Si PV starts by mid-1970s, including in Spire's work (see SP2 and SP6)	Targeted application of existing external knowledge by an entrepreneurial firm	Defense R&D funding (U.S. Air Force)	Firm structured as cross-industry joint venture Cross-disciplinary hiring
SP2 **Pulse annealing**	Semiconductors (T) Particle accelerators (T)	c-Si PV (T)	1974–75: Spire demonstrates application of electron beam annealing of ion implantation damage in silicon solar PV	Internal firm knowledge and skills in accelerator technology and ion implantation of semiconductors	Patents: US3950187 US4082958	Enabled pulse annealing in PV	Patents – entry points integrate into c-Si PV in 1980–1985. Integration stops after 1985.	Targeted application of novel external knowledge by an entrepreneurial firm	Energy and defense R&D funding (U.S. DOE and Air Force)	Spin-off from a firm with knowledge stock in source domains Oil crisis spurs public interest in solar energy
SP3 **Pulse annealing**	Optics (R) Lasers (T)	Semiconductors (R)	1975: Russian physicists specializing in optics and lasers discover laser annealing of ion implantation damage in semiconductors	Knowledge and skills of team members in optics and lasers	Publications: Shtyrkov et al. (1975) Kachurin et al. (1975)	Started international R&D boom in semiconductor pulsed processing technologies	Evidence from citations that discovered knowledge quickly integrated into semiconductor domain	Undirected serendipitous discovery of novel application of external knowledge by public sector researchers	Public block funding for "blue-sky" research (Acad. of Sciences USSR)	Easy cross-domain access to required equipment and materials Collaborative networks and events
SP4 **Pulse annealing**	Semiconductors (R) Lasers (T)	c-Si PV (T)	1978: ORNL applies knowledge in laser annealing of semiconductors to develop laser annealing in c-Si PV	Shtyrkov et al. (1975), Kachurin et al. (1975), follow-up publications on laser annealing in semiconductors Patents: US3458368, US3940289	Patent: US4181538	Breakthrough in pulse annealing in PV	Cited patents (spillover sources) integrate into c-Si PV over short term until 1980 No clear integration of citing patent (entry point) into c-Si PV	Targeted application of novel external knowledge by public sector researchers	Energy R&D funding (U.S. DOE)	International R&D boom in semiconductor pulsed processing International collaborative workshops
SP5 **Laser doping**	Semiconductors (R) Lasers (T)	c-Si PV (T)	1978: ORNL applies knowledge in laser doping of semiconductors to develop laser doping in c-Si PV	Fairfield and Schwuttke (1968), other publications on laser doping in semiconductors Own publications on laser annealing in semiconductors	Patent: US4147563	Enabled laser doping in PV	No integration of citing patent (entry point) into c-Si PV until late 1990s. Evidence from patent citations that integration started in 2000s.	Targeted application of novel external knowledge by public sector researchers	Energy R&D funding (U.S. DOE)	International R&D boom in semiconductor pulsed processing International collaborative networks and events
SP6 **Ion implantation**	Semiconductors (M) Ion beam sources (T)	c-Si PV (D)	1979: Spire Corp/ 1980: Hitachi adapt semiconductor ion implanters to develop prototypes of ion-implanted c-Si PV manufacturing equipment	Spire: existing semiconductor ion implantation equipment Hitachi: existing ion beam sources, internal knowledge in semiconductor	Publications: Minnucci (1979) Tokiguchi et al. (1981)	PV ion implantation advances to demonstration stage	Evidence from citations of integration into c-Si PV until mid-1980s	Targeted application of knowledge and manufacturing equipment from another industry or technology by private government contractors	Energy R&D and demonstration funding (U.S. DOE/MITI in Japan)	Spire: collaborative ties with equipment supplier Hitachi: firm works in multiple sectors

(*continued on next page*)

Table 1 (*continued*)

Spillover/ Affected innovation	Source domain (stage)[a]	Recipient domain (stage)[a]	Spillover event	Spillover source	Spillover entry point	Impact on innovation	Evidence of spillover integration	Spillover mechanism	Enabling factors – policy	Enabling factors – other
				manufacturing processing						
SP7 **Ion implantation**	Semiconductors (M)	c-Si PV (M)	Early 2010s: Semiconductor manufacturing equipment producers develop dedicated PV ion implanters	Existing semiconductor ion implantation equipment	New product announcements	PV ion implantation advances to commercial manufacturing	Indirect evidence of integration through procurement of PV ion implanters by PV manufacturers	Targeted application of manufacturing equipment from another industry by entrepreneurial firms	Renewable energy deployment policies (Worldwide)	Rapid PV market growth International R&D boom in selective emitters in PV

