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Photovoltaics in Sweden – Success or failure?

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A B S T R A C T

Promoting global energy transitions while stimulating domestic industrialization requires national policymaking that shapes technological innovation towards specific outcomes. Although this is inherently difficult, historical case studies may bring a better understanding of innovation dynamics and thereby guide the design of future policy interventions. The purpose of this paper is to review and analyze the emergence of Swedish photovoltaics technology from a policy perspective. Our main aim is to provide a retrospective account of historical developments, but we also derive more general insights about technological innovation and related policy challenges. The paper departs from an adapted analytical framework based on the technological innovation systems approach. Our review identifies four decades of Swedish research that has largely failed to drive domestic commercialization, the rise and fall of an industry that mainly served international markets, and a rapidly growing domestic market based on imported products. This situation is the result of mismatches and fragmentation among key innovation processes, which have not been addressed by strategic policy interventions. We suggest that policymakers should promote a full range of innovation processes and consider making innovation support subject to a payback mechanism that delivers a return on public investments even if industries and markets emerge abroad. Our study also demonstrates how the technological innovation systems approach can be extended to include the function commercialization and emphasizes the importance of paying attention to the directionality of technological innovation processes.

1. Introduction

The climate crisis calls for a rapid global transition to a low-carbon energy system [1]. Policymakers in many countries therefore support the development and diffusion of new energy technologies, such as solar, wind, tidal and wave power, while also aspiring to promote the emergence of domestic industries [2–4]. This double challenge has led researchers studying sustainability transitions to pay more attention to the geography of innovation [5,6]. It has also stimulated the development of mission-oriented [7] and transformative [8] policy approaches, as alternatives to a traditional focus on policy interventions aimed at promoting economic growth. However, technological innovation is a cumulative, collective and uncertain endeavor, which is inherently difficult to steer towards specific outcomes [9,10]. In addition, national policy objectives related to climate change and domestic industrialization are sometimes in conflict [11]. Nonetheless, by learning from historical cases, it is possible to develop a better understanding of alternative directions of change, how innovation dynamics may lead to certain outcomes, and the role of policymakers and other actors in the innovation process. This may in turn guide national governments in their efforts to shape technological innovation in the energy sector towards trajectories that not only contribute to global energy transitions, but also involve domestic industrialization.

The challenge for a national government involves determining when to intervene, how to design interventions, and what alternative technological designs and market applications to promote. Solar photovoltaics (PV) technology provides an interesting example of this challenge. It is a renewable energy technology with a huge market potential [12]. Over the last three decades it has grown into a global industry with value chains stretching across the world, encompassing significant upstream and downstream diversity. While 95% of the PV market is made up of flat crystalline silicon modules, a range of alternative designs are continuously developed, mainly based on various thin-film materials [13]. Similarly, there is a wide range of market applications, from centralized on-grid solar farms and distributed on-grid rooftop installations to uncountable off-grid systems.

Abbreviations: Photovoltaics, (PV); Research development and demonstration, (RD&D); Technological innovation system, (TIS).

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Sweden is one of many small countries that have taken part in the development and diffusion of PV technology. Since research on thin-film technology was initiated in the early 1980's, the country has built a strong academic knowledge base, given rise to a number of venture companies, and seen the rise and fall of a quite substantial industry [14,15]. Market development for long lagged behind many other European countries, but in recent years installed capacity has grown rapidly with respect to both centralized and distributed on-grid applications. However, Sweden has struggled to establish and sustain industrial activity beyond research, development and demonstration (RD&D), even though policymakers have provided substantial support with domestic industrialization as one of the main objectives.

This makes the emergence of PV in Sweden an interesting case to investigate in order to shed new light on innovation dynamics and policy challenges in small countries that strive to promote and benefit from global energy transitions. Most previous studies of PV in Sweden concern specific aspects of the PV market, such as grid integration [16,17], economic feasibility [18,19], and barriers and drivers of deployment [20–25]. The only publication focused on industrial development analyzes the emergence of one Swedish PV venture [26].[1] However, except for a conference paper and two reports [15,27,28],[2] there is a lack of studies that analyze innovation dynamics in relation to both upstream and downstream parts of the value chain.

The purpose of this paper is therefore to review and analyze the emergence of PV in Sweden from a policy perspective. By providing a historical account of how research activities, industries and markets have developed over time, together with an analysis of the underlying innovation dynamics and the role of policy intervention, we mainly aim to contribute to the literature on PV innovation [29–36]. In addition, we aim to derive more general insights with relevance for emerging and related strands of literature that engage with the geography of technological innovation [5,6], the directionality of innovation processes [37,38], transformative and mission-oriented innovation policy [7,8], and the specific prerequisites for regions to capture segments of global value chains [39,40].

The paper departs from the technological innovation systems (TIS) approach, which offers theoretical tools for analyzing innovation dynamics related to specific technologies and informing policy intervention [41–43]. Over the years, these tools have been used extensively (see Ref. [44] for a recent review) to investigate the emergence of new technological systems (i.e. a set of interlinked social and technical components associated with a given technology) [45–47]. In this paper, we develop and employ an adapted analytical framework based on the TIS approach, which highlights commercialization as a key innovation process. We also illustrate that the emerging technological system may be conceptualized as a group of value chains [46,48].

2. Research design

2.1. Analytical framework

The TIS approach has gained prominence as an appropriate tool for analyzing the development and diffusion of new technologies from a policy perspective [41]. It is based on evolutionary economic theories and has strong linkages to other innovation systems approaches that take nations, regions or sectors as the analytical starting-point [49–52]. The TIS literature emphasizes that technological innovation is a collective and cumulative endeavor that involves both social and technical change [10,42,43,45].

Studies based on the TIS approach have developed a rich understanding of technological innovation by focusing on the key processes (commonly referred to as functions) performed by an innovation system, i.e. key innovation processes [42,43,45,53].[3] The functions framework enables a dynamic analysis, which accounts for interrelatedness and feedback among factors that influence the innovation process, and focuses on the identification of systemic problems that hinder innovation and diffusion [42,54]. In addition, it provides a conceptual link between technology specific and contextual factors, since the strength of innovation processes results from developments both within and beyond the emerging technological system [45,55,56].

Building on two seminal publications [42,43], most TIS studies analyze functions such as knowledge development, knowledge diffusion, entrepreneurial experimentation, resource mobilization, legitimation, guidance of search and market formation. However, it is also common to suggest new perspectives and make adaptations to suit the purpose and characteristics of the study at hand. For example, scholars have introduced new functions such as price-performance improvements [57] and development of social capital [58], while others have collapsed functions such as knowledge development, knowledge diffusion and entrepreneurial experimentation into higher-level categories [59].

In this paper, we make two adaptations to the commonly used sets of functions, in order to derive an analytical framework that is suitable for reviewing and analyzing the emergence of PV in Sweden (Table 1). Firstly, we collapse knowledge development, knowledge diffusion and entrepreneurial experimentation into the function knowledge development, and also let the function legitimation include guidance of search. The reason is that a more parsimonious framework, which groups similar processes into higher-level categories, makes for a more accessible review and analysis. Secondly, we choose to distinguish between commercial diffusion of new technology in upstream and downstream parts of the value chain, by introducing the function commercialization. This process has traditionally been covered by market formation, which, although pointing to the emergence of a downstream value chain, presupposes that there is also an upstream industrial supply. But since upstream industries and downstream markets may emerge in different places, and are also associated with different policy objectives, it is key to distinguish between the underlying diffusion processes, in particular when analyzing innovation in a specific region.

Table 1
The five functions used to review and analyze the emergence of PV in Sweden.

Function	Description
Legitimation	The favorable alignment of institutions such as attitudes, regulations and standards, which guide actors to engage with and promote the focal technology.
Resource mobilization	The mobilization of investment, infrastructure and competence to support the development and diffusion of the focal technology.
Knowledge development	The development and diffusion of knowledge through public and private research, experimentation, testing and demonstration of the focal technology.
Commercialization	The emergence of commercial producers in upstream parts of the value chain for the focal product.
Market formation	The emergence of commercial users, including firms, consumers and other actors, in downstream parts of the value chain for the focal product.

