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Escaping the niche market: An innovation system analysis of the Dutch building integrated photovoltaics (BIPV) sector

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ABSTRACT

Over the past years, a new technology has emerged in the solar photovoltaics market: building-integrated photovoltaics (BIPV). Even though this technology has a lot of potential, the diffusion of BIPV has remained rather limited, globally and also in the Netherlands. In this paper, the Technological Innovation System (TIS) approach is used to analyze the historical development of the Dutch BIPV innovation system and to provide a comprehensive overview of the systemic problems that hamper further diffusion of BIPV in the Netherlands. Several systemic problems are identified, including 1) lack of policy support for the industrialization and commercialization of BIPV, 2) the absence of large firms from the construction industry resulting in the lacking industrial capacities of the BIPV innovation system, and 3) the limited value chain coordination and collaboration to help improve the compatibility and complementarity of BIPV with traditional building components and (electrical) installations. To overcome these systemic problems and enable the Dutch BIPV innovation system to move from the present niche market phase to the commercial growth phase, multiple recommendations are provided to both policymakers and value chain actors.

1. Introduction

In the past decade, a new technology has emerged in the solar photovoltaics (PV) market: building-integrated photovoltaics (BIPV). In contrast to building *applied* photovoltaics (BAPV), BIPV is integrated in the building envelope as a construction material that fulfills at least one additional function besides generating electricity (e.g., insulation or weather protection) [1,2]. BIPV technologies use either silicon or non-silicon based PV cell technology and applications include roof-integrated and façade-integrated products [3,4]. The European BIPV market is expected to grow significantly [5,6]. One of the reasons for the expected growth is the target of the European Union (EU) to increase renewable energy generation from 10% to 27% [7] and the EU Energy Performance of Buildings Directive that requires all new buildings to be nearly zero-energy buildings (nZEB) [8,9]. In addition, roof and façade potential capacities for PV are far from being fully exploited and are estimated to be near 1 TWp for the EU [6,10].

One of the EU member states that has a vibrant BIPV sector is the Netherlands. The main goal of the National Climate Agreement of the Netherlands is to reduce national greenhouse gas emissions with 49% by 2030 [11]. To foster innovation and cross-sector cohesion, the Dutch government has formulated a so-called Integrated Knowledge and Innovation Agenda (IKIA) [11,12]. This IKIA contains five main missions, of which the first two missions are to realize a completely CO_2 neutral electricity system by 2050 (Mission A) and to achieve a CO_2 neutral built environment by 2050 (Mission B). Although these missions offer significant opportunities for technological innovations like BIPV, the Dutch BIPV market is still considered to be a niche market. In 2014, BIPV only contributed about 1% to the total installed PV power in the Netherlands [13]. Currently, the Dutch BIPV market is estimated to make up about 2% of the total PV market of the Netherlands. Previous research has found multiple barriers to the development and diffusion of BIPV in the Netherlands, including financial barriers, standardization of BIPV solutions, lack of value chain collaboration, and lack of education of value chain actors (including architects, building companies, installers, and roofers) [1,13–17]. Nevertheless, this research remains

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rather fragmented and BIPV technologies still struggle to compete with incumbent technologies. Moreover, previous research points towards future research topics such as the correspondence of BIPV with existing technologies and practices [17] and effective knowledge diffusion towards the construction and installation sector [16,17].

It is clear that technological advancements alone are not sufficient to transform the BIPV market from a niche market into a mass market, also changes in the social dimension are required. These social changes are often crucial to achieve a form of technological change that can be sustained [18]. To analyze the development and diffusion process and pinpoint technical *and* social systemic problems, the Technological Innovation System (TIS) approach developed by Hekkert et al. [18] is used. This approach helps to understand and evaluate the (technical and social) structures and processes that hamper the development and diffusion of a technological innovation [18,19]. By understanding and evaluating these structures and processes, one can provide recommendations to value chain actors and policymakers on how to intervene in the system to remove systemic problems. In this paper, we seek to answer the following research question: What systemic problems hamper further development of the Dutch building-integrated photovoltaics (BIPV) innovation system and what are the implications for policymakers and value chain actors? To this end, we will use a TIS approach.