[a] In the "Source domain (stage)" and "Recipient domain (stage)" columns, "stage" means the stage of the innovation process at which a spillover occurs, following the classification of innovation stages adapted from Grubler et al. (2012). Innovation stages are designated by the following letters in parentheses: R – research; T – technology development; D – demonstration; M – market deployment, combining the stages of market formation and diffusion. ORNL is Oak Ridge National Laboratory.

and sectors.

The same limitation complicated tracking spillover integration, as the method of constructing integration trajectories (Sun et al., 2021) described in SI1 section SI1.5 is currently applicable directly only to spillovers with entry points represented by patents (*SP2*, *SP4,* and *SP5*). In other cases, we relied on indirect evidence of integration, such as the dynamics of accumulation of citations to the entry point in the recipient domain (*SP1*, *SP3*, *SP6*), or purchase announcements that pointed to the take-up of the invention represented by the spillover entry point in the domain (*SP7*). However, even with these restrictions, tracking spillover integration provided a critical piece of evidence on the negative effect that the dramatic scaling down and defunding of the DOE's Low-cost Solar Array (LSA) program by the Reagan administration in the U.S. in the early 1980s (Gallagher et al., 1986) had on spillover integration and, subsequently, innovation in three technologies. For all five identified pre-1985 spillovers into c-Si PV, either their initially successful integration stopped after 1985, the same year the LSA program ended (*SP1*, *SP2*, *SP6*), or did not even properly take off after 1981, when the program was first scaled down (*SP4*, *SP5*), In other words, spillover integration into c-Si PV proceeded as long as PV innovation had strong public policy and funding support, and stopped once this support was removed, ultimately resulting in a significant delay or discontinuation of market deployment of laser doping, pulse annealing, and ion implantation innovations in PV. Interestingly, SP5 did eventually integrate into the c-Si PV domain, but it occurred much later, starting in the 2000s, when active R&D and deployment of laser doping and ion implantation in PV resumed in the context of selective emitter formation.

Regarding the spillover mechanisms, five spillovers out of seven (all except *SP3* and *SP7*) were a result of the targeted application of novel or existing external knowledge in the recipient c-Si PV domain in the process of learning or researching. *SP3* occurred as a serendipitous discovery of a novel application of external knowledge in the recipient domain in the process of research. Finally, in two cases (*SP6* and *SP7*) spillovers were embodied in manufacturing equipment from other domains. Notably, one of those cases (*SP6*) was also the case of targeted application of existing external knowledge in the recipient domain, which shows that spillovers can occur by several mechanisms acting simultaneously.

Three spillovers occurred in public research institutions: the Academy of Sciences in the Soviet Union (*SP3*) and the U.S. DOE National Laboratories (*SP4* and *SP5*). The remaining four were driven by private firms, operating entrepreneurially when looking for opportunities in a promising area of technology (*SP1*, *SP2*, *SP7*), or working as private government contractors on mission-driven publicly funded R&D (*SP6*). Interestingly, universities are not represented as active actors in this spillover history, playing only a secondary or intermediary role in it.

Among the enabling factors, we observe the key role played by public policy in all identified spillovers, with different types of policies supporting spillovers at different stages of the innovation process. Specifically, public R&D funding for energy, defense, or blue-sky research in physics directly enabled or indirectly supported spillovers *SP1-SP5,* all happening at the stages of research (R) and technology development (T). Dedicated funding for solar energy demonstration projects from the DOE LSA program in the U.S. and MITI in Japan enabled *SP6* at the demonstration stage (D). Finally, demand-pull renewable deployment policies implemented worldwide stimulated rapid PV market growth, attracting commercial interests of equipment manufacturers in adjacent markets and thus enabling spillover *SP7* at the deployment stage of innovation (M) in PV ion implantation.