[1] Bergek et al. to some extent use the case of Swedish PV innovation to explore legitimation and development of positive externalities as key innovation processes [45].

[2] There are also relevant reports and strategy documents that describe historical developments and ongoing activities, albeit without a sophisticated analysis of causes and effects.

[3] The concept of functions can be interpreted in different ways. In this paper, we choose to view functions as a set of processes that describe how structural components in TISs, together with contextual factors, stimulate the development and diffusion of a new technology.

The TIS approach can be used both retrospectively, to explain and evaluate historical developments, or prospectively, to forecast future developments and prescribe policy interventions to reach a particular goal. This paper offers a retrospective study, which mainly aims to review and analyze the emergence of PV in Sweden. However, it also provides an analysis and discussion of the underlying innovation dynamics and the role of policy intervention. This implies a normative ambition to assess how Swedish policymaking has contributed to accomplishing objectives related to industrial and market development. Notably, our review of the emergence of PV in Sweden constitutes a contribution that may for some readers be used independently from our normative policy discussion.

Applying the TIS approach to our research case involves setting boundaries in technological, geographical and temporal dimensions. Firstly, in the technological dimension, we define the focal technology as the production and use of PV modules. The module is accordingly a focal product that demarcates a value chain in which upstream parts consist of industries that produce raw materials, cells and modules as well as manufacturing equipment and other inputs, while downstream parts consist of markets where modules, combined with balance of system components such as inverters and mounting equipment, are used in different applications. Our investigation reviews and analyzes innovation throughout this value chain, but excludes the development and supply of generic inputs (i.e. nuts and bolts) and balance of system components (see Box 1), as well as markets for produced electricity. Note that cell production and module assembly are normally two separate steps of the upstream value chain. Furthermore, we group PV modules into two main alternative designs, silicon and thin-film, where both groups comprise several alternative materials and designs. Secondly, in the geographical dimension, we focus on innovation in Sweden and accordingly adopt a national boundary. International developments are considered contextual, but brought into the analysis as factors that influence the strength of functions and thereby affect the development in Sweden. Finally, in the temporal dimension, our investigation covers developments from the early 1980’s to the end of 2018. The description is subdivided into three time periods based on significant shifts in the pace and direction of development.

2.2. Methodology and data collection

Our investigation follows a case study approach focused on reviewing and analyzing the dynamics of historical developments in a single setting [60]. Since we aim to develop a holistic understanding of innovation over time, the analysis engages with data from desktop research and interviews.

The desktop research examined several different data sources. First, we identified Swedish PV publications by searching the database ‘Web of Science Core Collection’,[4] which covers scientific articles from the mid 20th century and onwards. This enabled us to map research output over time as well as to identify the most active researchers, their networks and their university affiliations. Second, we identified relevant newspaper articles by searching the database ‘Mediearkivet’,[5] which covers a wide range of printed and electronic sources in Sweden from the 1980’s and onwards. This provided an overview of key actors, networks and institutions as well as information about important events related to the functions framework described above. Third, we collected data from documents, reports and websites published by government agencies, firms and other organizations. Taken together, these three data sources made it possible to create a timeline of events, which forms the basis for the review narrative presented in this paper.

In addition, we constructed an extensive database with data about 450 publicly funded RD&D projects, conditional loans to venture companies and annual public expenditure for market subsidies. The database is based on information from Swedish government agencies (see Appendix for additional details) and covers the time period 1996 to 2018. It allowed us to quantify RD&D grants and market support over time as well as to examine which actor that had received funds and what type of innovation that had primarily been promoted. This in turn enabled us to further develop the narrative and strengthen its reliability.

Furthermore, we performed 29 interviews between 2018-02-13 and 2019-01-09. The interviews aimed to complement and strengthen desktop research and were designed to shine light on missing links in the emerging narrative as well as to provide access to different perspectives on historical developments (e.g. researchers at universities and institutes, entrepreneurs and industry representatives as well as policymakers and other experts). We therefore identified interviewees continuously throughout the research process, based on previous findings and earlier interviews. Furthermore, the interviews followed open-ended interview guides that allowed for follow-up questions and reflections. The interview guides were tailored to each interviewee and the questions focused on topics related to their respective roles in the innovation system. Each interview was also recorded and partially transcribed. Although the interviewees remain anonymous, their role in the innovation system is provided in the reference list (and in the Appendix which provides additional details).

In the end, the data collected through desktop research and interviews was used to develop a review narrative in three episodes about the emergence of PV in Sweden. The review is based on a synthesis of multiple sources of information and we highlight the most important references throughout the description of each episode. In addition, the collected data was used to analyze innovation dynamics and policy interventions in relation to the functions framework presented above. We followed a coding procedure that used each function as an analytical category. Information from interviews and desktop research was linked to the resulting set of categories (see Table 1), which enabled the identification of characteristics and dynamics of the innovation processes. After the review of each episode, we use tables to summarize the characteristics of each function, while their dynamics are discussed in Section 4.

3. Results

3.1. Episode 1: A foundation of promising initiatives (1980–2004)

In the early 1980’s, the Swedish Government initiated research to monitor international developments in PV technology [26,61]. Lars Stolt, a young researcher at the Institute for Microelectronics in Stockholm, was granted funds to start a first project, and he chose to focus on thin-film technology based on the material copper-indium-gallium-selenium (CIGS) [62].[6] After more than a decade of knowledge development focused on methods for producing this material, the results were considered promising enough to start focusing on commercial applications. Stolt’s research project was transferred to the Royal Institute of Technology in Stockholm (KTH) and

[4] The search was performed on 2018-05-18, 2018-05-21 and 2019-09-18. It covered the entire historic record provided by the database and was designed to capture PV-relevant publications through a variety of English keywords (e.g. “solar cell*” and “photovoltaic*“). To facilitate the analysis, and since Web of Science Core Collection includes most of the relevant publications, we refrained from adding search results from other databases. Web of Science Core Collection is available at www.webofknowledge.com.

[5] The search was performed on 2018-05-16, 2018-05-17 and 2018-07-16. It covered the entire historic record provided by the database and was designed to capture PV-relevant newspaper articles through a variety of Swedish keywords (e.g. “solcell” and “solenergi”). Mediearkivet is available at www.retreiver.se.

[6] In fact, the research efforts focused on copper-indium-selenium, while gallium was added at a later stage. For simplicity, we will nonetheless refer to early variants of copper-indium-selenium as CIGS.

Box 1
Swedish innovation in complementary products and services.

There has also been Swedish innovation and production activity in complementary products and services such as storage, mounting equipment, inverters and information systems. While most Swedish actors offer products and services that are not specific to PV systems, some firms focus on PV applications and are therefore often highlighted in a solar context. Examples include Ferroamp, which offers DC-based power systems with smart electronics at the building scale, and Optistring, which offers a new type of inverter for solar modules. Moreover, a few large firms develop and produce complementary products. For example, ABB, a leading actor in the global power electronics industry, offers inverters and other electronic components, but these are mainly produced in other countries. Other firms can be found in the construction industry, where actors such as SAPA manufacture steel profiles and mounting equipment. Finally, some firms combine solar heating and PV technology. An interesting example is Solarus, which was founded in 2006 as a spin-off from Vattenfall and also had strong connections to Swedish research. However, after failed efforts to establish commercial production of their combined heat and power panel in Sweden, Solarus is now based in the Netherlands from where it is expanding globally. In addition, the Swedish firm Absolicon has previously engaged with this technology, but currently focuses on developing manufacturing equipment for solar heating products.

the level of public funding increased. In 1994, a first spin-off company was founded by Stolt and colleagues, but the business failed to attract sufficient investment to develop a commercially viable product and finally stopped its activities in 1997 [26].

Another line of knowledge development emerged at Uppsala University. During his PhD studies, the chemist Anders Hagfeldt visited a Swiss university and got to know Michael Grätzel, who had discovered the potential for using dye-sensitized materials in thin-film modules [63,64]. Hagfeldt was inspired by the opportunities this brought, oriented his research towards these materials and eventually did a post-doc in Grätzel's research group. In 1994, he returned to Uppsala University and established a research group working on dye-sensitized solar cells (DSSC).