This paper is further structured as follows. In the following section, the theoretical framework is described in further detail, reviewing the TIS approach. Subsequently, Section 3 describes the methods used in this study. In Section 4, the results regarding the historical development and current state of the Dutch BIPV innovation system are described and the systemic problems are identified. The findings are discussed in Section 5. Finally, Section 5 concludes this paper by answering the research question.

2. Theoretical framework

The theoretical framework used to analyze the Dutch BIPV sector is the Technological Innovation System (TIS) approach. A TIS can be defined as "a network of agents interacting in the economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" [20, pp. 94]. A TIS structure is comprised of actors, hard and soft institutions, networks, and infrastructures [21]. Hard institutions are formal institutions, such as laws, intellectual property rights (IPR), and industry standards. Soft institutions are more informal institutions such as norms and values. Within the overarching institutional framework, actors collaborate and interact with each other, which over time results in the formation of networks. Infrastructures include physical (e.g., technological artifacts, machines), financial (e.g., subsidies), and knowledge (e.g., expertise, know-how) infrastructures.

The extensive stakeholder analyses of previous studies [13–15,17] were used to comprise an overview of the actors that are active within the Dutch BIPV innovation system (see Fig. 1).

As pointed out by previous research [15,17] most BIPV products are considered to be in the niche market phase, meaning the technology itself and the structure supporting it are still in development. An overview of the BIPV product categories that are offered on the Dutch market and their corresponding development phase is shown in Fig. 2. As pointed out by Hellsmark and Söderholm [22], the development phases up to the commercial growth phase must result in the creation of industrial capacities. This capacity is built through knowledge development and diffusion to other actors, the development of new production methods and value chains, and the implemtation of new laws and regulations that foster the development of industrial capacities and large-scale diffusion. Subsequently, a technology will only move to the commercial growth phase if it has developed a favorable price/-performance ratio and the surrounding TIS has developed the capacity to enable large-scale deployment of the technology [22].

The ongoing development of a TIS is the result of processes (i.e., interactions and activities) that happen within a TIS. Hekkert et al. [18] define seven key processes, called system functions, that determine the rate of development of a TIS in terms of structural elements (see