Importantly, we can also see how stop-go public funding cycles acted as barriers to the integration of several identified spillovers and delayed c-Si PV innovation in general. As noted above, the sudden defunding and scaling down of the DOE's LSA project in 1981, following the surge of funding in 1979, negatively affected all three PV innovations that we study: ion implantation and pulse annealing, which were at the demonstration stage, and laser doping, which was at the technology development stage. Following this shock, pulse annealing in PV was completely discontinued; ion implantation in PV was abandoned for several decades but made a comeback from the semiconductor industry via *SP7* when it became economically promising in the 2010s; and laser doping in PV was pushed back to the stage of research which then happened mostly outside the United States. Eventually, after decades of R&D efforts, laser doping has become the dominant method of selective emitter formation in solar cells, with a projected ~80% share of the p-type PV market by 2030 (ITRPV, 2021).

Among non-policy factors that enabled spillovers in this case, we find an important role for collaborative networks and events that stimulated knowledge exchange across organizational, geographical, and domain boundaries; organizational structures such as cross-industry joint ventures or spin-offs; cross-disciplinary hiring practices; ease of access to specialized equipment and suppliers across domains; R&D booms that attracted the attention of researchers and inventors from different disciplines and technology areas; and external shocks, such as the 1973 oil crisis that stimulated public interest in PV technology. We provide further details on different spillover mechanisms and enablers identified in the reconstructed spillover history in SI2, section SI2.2. In section SI2.3 in SI2 we also discuss long time spans observed in c-SI PV innovation and spillover integration.

4. Discussion

4.1. Advantages and limitations of process-tracing methodology

In this section, we reflect on the process and results of the application of our process-tracing methodology for identifying and analyzing individual technology spillovers to the illustrative empirical case study of three c-Si PV innovations described in section 3 and SI2.

The key feature of our approach is the complementary way in which individual research methods are used to inform each other and ensure the triangulation and cross-validation of findings. For example, iterative analysis of citations in patents and publications was instrumental in identifying the sources for the literature survey. It allowed us to identify both primary sources, such as publications, patents, and technical reports that described relevant inventions and discoveries associated with potential spillover sources and entry points, and secondary sources such as literature reviews, industry reports, and studies on the history of PV and semiconductor technologies. The primary sources helped us understand the technical essence of innovations, spillovers, and the relationships between them, while the secondary sources (e.g., Dearnaley, 1974; Robinson, 1978; Gallagher et al., 1986; Saitoh, 2003; Green, 2005; Swanson, 2006; Lecuyer and Brock, 2009; Husmann, 2011; Voelskow et al., 2014; Current et al., 2018; ITRPV, 2015; ITRPV, 2021), in turn, provided the bulk of evidence on the context and details of each relevant spillover and the mechanisms by which they occurred.

Complementing the literature survey and citation analysis, interviews provided us with an invaluable insight into the connection between laser doping, pulse annealing, and selective emitter solar cell architectures, as well as the process of early market entry for laser doping in the late 2000s. A final critical piece of evidence was obtained by tracking spillover integration that showed how innovation processes under discussion were delayed or discontinued after defunding and descoping of the policy support for PV innovation in the U.S. in the early 1980s.

No single method would have allowed us to reconstruct such a rich and detailed spillover history. Neither patent analysis nor citations alone were able to capture all the important spillovers that we identified, as only three spillover entry points were found to be associated with patents, and another three with journal publications. Interviews provided detailed insights into the more recent crucial turning point for the laser doping innovation, but not into its early history. The literature survey helped us reconstruct this early history in detail, but not for the most recent events, especially when innovation happened in the manufacturing setting that paid little attention to publications or patents. Finally, our text mining-based method for tracking knowledge integration provides deep insights into the relationship between spillovers, innovations, and the evolution of the whole recipient technological domain, but it was also limited by its reliance on patents. Only by synthesizing the output of different methods in a synergistic and complementary way in a process-tracing framework, we were able to reconstruct a reasonably detailed spillover history that provided empirical evidence needed for answering the research questions about spillover sources, mechanisms, determinants, and impact on innovation in our case study.

We acknowledge two important limitations of our methodology. The first issue is associated with a reliance on pre-constructed lists of important innovations in a focal domain needed to launch spillover process tracing. Such lists are rarely comprehensive. It is very likely that certain historically important innovations are omitted in any given list, potentially resulting in spillovers missing in the reconstructed spillover histories. However, our process-tracing methodology overcomes this fundamental deficit of inductive research thanks to its iterative nature, and interconnectedness of different materials, processes and components constituting any technology (Beach and Pedersen, 2019). By iteratively integrating outputs from different methods and sources of empirical evidence, we can reconstruct a robust and detail-rich spillover history of the technology from just a few starting points. This is demonstrated in our illustrative case study, where we reconstructed almost 60 years of history of three c-Si PV processing innovations from a single starting point, a patent on pulse annealing, by iteratively tracing back and forth its knowledge origins and outcomes.