In 1996, Stolt's research group left KTH to form the research platform Ångström Solar Center (ÅSC) at Uppsala University, together with Hagfeldt's group and a third group working on electrochromic windows. ÅSC was designed as a coordinated policy effort to commercialize Swedish research [65]. Financial resources were mobilized from the Swedish Energy Agency and the Swedish Foundation for Strategic Environmental Research to fund a four-year period, between 1996 and 2000, and policymakers involved experienced industrialists in managing and overseeing activities [26,62,65]. ÅSC explicitly aimed to commercialize research results through established industry in Sweden or by creating a venture company. A key driver of policy support to the research platform was accordingly to achieve domestic industrialization, even though commercialization through a foreign company was stated as a potential, but less-preferred, option.

When the first phase of ÅSC was drawing to a close in 2000, Stolt's research group had demonstrated the potential of CIGS technology by reaching world-leading cell efficiencies on small substrates, and it was time to start scaling-up the complicated production process [26]. Policy efforts were first made to involve the Swedish industry in commercializing the technology. But while the legitimacy of solar energy was at the time high among the general public [66], it was low among incumbent actors in the energy and power electronics industries, such as Vattenfall and ABB, who did not see a clear business case and had other strategic priorities [26,62]. Instead, the company Solibro was founded by Stolt and colleagues. With support from policymakers at a high level within the Swedish government, who saw the potential for creating a new export industry, Solibro managed to mobilize 1.75 MEUR in venture capital, mainly from Swedish industry actors and a pension fund, and also received a 1.75 MEUR grant from the Swedish Energy Agency [26]. This meant that Solibro could get started with the difficult process of scaling-up CIGS technology towards commercial production.

Meanwhile, ÅSC was granted funding for a second four-year period between 2000 and 2004. The research on CIGS technology was oriented towards scaling-up the deposition process and accordingly aligned with the activities of Solibro [62]. Although DSSC technology was considered less promising in the short term [67], research continued and a network was formed with researchers from KTH and the Swedish research institute Swerea [68,69].

In the early 2000's, early-stage research on other thin-film PV materials also appeared at a few other Swedish universities (Fig. 1). Researchers at Linköping University and Chalmers University of Technology initiated a collaboration to develop organic PV, while a research group at Lund University focused on using nanomaterials in PV applications [70,71].

Furthermore, although Sweden had no research on silicon technology, commercialization in the form of a small industry that assembled modules from imported silicon cells emerged in the early 1990's. In 1992, Gällivare Photovoltaics (GPV) was founded by Swedish entrepreneurs in collaboration with an Italian PV firm [67,72]. A factory was built with support from the Swedish Government, which covered 35% of the investment cost in order to stimulate regional economic growth in the wake of mining industry lay-offs [27]. In the early 2000's, GPV was bought by a German PV firm. This led parts of the staff to set-up the new company Arctic Solar together with two of the previous customers, a Finish-Swedish and a German firm [73]. The former CEO of GPV also started a third company, with some support from the Swedish energy utility Vattenfall, but the venture ran into financial problems and was bought by a Danish PV firm, while the founder moved to southern Sweden to found a fourth company [73,74].[7] In addition, the vertically integrated Norwegian PV corporation REC set-up the company REC Scanmodule and built a factory close to the Norwegian border [67,75].[8] As a result of the expansion, production output increased and reached a level of about 30 MW per year in 2004. The Swedish factories were supplied with silicon cells through channels controlled by their international partners or owners, and most of the output was exported to the European market [76,77].

Finally, the early 1990's also saw the formation of a small Swedish market for modules in off-grid applications mainly to power private cabins, motorhomes and boats [67,77].[9] While installed capacity in the off-grid segment increased with about 0,2 MW/year, only a few on-grid installations were made for test and demonstration purposes [77]. However, knowledge development oriented towards PV systems and markets, and related network building, was initiated and funded through the Solar Power Program [78–80]. It was first established as a

[7] Sweden thus had three factories producing PV modules above the polar circle.

[8] The entrepreneur behind REC owned property close to Arvika and was therefore familiar with the area [75]. There are also indications that European trade policy had some influence on REC's investment decision, since they had an incentive to locate module production within the customs union [62,75].

[9] Calculators, watches and other electronic devices with integrated low-efficiency modules were also sold on the Swedish market.

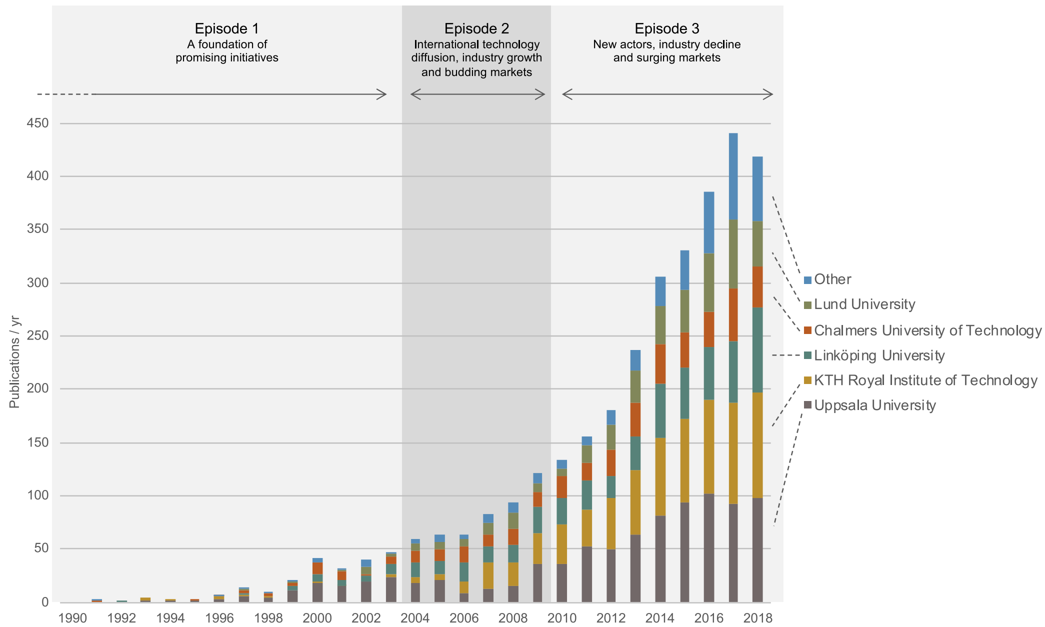

Fig. 1. Scientific publications related to PV with at least one Swedish author between 1990 and 2018. 'Other' includes contributions from various universities with few PV publications. Based on data obtained from a topic search ("solar cell*" OR "photovoltaic*") in Web of Science Core Collection, performed 19-09-18.

collaboration between public agencies and energy companies, but gradually came to include other stakeholders as well. Still, while substantial market support was initiated in many other countries, Swedish policymakers and energy companies largely remained passive [28], favoring other energy technologies such as wind, biomass combustion and nuclear that were considered more promising.

To summarize, the first episode is characterized by two decades of academic knowledge development around thin-film technology as well as repeated attempts to commercialize research results. In parallel, a small industry producing silicon modules emerges with very weak links to Swedish research, and a small market for off-grid systems is formed [28]. But although PV technology has high legitimacy among the general public [66], policymakers and established industry refrain from actively promoting domestic market formation [28]. The characteristics of functions throughout the episode is summarized in Table 2.

Table 2
Characteristics of functions in the Swedish photovoltaics innovation system between 1980 and 2004.