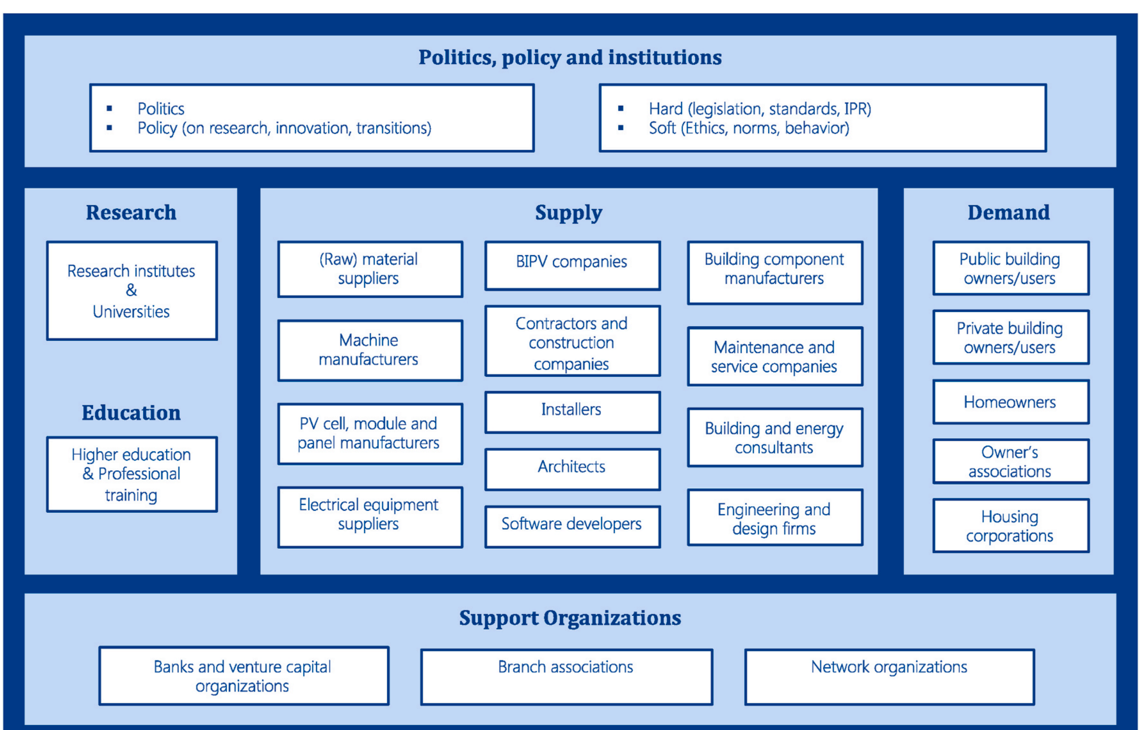

Fig. 1. An overview of the Dutch BIPV innovation system. Based on Van den Hurk and Teunissen [13], Van Horrik et al. [14], Osseweijer et al. [15] and Van der Poel et al. [17].

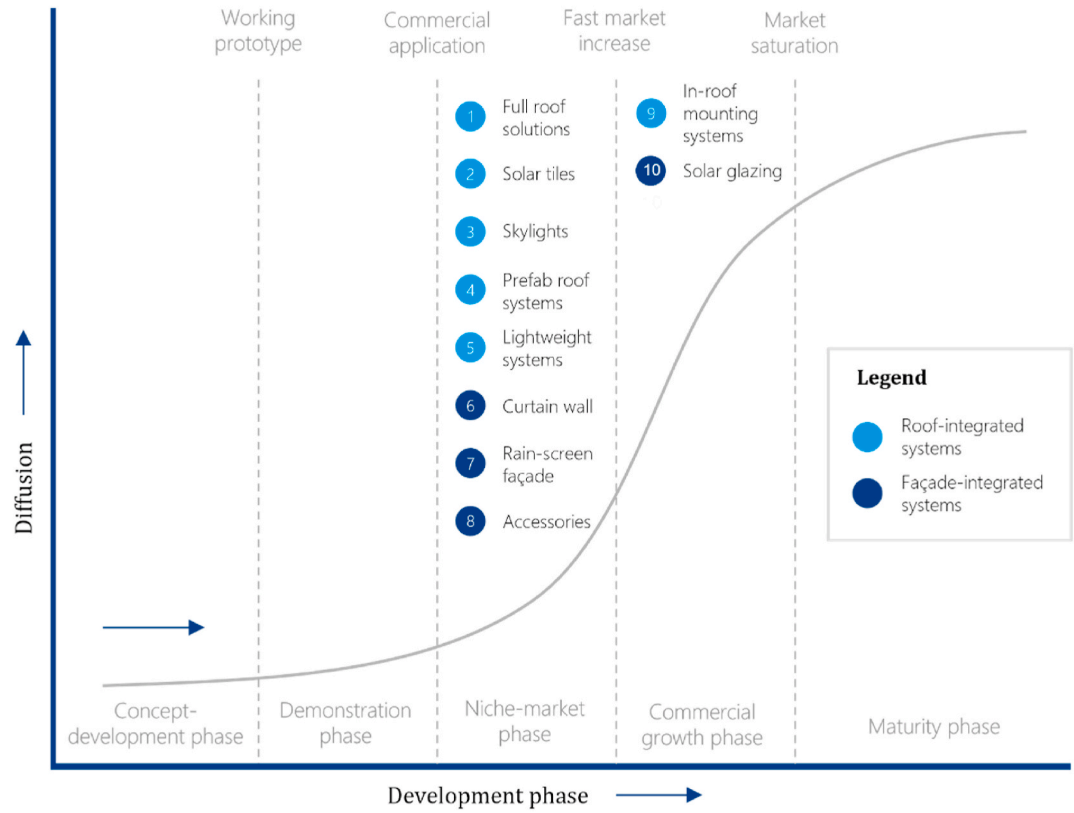

Fig. 2. An overview of the different BIPV product categories on the Dutch market and their corresponding phase of development. Development phases based on Hellsmark and Söderholm [22]. Product categorization based on Biyik et al. [4] and SUPSI and SEAC [23].

Table 1). These seven functions were used to analyze the development and diffusion of the Dutch BIPV innovation system.