The second limitation is that our methodology is systematically biased towards the cases of technology spillovers that successfully contribute to innovation and technological change, rather than potential spillovers with unsuccessful events or incomplete integration that are much less likely to be identified from pre-constructed lists of important innovations currently needed to launch spillover process tracing. As a result, it is relatively harder to find what factors make potential spillover events unsuccessful or what barriers can prevent full spillover integration. Our illustrative case study shows that this is not impossible, as we were still able to identify clear barriers to spillover integration in it. However, it is hard to generalize from such cases in the same way as for spillover mechanisms and enablers, as many ‘unsuccessful’ spillovers likely remain unidentified with our current approach.

One potential way to address these limitations is to expand the scope of search by replacing pre-constructed lists of innovations with the outcomes of a large-scale automated analysis of citation networks that connect spillover sources and entry points represented by publications and patents. In these networks, potential cases of ‘successful’ spillovers can be identified with the help of quantitative methods of screening for technological breakthroughs discussed in SI1, section SI1.1.7. The remaining cases of potential spillovers not identified by these methods as contributing to technological breakthroughs can then be considered as ‘unsuccessful’ for the purpose of analyzing spillover barriers and constraining factors.

It is worth noting that the key requirement in our methodology is the need for technical knowledge and domain expertise for its proper implementation. Technical knowledge is needed to define and validate the recipient technology domain, identify and correctly understand primary literature sources written in highly technical language, and interpret the interview results. From a broader methodological and organizational perspective, this observation highlights the importance of the multi- and interdisciplinary composition of research teams that study technological innovation, as such teams should include experts both in social sciences to design and implement appropriate methodologies to investigate the socio-technical context of innovation (Fri and Savitz, 2014), and sciences and engineering to interpret the results and observations obtained with these methodologies.

4.2. Conclusions and policy implications

The main objective of this paper was to develop new conceptual and methodological tools to enable the analysis of technology spillovers as a micro-level process of knowledge transfer between technology domains and demonstrate how these tools generate novel insights for R&D and innovation policy and management, with a practical focus on recommendations to support and accelerate innovation in clean energy technologies.

The paper makes three important contributions towards this objective. Firstly, we contribute to innovation theory by formulating a framework that conceptualizes technology spillovers as a knowledge transfer process, enabling a systematic and dynamic analysis of technology spillovers and their impact on innovation processes on a micro-level of individual cross-domain knowledge transfer events, mechanisms, and determinants. Importantly, the process-based perspective on spillovers does not contradict more 'traditional' perspectives on spillovers as knowledge externalities or knowledge input into the recombinant innovation. Instead, it directly builds up on both perspectives to open up the "black box" of recombinant innovation and explain how and through which micro-level processes external knowledge contributes to individual innovations. An important theoretical implication of our framework is that the same process-based approach can be taken to characterize other micro-level processes involved in recombinant innovation, such as local knowledge search, recombination, and integration, eventually building up to a comprehensive micro-level process-based theory of recombinant innovation.

Secondly, we make a methodological contribution by developing a multi-method process-tracing approach to identifying and analyzing individual technology spillovers based on our conceptual framework. As the illustrative case study presented in this paper shows, our methodology can provide an unparalleled depth of insight into the complexity of spillover sources, events, mechanisms, enabling and constraining factors, and spillover impacts on innovation and technological change. Applying it systematically in different technology areas with varying characteristics, such as technology modularity, granularity, or complexity (Huenteler et al., 2016; Wilson et al., 2020; Malhotra and Schmidt, 2020), will enable generalizations on a larger set of micro-level observations of spillovers that may help explain the differences in spillover patterns and mechanisms, innovation dynamics, and macro-level aggregate knowledge flows between different technology domains. In turn, it can help formulate concrete recommendations for research and innovation policy and R&D management practice aiming to support and accelerate innovation in technology areas with significant spillover potential (cf. International Energy Agency, 2020).