Legitimation	• Strong legitimacy among the general public • Skeptical attitudes to domestic market development among policymakers and established industry
Resource mobilization	• Policymakers fund RD&D in various thin-film technologies • Policymakers provide some investment support to the silicon module industry • International PV firms supply key inputs and investments that enable the emergence of silicon module production
Knowledge development	• Promising academic research on various thin-film technology • Solibro is spun-out to commercialize CIGS technology • No academic research on silicon technology, but development of know-how in module production • Limited applied research on PV systems and lack of learning processes in downstream parts of the value chain
Commercialization	• Some commercial production of silicon modules – the output is mainly exported to international markets
Market formation	• Small and stable market for off-grid PV systems, which are imported and distributed by retailers in related industries • No market formation for on-grid PV systems, but a few installations are made for experimentation and demonstration purposes

3.2. Episode 2: international technology diffusion, industry growth and budding markets (2004–2010)

When the second and final phase of ÅSC was drawing to a close in 2004, Solibro had verified that they could produce a commercial-size CIGS module in a small-scale process [62]. However, to make the technology commercially viable, the process had to be scaled up significantly. This required large investments that Swedish incumbent actors were unwilling to make due to the very small domestic market and the perceived lack of complementarity with existing industry [26,62,81]. Instead, Solibro entered a joint venture with the German PV firm Q-Cells, which at the time was one of the largest module suppliers on the global market [30]. Two commercial-scale production lines for CIGS modules based on Solibro's technology were built in Germany, but RD&D was kept in Sweden as a part of the new company Solibro Research [82]. In 2009, Q-Cells bought the remaining shares from Swedish investors, which meant that the CIGS technology developed through decades of Swedish research was finally controlled by German actors [26], with commercialization set to occur abroad. Nonetheless, Solibro Research remained in Sweden as a subsidiary to Q-Cells, and knowledge development focused on CIGS modules continued at Uppsala University, even though policymakers may have adopted a less supportive attitude when Solibro was acquired by Q-Cells [62].

The research on DSSC technology was still not considered ready for commercialization. After the second phase of ÅSC, activities were transferred to the Center for Molecular Devices (CMD) at KTH, which also involved the research institute Swerea and Uppsala University [68,69]. For a number of years, funding from the Swedish Energy Agency enabled a collaborative effort to develop DSSC modules, which was also facilitated by access to a more closed environment at Swerea where key advancements could be kept secret [69]. Around 2008, efforts to commercialize the DSSC technology developed within CMD intensified. The Swedish Energy Agency played an active role by encouraging the researchers to start a Swedish business development project, rather than engaging with interested international investors, and also formed an advisory group led by a well-connected industry profile [69,83]. This led the researchers to start the company Dyenamo, while they were supported with business development knowledge and industry contacts through the advisory group.

In addition, PV research at other universities expanded. Researchers at Lund University founded the company Sol Voltaics to commercialize gallium-arsenide nanowires that can function as a stand-alone cell material or be applied to different types of modules as an enhancing layer [84]. At Linköping University and Chalmers University of Technology, the efforts to develop organic PV technology continued and led to an increasing number of publications [70]. However, there was still very limited knowledge development focused on silicon technology, even though it increasingly dominated the global PV market.

Furthermore, the development of CIGS and DSSC technology attracted the attention of Swedish entrepreneurs outside of academia. In 2004, the company Midsummer was founded by engineers who saw an opportunity to use sputtering technology from the declining compact disc industry in the production of CIGS modules [85]. Notably, they competed with Solibro in the CIGS segment and were not a part of the research network formed around Uppsala University [86]. Nonetheless, a 1.1 MEUR EU grant, matched by investments from Swedish venture capitalists, enabled Midsummer to develop a production process [86]. By the end of 2008, they were ready to start large-scale module production in Sweden, but the global financial crisis made it difficult to find investors. However, at the same time, Midsummer identified a strong interest in building PV factories among Chinese actors, and therefore chose to reorient their business towards supplying manufacturing equipment [86]. They received a 49 MSEK grant and an 8 MSEK conditional loan from the Swedish Energy Agency to develop and demonstrate their technology (Fig. 2). This paved the way for commercialization and in 2010 Midsummer sold the first turnkey production line for CIGS modules to an international customer [87].

Another PV venture, NLAB Solar, was spun-off from a nanotechnology firm, which had received RD&D grants from the Swedish Innovation Agency to develop flexible DSSC modules [88]. Although NLAB Solar did not collaborate with the research network within CMD [68], the founding entrepreneur at an early stage involved a DSSC researcher that had done his PhD at Uppsala University in the 1990's, under the supervision of Anders Hagfeldt [89].

Furthermore, Swedish module production sustained its growth, driven mainly by increased production in REC Scanmodule's factory, and reached an annual production level of roughly 180 MW in 2008 (Fig. 3). At this time, the industry employed around 500 people and remained focused on assembling modules based on imported cells [90]. The production level still widely exceeded Swedish market demand and the vast majority of modules were exported to other European countries.

In 2005, Swedish policymakers introduced the first support oriented towards market formation. It consisted of a subsidy that covered 70% of the investment cost, but was only eligible for on-grid installations on

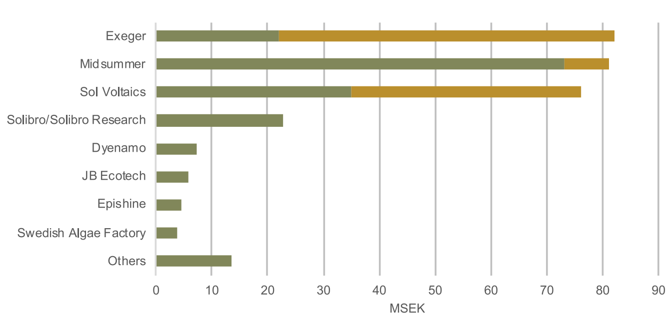

Fig. 2. Swedish public financial support to PV-oriented RD&D within private companies from 1996 to 2018. Based on database constructed for this paper, see Appendix for source information.

public buildings and had a small budget of 150 MSEK for the period 2005–2008 [91]. After a short period without investment support in the first half of 2009, the subsidy was reintroduced and expanded to cover any distributed on-grid installation, with a 200 MSEK budget for the period 2009–2011 [92].[10]

The subsidy scheme in combination with rapidly falling prices made the Swedish market grow exponentially, albeit from low initial levels (Fig. 3). In 2010, cumulative installed capacity in the distributed on-grid segment had reached 5 MW, for the first time surpassing the off-grid segment which had kept growing at a moderate rate.

Market developments guided some actors to downstream parts of the value chain [80]. Largely driven by environmental concerns, a number of households and firms invested in PV systems [93]. Their demand was met by a few small companies that offered turnkey installations, but many customers were still expected to install modules themselves [93]. However, although energy utilities and other established industry actors were involved in systems- and market-oriented knowledge development, they remained passive in relation to the emerging market [27]. At the same time, polls show a high and stable legitimacy among the general public [66].

To summarize, the second episode is characterized by failed attempts to mobilize Swedish industry and investors in commercializing thin-film technology based on Swedish research, which instead leads to industrialization abroad. At the same time, however, the Swedish silicon module industry expands significantly. There is also some initial market formation for on-grid systems as a result of policy support, which guides a few actors to downstream parts of the value chain. The characteristics of functions throughout the episode is summarized in Table 3.

3.3. *Episode 3: new actors, industry decline and surging markets (2010–2018)*

After 2010, the global shift in production towards Asia challenged the European PV industry. Q-Cells ran into financial problems and entered reconstruction in Germany, and as a result Solibro was acquired by the Chinese PV corporation Hanergy [26]. This meant that Swedish RD&D could be sustained, together with the German production lines that at the time employed around 200 people [82]. However, in 2018, growth was mainly occurring in China, where more than 1000 people were involved in building production lines for CIGS modules based on Solibro's technology [82].

For Midsummer, falling prices on silicon modules made it difficult to find customers that were willing to build CIGS factories [86]. Their technology was therefore adapted to the production of flexible modules for which thin-film technology was considered more competitive [85]. After a few challenging years, Midsummer received a large order from a Chinese customer that also invested and became the company's main owner, which paved the way for additional sales, a renewed focus on R&D and an IPO at a Swedish stock exchange [86]. They also developed some in-house capacity for producing CIGS modules integrated in roof sheets and increasingly targeted the Swedish market for building-integrated installations. In 2018, Midsummer was a profitable business [85].