Both the individual fulfillment of each system function *and* the interactions between the different functions are important to consider when analyzing the dynamics within innovation systems. This is because the individual functions can influence each other, resulting in forms of cumulative causation (i.e., positive feedback loops) which in turn result in the further development of an innovation system [24]. Therefore, it is important to be able to identify which problems hamper the fulfillment of system functions that can start this cumulative causation. It is argued by Wieczorek and Hekkert [21] that low fulfillment of a system function is often associated with the absence or insufficient capacity of certain actors, institutions, interactions, or infrastructures. For example, low fulfillment of the function market formation can be caused by the absence or lack of entrepreneurial capabilities to identify and exploit market opportunities. A coupled structural-functional analysis helps to identify the systemic problems behind the low fulfillment of certain TIS functions [21]. Systemic problems can be categorized into four categories: actor's problems, institutional problems, interaction problems, and infrastructural problems. A short description of the systemic problems can be found in Table 2.

Based on the type of systemic problem, specific systemic instruments can be proposed to policymakers and value chain actors to help overcome the systemic problems, thereby increasing the fulfillment of the affected systemic functions. The goal of these systemic instruments is specific to the type of systemic problem (see Table 2). Once the systemic instrument effectively solves a systemic problem, the fulfillment of the previously affected function will be more fulfilled. This can in turn positively influence the fulfillment of other system functions. Ultimately, this results in favorable conditions for the BIPV innovation system to move from the niche-market phase to the commercial growth phase.

3. Methodology

This study was conducted in three phases: 1) mapping the historical functional development of the Dutch BIPV system, 2) assessing the current functional fulfillment of the Dutch BIPV system, and 3) performing a structural-functional analysis to identify the systemic problems that hamper further development of the innovation system. In the first phase, secondary data was used to construct the historical development of the functional fulfillment of the Dutch BIPV innovation system. Here, the approach of Negro et al. [25] was followed, which is to analyze the innovation system dynamics by mapping as many events (e.g., patents filed, innovation projects started) as possible that have taken place in the innovation system over time by using secondary data sources such as peer-reviewed articles, company and industry reports, policy reports, professional journals and (subsidized) innovation project databases. Specific indicators were used per function to map events per system function, as shown in Table 3. Since the weighting or effect of an event can only be assessed in retrospect, events that have a positive effect are indicated with a + (e.g., new entrants entering the BIPV market, +F1) and the events that have a negative effect are indicated with a – (e.g., less subsidies allocated to BIPV innovation projects, –F6).

For the second phase, primary data was collected by conducting 29 semi-structured interviews with all actor types from the innovation system (i.e., governmental actors, research and educational institutes, supply-side actors, demand-side actors, and support organizations). The interview data was used to verify the reconstruction of the historical development of the system functions, but more importantly, to gain deeper insights into the current functional fulfillment of the BIPV innovation system. The final interviewee list is shown in Appendix 1. The interview guide that was used to interview respondents is based on the diagnostic questions developed by Hekkert et al. [26] and Wieczorek et al. [27] to interview actors within TISs. Based on the analysis of gathered secondary and primary data the current fulfillment of every

Table 1
Seven functions of technological innovation systems [18].

Function	Description
Function 1. **Entrepreneurial activities**	Entrepreneurs are crucial for a well-functioning TIS. It is the role of entrepreneurs to experiment and turn the potential of new knowledge, networks and markets into concrete action to explore and exploit business opportunities. Entrepreneurs can be both new entrants and incumbent companies that aim to diversify and exploit new business opportunities.
Function 2. **Knowledge development**	Mechanisms of learning are crucial to the development and diffusion of technology. Therefore, research and development (R&D) and overall knowledge development are prerequisites for a well-functioning innovation system. This function includes 'learning by searching' and 'learning by doing'.
Function 3. **Knowledge diffusion through networks**	Information exchange is the essential function of networks. This aspect is particularly important in a heterogeneous context in which R&D meets government, competitors, and the market. Network activity is regarded as a prerequisite for 'learning by interacting'. When user-producer interactions are involved, it can also be considered as 'learning by using'.
Function 4. **Guidance of the search**	When several technological options exist, specific foci are needed to stimulate (and guide) investments. Guidance of the search refers to the activities that can positively affect the visibility and clarity of specific requirements of technology users. This aspect also includes government and market expectations, as these can guide change toward a specific direction. This function cannot be seen as a one-sided endeavor, but rather an interactive and cumulative process of exchanging ideas between producers, users, and other actors.
Function 5. **Market formation**	New technologies often experience difficulties when competing with incumbent technologies. They are often relatively costly and inefficient and require time to develop further to be able to compete with incumbent technologies. Therefore, it is important to create protected spaces in which for instance temporary niche markets can be formed. Another possibility is to create a temporary competitive advantage using favorable tax regimes or subsidies. Furthermore, the formation of industry standards is an important part of this process.
Function 6. **Resources mobilization**	Resources include financial and human capital. These resources are necessary as input to be able to execute all activities that happen within the innovation system.
Function 7. **Creation of legitimacy**	To continue to develop and diffuse, a new technology has to become part of the incumbent socio-technical regime (or has to overthrow it). This force of 'creative destruction' is often opposed by incumbent organizations that have vested interests. In this context, advocacy coalitions can enable the creation of legitimacy for the new technology, counteracting resistance to change.