Thirdly, we contribute to a growing literature on clean energy innovation by identifying important lessons about technology spillovers in clean energy, as well as the role of policy support and other factors in these spillovers. By applying our framework and methodology in the case study of three innovations in crystalline silicon photovoltaics, we find that technology spillovers played a crucial role in enabling these innovations and advancing two of them towards the market. We also find that spillovers can occur multiple times between the same technologies at different innovation stages. Among the seven identified spillovers, we find evidence of at least three spillover mechanisms: targeted application of external knowledge in the recipient domain, undirected "blue-sky" research, and re-utilization of manufacturing equipment from other industries. Among the enabling factors for the identified spillovers, we find an important role for cross-disciplinary and cross-industry networks, events, collaborations, and hiring practices, along with the ease of access to specialized equipment and suppliers across domains, and external events such as R&D booms in related technologies or external shocks that stimulate public interest in the recipient technology.

We also find evidence that policy support played either the key enabling role or indirectly incentivized all seven individual technology spillovers that we identified, with different types of policies supporting spillovers at different stages of the innovation process, from research and development to technology demonstration and market deployment. Finally, we find that stop-go funding cycles, such as generous U.S. DOE funding for PV innovation and deployment that emerged in the late 1970s but abruptly stopped in 1981, can act as barriers to spillover integration, delaying market deployment of corresponding innovations by (possibly) decades.

These empirical findings have important implications for public policy and knowledge management practice that aim to support innovation in critical areas such as clean energy. First, policy support for innovation should be consistent and continuous across all stages of the innovation process, not just R&D. Stop-go cycles of institutional support for innovation processes create uncertainty that makes it difficult for innovators and organizations to invest in long-term or riskier endeavors, including those that integrate external knowledge. To act on this recommendation, our findings suggest that mission-oriented and stage-appropriate policy measures in support of technology demonstration and deployment should be viewed as just as essential to the acceleration of innovation as providing initial public funding for basic research.

Second, both public institutions and the private sector involved in innovation in critical areas should continuously build absorptive capacity for relevant external knowledge by investing in interdisciplinary education and training, talent mobility, and multidisciplinary hiring and team composition. As our findings of enabling factors demonstrate, spillover processes often relied on having organizational norms and policies in place that facilitated the cross-pollination of ideas before a spillover event could occur.

Third, intentional structures of cross-disciplinary, cross-industry, and cross-sectoral collaboration and knowledge exchange are needed to ensure the discovery and appropriate transfer of external knowledge. These structures can take many forms, from industry placements for individual academics and cross-sectoral conferences convening experts from both industry and academia, to firm alliances, R&D consortiums, and industry-wide coordination mechanisms such as technology roadmapping exercises. Policymakers and actors in leadership positions within industry, academia, and public research sector should encourage and support these intentional structures of collaboration, including through investment and creative development of new mechanisms of collaboration that leverage evolving collaboration technologies.

Overall, our framework and methodology allow us to answer the questions about the role of technology spillovers in particular innovations, the mechanisms by which these spillovers occur, and the factors that enable or affect them. However, it is just a part of a much broader set of questions that must be answered to understand innovation processes at different levels, from the micro-level of individual innovations discussed in this paper to the macro-level of technological innovation systems (TIS) (Hekkert et al., 2007; Bergek et al., 2008) and socio-technical landscapes (Rip, 2012). Relevant theories of innovation at different levels can help us better understand technology spillovers as an input into the innovation process. For example, spillover mechanisms that we identify may correspond to particular TIS functions (Bergek et al., 2008; Mäkitie et al., 2018), while the innovation journey perspective (Van de Ven et al., 1999; Loft et al., 2020) with its inventory of micro-level events and processes occurring in the innovation process can help us structure and formally analyze spillover histories and contributions of spillovers to innovation. In our future research, we aim to gather more empirical evidence for a larger set of spillovers in different technologies and use our conceptual framework and related innovation theories to systematize this evidence and generate further insights necessary to answer the question of *how* we can design public policies that actively leverage technology spillovers to accelerate innovation.

CRediT authorship contribution statement

Sergey Kolesnikov: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing

– original draft, Writing – review & editing. **Anna P. Goldstein:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. **Bixuan Sun:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Gabriel Chan:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing, Investigation. **Venkatesh Narayanamurti:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Laura Diaz Anadon:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix A. Supplementary information

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