Meanwhile, Dyenamo's efforts to commercialize DSSC modules continued. Although engaging Swedish industry actors proved challenging, they eventually initiated a collaboration with a property developer and a few other industry actors, involving a demonstration installation as well as a joint plan for continued R&D, up-scaling and

[10] At first, the budget was 150 MSEK, but an additional 50 MSEK was allocated in response to market demand. Centralized installations with a total budget exceeding 2 MSEK were excluded and the subsidy level was reduced to 60% (55% for large firms). There was also a maximum cost per kW of 75 kSEK. More expensive installations were only eligible for support calculated based on the maximum cost.

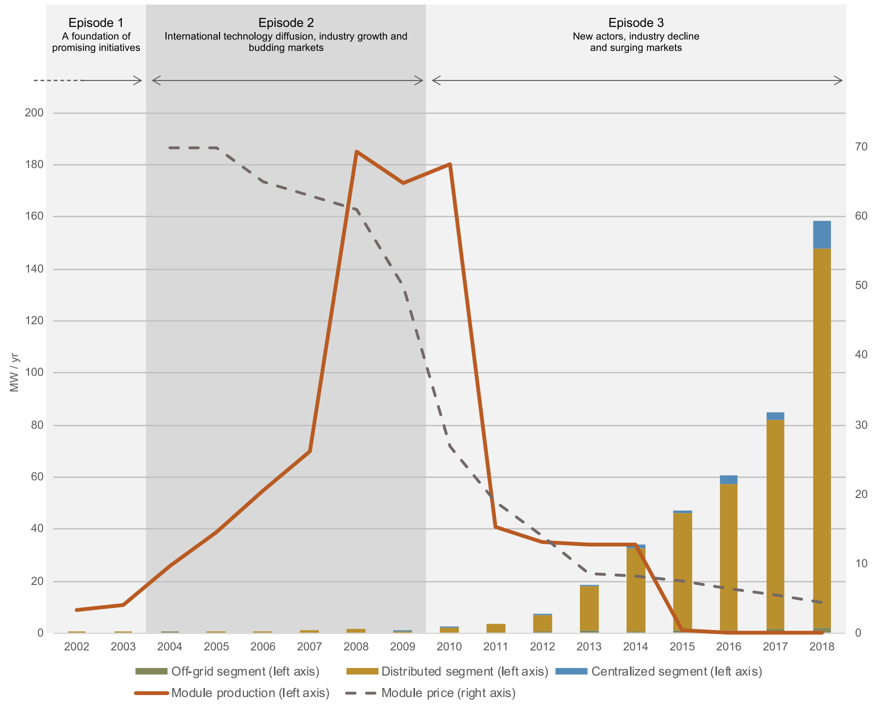

Fig. 3. Annual installed capacity in the off-grid, distributed and centralized segments of the Swedish PV market, together with annual module production and typical module price, from 2002 to 2018. Based on [14].

Table 3
Characteristics of functions in the Swedish photovoltaics innovation system between 2004 and 2010.

Legitimation	• Strong and stable legitimacy among the general public • Skeptical attitudes to domestic market development among policymakers and established industry persist
Resource mobilization	• Public research grants to thin-film RD&D increase • Some mobilization of private investment to venture companies • Venture companies mobilize competence from universities and established industry • Financial resources to advance commercialization of CIGS technology in Sweden are lacking • International PV firms supply key inputs to the silicon module industry • Market subsidies provide some financial support to customers of PV systems
Knowledge development	• Solibro is acquired by a German PV firm, but RD&D remain in Sweden • Continued academic research on various thin-film technologies • Several spin-off companies from academia and industry develop different thin-film technologies • Some systems- and market-oriented research • Some learning among distributors, installers and customers in downstream parts of the value chain
Commercialization	• CIGS technology developed in Sweden is used to establish commercial factories abroad • Production of silicon modules increases and reaches 180 MW per year in 2008 – the industry is dominated by REC Scanmodule
Market formation	• Installed capacity in the distributed on-grid segment grows exponentially and surpasses the off-grid segment which grows at a moderate rate • A few distributors and installers are guided towards the PV market – established industry in the energy sector remains passive

business development [69]. However, the Swedish Energy Agency did not adopt the coordinating and supporting role it had had in previous years. As a result, Dyenamo and the research network within CMD failed to mobilize financial resources to several key RD&D projects. In 2018, Dyenamo had abandoned their plans to develop and produce modules, and instead developed a small business supplying advanced cell materials and expert services to academic and private R&D departments [69].

Furthermore, NLAB Solar and Sol Voltaics emerged as promising venture companies, even though both lacked commercial revenue in 2018. NLAB Solar started to grow in 2010 when they received a 17.3 MSEK EU grant and a substantial investment from a Swedish window manufacturer [94]. After a few years of R&D focused on improving their DSSC technology, NLAB Solar received a 60 MSEK conditional loan from the Swedish Energy Agency and a large investment from a Swedish real-estate firm, and also changed their name to Exeger [89]. This enabled them to build a pilot factory in Stockholm – claimed to have been the world's largest printing press for solar cells – which was geared towards producing small modules that can be integrated in electronic devices, such as tablets and headphones, and used to harness indoor light [95]. Sol Voltaics also started to grow in 2010 and has subsequently developed a production process and pilot factory for their nanowire material [96]. They received an early investment from a Swedish non-profit venture capital fund and a 41 MSEK conditional loan from the Swedish Energy Agency, but has also attracted EU grants and private venture capital [97,98].

Moreover, new Swedish actors started to engage with RD&D focused on new PV technologies. Soltech Energy, which used to be active in the solar heating industry, developed a number of building-integrated thin-film module designs in collaboration with a Chinese manufacturer [99]. In 2018, the modules were sold on the Swedish market, sometimes in collaboration with actors in the construction industry, but most of the production was outsourced to other countries. New module designs based on either silicon or thin-film cells were also developed by small distributors and installers of PV systems, in collaboration with international suppliers [100]. In addition, JB Ecotech developed a process innovation for the production of silicon modules that was planned to be commercialized in collaboration with a Finish supplier to the global PV industry [101], while a few established firms showed ambitions to supply inputs and manufacturing equipment to emerging value chains for thin-film modules.

Within universities, publication rates and public funding increased (Fig. 4), and a number of smaller universities entering the field by attracting international researchers [71,102]. Although the historical technological focus largely remained at the leading universities, most groups broadened their activities [68,70,71,103–105]. Especially, perovskite cells, tandem designs and other emerging technologies, such as photon up-conversion, attracted wide-spread attention and gradually blurred the traditional differences between universities [68]. In addition, some research on silicon technology was initiated at one university [106].

The intensifying academic research also resulted in two new spin-off companies. Swedish Algae Factory was spun-off from algae research at Gothenburg University, aiming to develop a method for growing silicon algae and extracting a material that can be used as an efficiency-enhancing coating on different types of modules [107], while the longstanding collaboration between Linköping University and Chalmers University led to the spin-off company Epishine, which developed organic PV modules [70,108].

Among research institutes, the DSSC research at Swerea faded as the ambition to establish commercial module production was abandoned by Dyenamo [69]. At the same time, other institutes developed competence and infrastructure for testing and certifying modules, but this coincided with a decline in domestic module production and the target group became firms that imported modules from international suppliers [109]. In addition, a few research institutes started to engage with different thin-film technologies, but the links to venture companies remained quite weak [110,111].

While both academic and private efforts to develop new thin-film technologies expanded, the silicon module industry was increasingly challenged by the financial crisis and competition from Asian producers [90]. The output plummeted in 2010 when REC Scanmodule moved production to a newly built factory in Singapore (Fig. 3). And in the following year, the other module producers were forced to shut down [112,113]. Although a newly formed company bought REC Scanmodule's factory and continued production at a lower level until 2015, there was no production of silicon modules in Sweden in 2018 [14]. However, the entire factory remained intact and some actors still nursed plans to restart production [75]. Some of the people involved in REC Scanmodule also established Glava Energy Center, which is a platform for education and innovation that has strong links to Norwegian actors [75].

While module production vanished in the period, the Swedish market for modules kept growing exponentially, with cumulative installed capacity increasing from 5 MW in 2010 to 425 MW in 2018 [14]. The market was still dominated by distributed installations on residential and commercial buildings, but towards the end of the period the centralized segment started to expand as well. The off-grid segment continued to grow at a more moderate rate (Fig. 3). Following the international trend, most installations used standard silicon modules. There are no available statistics on the market share of thin-film technologies, but it can be expected to be very small, amounting to less than a few percent. Nonetheless, thin-film modules have been installed in various demonstration projects.