system function was determined, and a score was given based on a 5-tier Likert scale of absent (1), weak (2), moderate (3), strong (4), excellent (5). Subsequently, a workshop was organized with 4 international BIPV experts that participate in the IEA-PVPS Task 15 [28] to discuss and verify these scores.

In the third phase of this study, a structural-functional analysis was performed to identify the systemic problems behind the low fulfillment of certain TIS functions (which were identified in the second research phase). Based on the identified systemic problems, specific systemic instruments are proposed to policymakers and value chain actors to move the BIPV innovation system into the next development phase, i.e., the commercial growth phase.

Table 2
Types of systemic problems and proposed goal of systemic instruments [21].

Systemic problem	Type of systemic problem	Description	Proposed goal of systemic instrument
1. Actors' problems	Presence-related	Presence-related problems refer to whether relevant actors may be absent.	Stimulate and organize the participation of relevant actors
	Capacity-related	Capacity-related problems refer to the capacities that actors within the innovation system hold. These include their capacity to use available resources effectively, identify opportunities, and establish exploitation strategies.	Create space for actors capability development
2. Institutional problems (hard and soft)	Presence-related	Presence-related institutional problems occur when hard or soft institutions are absent.	Stimulate occurrence of interactions
	Capacity-related	Capacity-related institutional problems occur when the quality of these institutions is insufficient (e.g., when stringent institutions favor incumbent technologies).	Prevent too strong and too weak ties
3. Interaction problems	Presence-related	With presence-related interaction problems there is insufficient interaction between actors, which can be due to cognitive distances between actors, differences in goals and capacities, or distrust.	Secure presence of hard and soft institutions
	Quality-related	Quality-related interaction problems refer to the quality or intensity of interactions. Strong network problems occur when actors are wrongly influenced by stronger actors and therefore, cannot supply others in the network with relevant knowledge. Weak network problems occur when ties between actors are weak due to complementarity problems.	Prevent too weak and too stringent institutions
4. Infrastructural problems	Presence-related	Presence-related infrastructural problems occur when necessary infrastructures are absent.	Stimulate physical, financial, and knowledge infrastructure
	Quality-related	Quality-related infrastructural problems are present when the infrastructures are insufficient or not functioning properly.	Ensure adequate quality of infrastructure

4. Results

Following the methodology described in section 3, the results presented in this section are threefold. First, the historical development of the Dutch BIPV, based on various documents, is analyzed to identify the

Table 3
Used indicators and data sources per innovation system function. Adapted from Hekkert et al. [18], Bergek et al. [19] and Hekkert et al. [26].

Functions	Indicators	Data sources
Function 1. **Entrepreneurial activities**	• Number of subsidized innovation projects over time (both national and European) • Number of new entrants and diversification activities of incumbents	Database Netherlands Enterprise Agency (RVO), Cordis Database, professional journals, company and industry reports, peer-reviewed articles
Function 2. **Knowledge development**	• Number of BIPV-related patents • Number of academic publications related to the Dutch BIPV sector	European Patent Office database, peer-reviewed articles
Function 3. **Knowledge diffusion through networks**	• Network size and intensity over time • Mapping inter-organizational knowledge transfer and collaboration	Database Netherlands Enterprise Agency (RVO), professional journals, peer-reviewed articles
Function 4. **Guidance of the search**	• Specific policies and targets set by the Dutch governments regarding BIPV • Number of articles in professional journals that raise expectations of BIPV	Policy reports, peer-reviewed articles
Function 5. **Market formation**	• Market development and potential • Specific policies and regulations that favor BIPV • Presence of industry standards	Company and industry reports, policy reports, peer-reviewed articles
Function 6. **Resources mobilization**	• The number of financial resources that are made available through subsidies • Number of employees (FTEs) working in the energy (and BIPV) sector • Number of obtained diplomas in intermediate vocational education, higher vocational education, and academic education programs related to the energy (and BIPV) sector	Database Netherlands Enterprise Agency (RVO), Cordis Database, company and industry reports
Function 7. **Creation of legitimacy**	• Mapping interest groups and their lobby actions	Professional journals, industry reports

pattern of the functional development of the BIPV innovation system over the years and explain why BIPV has not yet moved to the commercial growth phase. Second, deeper insights into the current functional fulfillment of the innovation system are provided in the following section through in-depth expert interviews. Third, a coupled structural-functional analysis is performed in the third section in order to identify systemic problems and policy intervention points.

4.1. Historical functional development of the Dutch BIPV innovation system

This subsection provides insights into the functional pattern of the Dutch BIPV innovation system over the years. The main events that occurred within the innovation system are described in four periods (1995–2007, 2008–2011, 2012–2015, and 2016–2019). The length of the time periods differ due to a change in systems dynamics triggered by a key event. For each event it is indicated which system function(s) it fulfills in a positive of negative way (e.g., +F1 or -F2).

4.1.1. 1995–2007: the dawn of the BIPV innovation system

In the Netherlands, the exploration of the technological domain of BIPV starts in the mid-1990s. The period from 1995 until 2007 is largely centered around knowledge development and the start of BIPV-related entrepreneurial activities. R&D programs are initiated by several companies [29,30], and BIPV-related patent applications are filed (see Fig. 3) (i.e., "learning by searching") (positive effects on functions F1 and F2: +F1, +F2). The first EU subsidized BIPV-related innovation projects with Dutch participant firms are initiated as well (+F1, +F6) (see Fig. 4). Furthermore, three (large) pilot projects BIPV are realized (i.e., "learning by doing")), including a large (pilot) construction project in the neighborhood Nieuwland in Amersfoort (from 1995 until 2002) [31,32] and the neighborhood "De Stad van de Zon" in Heerhugowaard (realized from 2000 until 2009) [32–34] (+F1). In 2002, the Expo Haarlemmermeer is realized, which is until today one of the largest non-residential BIPV projects that is realized in the Netherlands [32].

4.1.2. 2008–2011: increasing inter-organizational network formation around BIPV

From 2008 onwards, a steep decrease in PV module prices [37] lead to BIPV becoming one of the focus areas of the PV industry. The reason for this is that the industry expects that BIPV can be a more cost-efficient solution than BAPV because it combines multiple functions (+F4) (i.e., the function of a building component and electricity generation). These positive expectations reinforce the development of other system functions, as they lead to investments in the knowledge infrastructure around BIPV and the start of the first nationally subsidized BIPV-related innovation projects (+F1, +F6). An important subsidy scheme that helps support the development of the BIPV innovation system is the Innovation Program on Solar Power (In Dutch: Innovatieprogramma Zonnestroom, IPZ) which is launched in 2010 [38]. This program supports entrepreneurs to conduct feasibility studies, start R&D activities, and develop commercial (BI)PV products. Alongside the subsidized innovation projects, significant investments are made to establish a strong knowledge infrastructure around BIPV, including the realization of R&D district "De Wijk van Morgen" (district of tomorrow) of the Zuyd University of Applied Sciences in 2009 [39], the establishment of research partnership Solliance (between Eindhoven University of Technology (TU/e), TNO, ECN, Holst Centre, and imec) in 2010, and the establishment of Solar Energy Application Center (SEAC) in 2011, which was founded to strengthen downstream activities and develop commercially viable BIPV solutions (among other things) [40].

Parallel to these activities, startups, SMEs, and incumbents start R&D programs and launch their first prototype and commercial BIPV products (+F1, +F2). A cluster of BIPV companies is being formed in the southern provinces Brabant and Limburg (+F3). Pioneering firms include Ubbink, Scheuten Solar, and Stafier Solar [40,41]. Whereas previously R&D activities were initiated in isolation, this period is characterized by more collaboration between companies, research institutes, and universities, resulting in the formation of a network around the technological domain of BIPV (+F3). At the end of 2011, Agentschap NL (since 2014 the Netherlands Enterprise Agency, RVO) publishes a report titled "Integration of solar power systems in buildings" which provides an overview of the different available and possible future BIPV systems including example cases (+F4, +F7) [42].