Market formation was associated with sustained high legitimacy among the general public [66], falling module prices (Fig. 3) and strengthened policy support (Fig. 5). Allocated funds to the investment support scheme increased rapidly after 2015, while cost coverage was reduced to reflect falling module prices.[11] In 2015, the scheme was supplemented with a tax credit for electricity from small scale generation (microgeneration) fed into the grid [76]. At the end of 2018, about 1500 MSEK had been distributed as investment support and 100 MSEK as tax credits.[12] Policymakers also made changes to the much debated regulatory framework that governs system installation and sales of electricity from microgeneration [114–118]. In 2010, microgeneration was exempted from costs associated with grid access (including metering equipment) and a system with guarantees of origin for renewable electricity was introduced [119,120]. More recently, in 2017, microgeneration was exempted from VAT[13] [121], while the obligation to apply for a building permit when installing building-applied modules was removed in 2018 [122]. Furthermore, the green electricity certificate system, which was introduced in 2003 and constitutes a transfer of funds from consumers of electricity to producers of renewable electricity [123], increasingly influenced the PV market. However, it was mainly used for centralized installations due to its complicated design and administrative costs, and the total funds transferred to owners of PV systems at the end of 2018 were limited to about 43 MSEK [14,22]. In addition, policymakers played a more active role in promoting PV technology. The Swedish Energy Agency proposed a strategy and increased their efforts to facilitate market development [83,124–127], while regional administrations and municipalities increasingly invested in, and promoted, PV systems [22,76,128].

As a result of market growth, a wide variety of actors populated the emerging downstream value chain. Although two thirds of PV capacity was installed on commercial or public buildings [14], most system owners were private households that were increasingly motivated by financial incentives [21]. The number of distributors and installers grew rapidly, and more than 282 such firms could be identified in 2018 [14]. Most were small businesses that had diversified from the electrical installation and construction industry, and they were estimated to employ about 1225 people working with PV systems [14,124]. Furthermore, the growing market attracted the attention of established industry actors, which had previously been passive. Small local energy utilities were involved in quite early and ambitious initiatives to promote market development [24]. And more recently, large energy utilities with national and international presence buy electricity from microgeneration and offer PV systems in collaboration with smaller distributors and installers [22]. Energy utilities have also started investing in centralized installations, often together with actors from the construction industry [129], while construction firms, property developers and architects increasingly include PV systems building projects and participate in RD&D [110,128]. In addition, a growing number of public and private initiatives promoted PV technology by demonstrating solutions, spreading information, developing strategies and setting goals, while universities and research institutes increasingly engaged with systems- and market-oriented research that also involved education and network-building [75,109,110,128,130,131].

To summarize, the third episode is characterized by expanding and broadening academic knowledge development focused on thin-film

[11] Although allocated funds increased, they have not been sufficient to meet demand. This has resulted in long waiting-times and uncertainty for both customers, distributors and installers [14]. Some customers have therefore chosen to use the ROT tax deduction scheme, which stimulates general demand in the construction sector by subsidizing housing renovations, as an alternative (the two support schemes cannot be combined [137].

[12] A separate investment support scheme targeting PV installations in the agricultural sector was implemented in 2015 [76]. The cost coverage was slightly higher since agricultural firms payed a lower energy tax, but only about 9 MSEK was distributed between 2015 and 2018 [14].

[13] Thus revoking a heavily criticized decision in 2013 that included them in this taxation system [21].

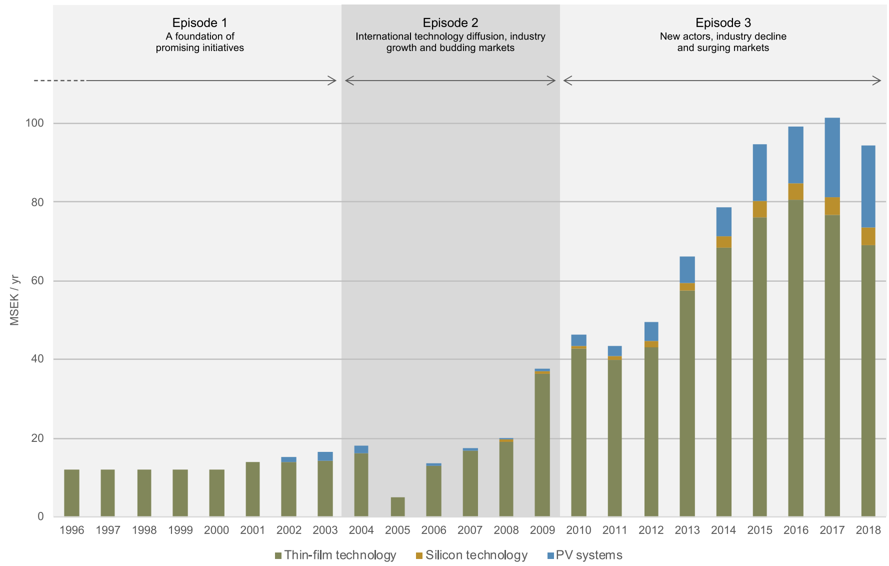

Fig. 4. Swedish public grants to PV research at universities and research institutes from 1996 to 2018. Categories distinguish between grants to projects oriented towards thin-film technology, silicon technology and PV systems. Based on database constructed for this paper, see Appendix for source information.

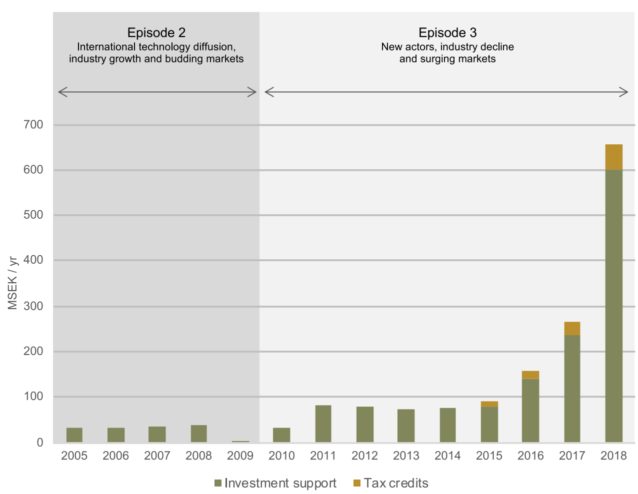

Fig. 5. Swedish public expenditure for investment support and tax credits between 2005 and 2018. Based on database constructed for this paper, see Appendix for source information.

technology. Several spin-off companies from universities and industry attract venture capital to develop new thin-film technologies, and there is some commercialization of manufacturing equipment and cell materials. However, the silicon module industry declines rapidly as a result of global competition and production ceases in 2015. This coincides with continued exponential market growth, which is fueled by falling module prices and strengthened policy support. The characteristics of functions throughout the episode are summarized in Table 4.

4. Discussion

4.1. Innovation dynamics

Our review shows that the emergence of PV in Sweden can be decomposed into three different development trajectories: the long-standing and growing RD&D activities focused on thin-film technology, the rise and fall of a significant silicon module industry, and the initially slow but eventually rapid growth of system installation. These trajectories show few interconnections and are the result of a fragmented innovation system that has been unable to enact a full range of innovation processes in virtuous cycles of positive feedback within Sweden. Fig. 6 illustrates this fragmentation in relation to the three identified trajectories, while we in the following proceed to analyze the underlying dynamics.

To begin with, thin-film RD&D has been propelled by the functions knowledge development, resource mobilization and legitimation (Fig. 6). The trajectory begun four decades ago when international developments encouraged Swedish policymakers to provide resources for academic PV research, which incidentally came to focus on thin-film technology due to the interests and networks of key individuals. Since then, the results of knowledge development have strengthened legitimacy for further investments, leading to increasing resource mobilization and expanded knowledge development, in a virtuous circle of positive feedback.

For two decades, knowledge development mainly consisted of academic research, but since the early 2000's a growing number of venture companies develop and aspire to commercialize different technologies. They have benefitted from knowledge and competence built up at Swedish universities, and also received grants that both enabled RD&D and facilitated the mobilization of additional resources by leveraging private investments and strengthening legitimacy [62,69,86,107]. In addition, they have been able to draw on knowledge and competence embedded in related industries and the international research community, by developing networks with Swedish and international actors, or by originating from entrepreneurs active in established firms [82,86,99,107,108].

Nonetheless, knowledge development has only driven very limited domestic commercialization. Venture companies have not managed to mobilize the substantial resources needed to establish commercial module production in Sweden, and instead had to seek other ways to advance their technologies. Solibro was acquired by foreign interests, and even though their technology has given rise to industries in Germany and China, Swedish activities are limited to RD&D. Midsummer and Dyenamo sought other positions in the value chain and developed commercial businesses supplying manufacturing equipment and advanced cell materials, which amounts to some, but limited, commercialization. Other venture companies remain focused on RD&D and lack commercial revenues. The difficulties in mobilizing resources to establish domestic production, despite an active support from policymakers, is likely a result of the initially weak domestic market formation and poor legitimacy of solar PV among industrialists and

Table 4
Characteristics of functional processes in the Swedish photovoltaics innovation system between 2010 and 2018.

Legitimation	• Strong legitimacy among the general public • Increasingly positive attitude to domestic market development among policymakers and established industry
Resource mobilization	• Public research grants to thin-film RD&D increase further • Increasing mobilization of private investment to thin-film RD&D • Venture companies mobilize competence from universities and established industry • Testing equipment for modules is offered by research institutes • Public subsidies to PV installations provide increasing resources to customers of PV systems
Knowledge development	• RD&D focused on CIGS technology continues • Expanding and broadening academic research on various thin-film technologies • Some limited academic research on silicon technology is established at one university • Universities and research institutes increasingly engage with systems- and market-oriented research • Several spin-offs from universities and industry develop thin-film technology – although activities are substantial with hundreds of workplaces, firms generally remain dependent on RD&D grants and venture capital • Several small firms develop new module designs in collaboration with international PV firms • Extensive learning processes in downstream parts of the value chain, which increasingly include industry actors in the energy and building sectors
Commercialization	• Declining production of silicon modules, which ceases in 2015 • CIGS technology developed in Sweden is used in commercial factories abroad • Some commercial production of manufacturing equipment and cell materials for thin-film modules • Commercial production of building-integrated thin-film modules is initiated but remains at very low levels
Market formation	• Installed capacity for distributed on-grid systems continues to grow exponentially – from 5 MW in 2010 to 425 MW in 2018 • The centralized segment also grows exponentially but from lower levels, while the off-grid segment grows at a more moderate rate • An increasing number of distributors and installers are guided towards the PV market • Energy utilities increasingly engage with PV technology by marketing systems, buying electricity from microgeneration and investing in centralized installations • Construction firms, property developers and architects increasingly include PV systems in real estate projects and also invest in centralized installations

investors, which made incumbent actors less prone to engage with researchers and venture companies. Indeed, access to domestic markets and/or collaborations with established industry have been shown to be important prerequisites for successful commercialization [39].

Secondly, and in sharp contrast, the rise and fall of the silicon module industry is the result of a commercialization process that had weak links to Swedish knowledge development, resource mobilization and legitimation. Established by international firms and Swedish entrepreneurs, module production built on knowledge and competence embedded in existing global supply chains. While practical knowledge development certainly occurred, it took place in a rather closed industrial network that had few collaborations with universities and research institutes. Infrastructure for testing and certification was eventually built up at research institutes, and some limited academic research in silicon technology was initiated, just when silicon module production had started to decrease. And policymakers played a role that was limited to providing investment subsidies as a part of regional development policy [75].

The silicon module industry had a more significant link to domestic market formation, since a small part of its output has been used in Swedish installations. But the fact remains that most of the production was exported. In fact, during its peak in 2008, the Swedish module industry could supply annual domestic demand in a couple of days (Fig. 3), which illustrates that the Swedish market was at the time too small to significantly support the module industry [27,76].

The weak links between the commercialization process underlying silicon module production and other functions in the Swedish PV innovation system, i.e. legitimation, resource mobilization, knowledge development and market formation (Fig. 6), exposed the industry to global developments that challenged its profitability. This led to an abrupt decline in 2010 and a few years later the industry had largely disappeared from Sweden, even though by then, the domestic market had paradoxically started to reach significant levels. It should be pointed out, though, that module production in countries such as Germany also declined heavily, even though the links to research, other industries and domestic markets were much stronger [32].

Lastly, the rapidly increasing system installation has been driven by positive feedback among the functions market formation, resource mobilization and legitimation (Fig. 6). Although a small and stable market for off-grid systems had been in place since the early 1990's, market formation for on-grid systems did not start until Swedish policymakers introduced the first investment support in 2005. This mobilized resources that enabled a few enthusiastic actors to engage with PV technology, not only by marketing, installing and buying systems, but also by mobilizing additional actors and spreading information, thus driving legitimation. Strong legitimacy for PV technology among these actors was accordingly key for early market formation, while skeptical attitudes among energy utilities and the broader political and industrial establishment is likely to have slowed down developments. The early developments enabled policymakers to increasingly promote resource mobilization and legitimation through expanded market subsidies, changes in regulatory frameworks, vision-building and knowledge diffusion. This drove continued market formation and led to the emergence of a downstream value chain with an increasing number of distributors and installers, which induced practical learning processes, resulted in cheaper products and services, and strengthened legitimacy among previously skeptical actor groups. In addition, universities and research institutes engaged more with systems-oriented research that supported market formation. Although these positive feedbacks were certainly important, it is unlikely that market growth would have been sustained without the rapidly falling prices of imported silicon modules after 2007 (Fig. 3). This was, however, driven by the expansion of international industries and not a result of domestic commercialization processes.

It should also be noted that market formation has had a weak link to the longstanding knowledge development focused on thin-film technology, since few modules based on technology developed in Sweden have actually been supplied to the domestic market. Nonetheless, thin-film RD&D has been important for market formation in a more indirect way. Academic research in the 1990's and early 2000's did not only create deep knowledge about specific thin-film technologies, but also initiated a network of proponents and developed general competence around PV systems, which later spread beyond universities and venture companies. For example, several key persons within public agencies, industry associations and market actors have backgrounds in thin-film research [15,132]. In addition, the failure to engage industry and investors in efforts to establish domestic thin-film module production may have highlighted the link between commercialization and domestic market formation for policymakers, and thus contributed to the first introduction of market subsidies.

To summarize, it is clear that the emergence of PV in Sweden is characterized by technological and temporal mismatches. Knowledge

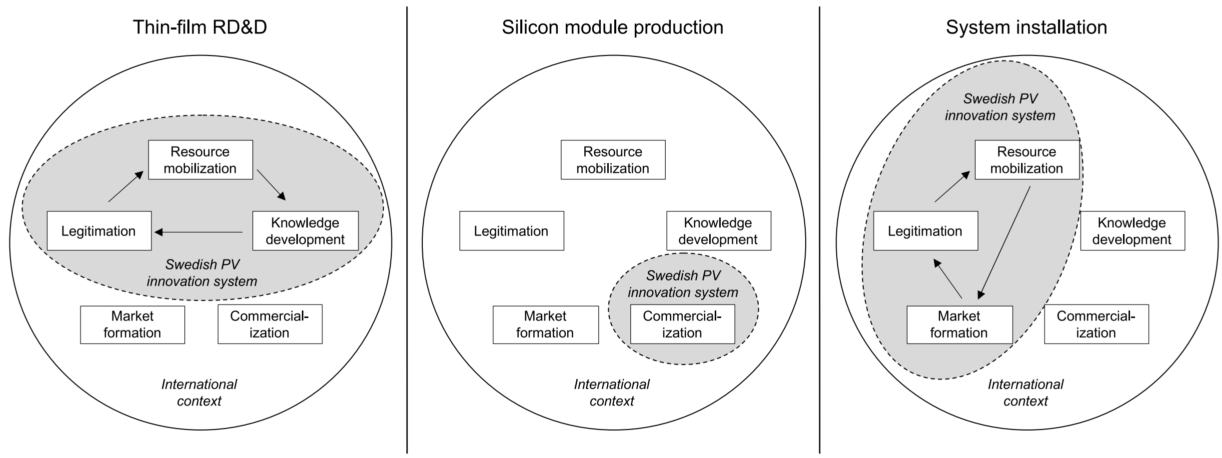

Fig. 6. Illustration of fragmented dynamics and international dependencies in the Swedish PV innovation system, in relation to three identified development trajectories.