4.1.3. 2012–2015: the acceleration of the Dutch BIPV innovation system

This period is characterized by increasing entrepreneurial activities with the rise of new entrants and diversifying incumbents as well as the sharp increase in innovation projects (+F1). Resources for innovation projects are (in part) acquired through project-specific subsidies (+F6). In 2012, the Dutch solar industry signs a so-called innovation contract with the Dutch government, in which it commits to investing millions of euros in R&D projects, demonstrating its commitment to innovation projects in the field of silicon, thin film (through Solliance), and BIPV (through SEAC) (+F4, +F6) [43]. Furthermore, this innovation contract

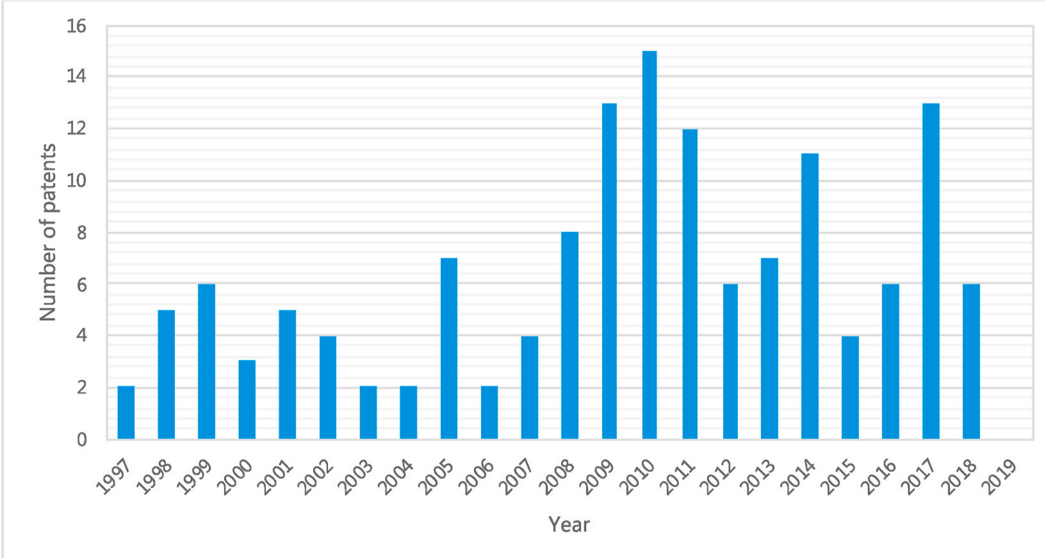

Fig. 3. The number of patents by Dutch applicants in patent classification Y02B10/10 (PV integration in buildings) [35].

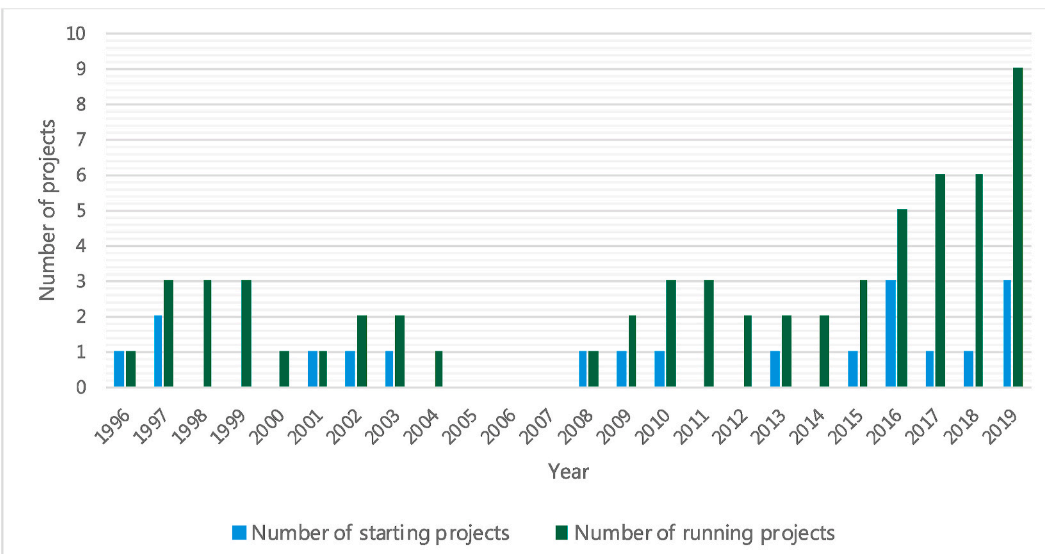

Fig. 4. The number of EU subsidized BIPV-related innovation projects in which Dutch organizations have participated or participate [36].