development has focused on thin-film technology, while both commercialization and market formation has favored silicon technology. And although the latter have revolved around the same type of technology, they have essentially been separated in time. These mismatches have resulted in a fragmented innovation system that has failed to enact a full range of innovation processes in virtuous cycles of positive feedback within Sweden (Fig. 6). Instead, thin-film RD&D, silicon module production and system installation have emerged as separate development trajectories that depend on industries and markets in the international context. This is likely to have hindered the commercialization of Swedish thin-film research, lowered the prospects of continued silicon module production and slowed down market developments. The situation is a result of the interplay of internal factors within the emerging technological system and external factors in its global context. On the one hand, internal factors have created some path-dependency through cumulative causation. On the other hand, and perhaps more importantly, external factors have exerted a strong influence on the pace and direction of change. Public policy has influenced innovation processes in several ways, but overall seems to have played a rather reactive role. As a result, policy interventions have failed to take advantage of internal momentum and global developments in a strategic way.

It should be noted, finally, that the recent emergence of a small Swedish market for building-integrated installations, where thin-film technologies are more competitive, has opened up for technological alignment between knowledge development, commercialization and market formation. Together with the characteristics of value chains for building-integrated applications, which are less standardized, involve a broader network of actors and thus favor geographical proximity, this has led to stronger links between different parts of the innovation process, with burgeoning domestic commercialization as a result.[14]

4.2. Policy implications

Our findings have policy implications with relevance for both Swedish PV and other technological and geographical contexts. To begin with, it is clear that public research grants can support development trajectories that result in industrial development abroad, while market subsidies may stimulate the deployment of imported products. It can be argued that such dynamics are integrated features of a global economy that promotes cost-efficient value chains by allowing market forces, rather than policymakers, to determine where new industries and markets emerge. But at the same time, it is reasonable for national policymakers to expect some payback on the investments in research, development, demonstration and deployment of new technologies. This is not only about distributing costs and benefits in a fair way, but also about capturing value that can be used to fund the next round of technological innovation and avoiding a situation where externalities erode national incentives for technology policy.[15] In addition, for certain technologies such as PV, which can be expected to become critical parts of the societal infrastructure as they diffuse at an ever-larger scale, there could be reasons to promote the build-up of distributed production capacity, rather than industries that are concentrated in specific places.

The question is how policymakers can influence where new industries emerge as a result of technological innovation.[16] Our analysis highlights the importance of promoting links between a full range of innovation processes, in order to avoid a situation where the domestic innovation system becomes fragmented and completely dependent on international industries and markets [39]. In the emergence of PV in Sweden, policymakers have made few efforts to achieve these dynamics, which has not only slowed down developments in the system as a whole, but also contributed to the current situation where domestic commercialization of cell and module technology is largely absent. Adopting a more proactive role could, for instance, have involved a support scheme that specifically targeted building-integrated installations, which may have fueled positive feedback mechanisms among knowledge development, commercialization and market formation related to thin-film technology. Notably, similar policies have been deployed internationally, where some countries adapt tenders to favor domestic suppliers [133]. However, although such policymaking could have facilitated the emergence of domestic industries, it may possibly have come at the expense of broader market formation, since subsidizing mass-markets for imported silicon modules is likely to have been a cheaper way to rapidly increase installed capacity. This highlights tensions between policy objectives in the energy and industry sectors, and underlines the need for a clear and informed political direction [11,134].

Another strategy that policymakers could possibly explore further is to make RD&D grants to private actors subject to a payback mechanism that delivers a return on public investments even if innovations are exploited abroad, as suggested by among others Mazzucato [135]. This may involve offering conditional loans or taking equity in venture

[14] Wesche et al. refer to this type of technology as configurational and find similar characteristics in a study on heat pumps in Germany [138].

[15] This is analogous to private investments in RD&D which are incentivized through the patent system.

[16] This topic can also give rise to arguments for centralized planning of economic activity and limited movement of capital, products and services. Such policies are clearly problematic given the benefits of free trade and global specialization [126,136,139].

companies that receive financial support. However, such measures are associated with administrative costs, which is why the Swedish Energy Agency has cancelled the use of conditional loans [136].

Finally, it should be emphasized that while Sweden may have failed to turn public RD&D investments into a domestic PV industry, it has benefitted from international policymaking when developing a domestic market. Without research efforts in countries such as USA, Japan and Germany, not to speak of crucial industry and market subsidies underwritten by German electricity consumers and Chinese taxpayers, the price of silicon modules would not have fallen by an order of magnitude in the last decade. And without a supply of modules that made PV systems attractive to many customers with quite moderate domestic subsidy levels, it is unlikely that the Swedish market would have taken-off the way it has. This highlights the "give and take" characteristics of international innovation systems and underlines that the costs and benefits of innovation have to be evaluated in relation to multiple policy objectives. In the end, whether the emergence of PV in Sweden represents a success or a failure depends on perspective – although domestic cell and module industries are largely absent, a surging market is increasingly contributing to the global energy transition.

4.3. Theoretical implications

The review presented in this paper illustrates how the emergence of a technological system may result in industries and markets that differ in their geographical location and technological focus, which has obvious consequences for the distribution of benefits from successful innovation. This supports the argument that geography matters [5,6]; not only for the dynamics but also for the results of the innovation process. In addition, it highlights the importance of accounting for not only the pace, but also the directionality of innovation processes [37,38]. In this paper, we have demonstrated how the function commercialization can be used to distinguish innovation dynamics related to upstream and downstream parts of the value chain for a specific technology, which complements the common practice of adopting system boundaries that highlight developments in different geographical domains. It remains for future research to validate whether this is a valuable addition to the TIS approach.

Furthermore, our analysis shows that a fragmented national innovation system may shape the emergence of a technological system towards a situation where industries and markets mainly develop abroad. This supports previous findings that industrial development in specific regions can be promoted by linking technology developers to domestic markets and/or incumbent industry actors with international networks [39].

Finally, our findings illustrate the often conflicting objectives that motivate innovation policy related to renewable energy technologies [11] and also shows how specific policy interventions may promote undesirable development trajectories. This underlines the need to develop theoretical tools that support the development of transformative and mission-oriented policymaking [7,8] with a clear objective in mind.

5. Conclusions

The purpose of this paper is to review and analyze the emergence of PV in Sweden from a policy perspective. We identify four decades of thin-film RD&D that has largely failed to drive domestic commercialization, the rise and fall of a silicon module industry that mainly served international markets, and a rapidly growing domestic market based on imported silicon modules. When analyzing the underlying dynamics of these development trajectories, we find mismatches and fragmentation among key innovation processes, which has created a dependence on international industries and markets. Our results highlight how public research grants can lead to industrial development abroad, while market subsidies may stimulate the deployment of imported products. We therefore suggest that policymakers which aim to stimulate domestic industrialization should strive to promote links between a full range of innovation processes. In our research case, this could for example have involved targeted market support to building-integrated photovoltaics. Policymakers may also consider making RD&D grants to private actors subject to a payback mechanism that delivers a return on public investments, even if innovations are exploited abroad. In addition, our analysis demonstrates how the TIS approach can be extended to include the function commercialization as a way to distinguish between developments in upstream and downstream parts of the value chain for the technology in focus. The findings also emphasize the importance of paying attention to the directionality of innovation processes, both with respect to alternative technological designs and markets applications, and the different geographical domains in which industries and markets based on new technologies emerge.

Credit author statement

John Andersson: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. Hans Hellsmark: Conceptualization, Writing – review & editing, Supervision. Björn Sandén: Conceptualization, Writing – review & editing, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.110894.

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