provides the basis for the establishment of the Top Consortium Knowledge and Innovation (TKI) Solar Energy (nowadays TKI Urban Energy), a public-private partnership (PPP) between a large group of Dutch companies and research institutions (+F3, +F4, +F6), which aims to accelerate the development and application of (BI)PV technologies in the Netherlands, in part by subsidizing collaborative innovation projects [44].

The positive outcomes of previously initiated innovation projects (+F4, +F7) lead to rising positive expectations for BIPV, which in turn leads to more BIPV-related innovation projects being subsidized (see Fig. 5) (+F6). In 2012, the development of a test site named SolarBEAT is subsidized (+F1, +F6) [45]. In the 6 years thereafter, SolarBEAT is used by over 50 companies and research institutes to test BIPV systems [46]. Whereas previously entrepreneurial activities were primarily focused on feasibility studies and other related R&D activities, now innovation projects are more focused on the development of prototypes and commercial products. Many first-generation BIPV roof systems are developed and launched onto the market by companies like Stafier Solar, Synroof, and SCX Solar (+F1). BIPV façade systems are launched onto the market as well but to a lesser extent. In addition, multiple BIPV companies are founded during this period (e.g., BEAUsolar, Solinso, and Physee) [47,48]. Incumbent firms from adjacent industries (e.g., the construction industry, chemical manufacturing industry also start diversification activities (+F1). The number of BIPV-related subsidized innovation projects peak in 2015 when a total of 16 projects are subsidized (see Fig. 5).

The increase in entrepreneurial activities also results in niche market activities (+F5), with BIPV products being increasingly applied in non-residential buildings (e.g., offices and public buildings). Large non-residential BIPV projects include a project at Rotterdam Central Station in 2014 and the realization of the office building "The Edge" in 2015 [32]. According to interviewees, one of the reasons for this is that this market segment has different buying motivations (e.g., increasing corporate image) and can pay a higher price for more esthetically pleasing solutions like BIPV. The five largest residential and non-residential BIPV projects in the Netherlands up to 2015 can be

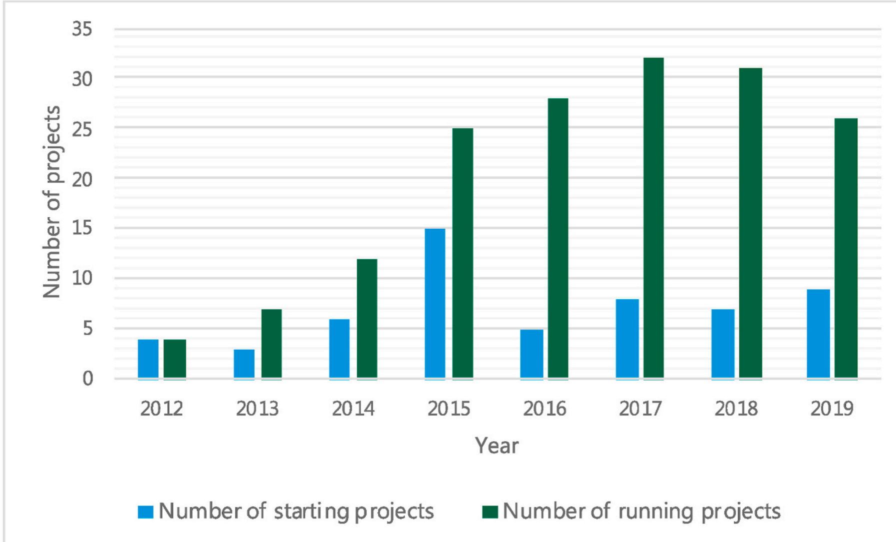

Fig. 5. The number of nationally subsidized BIPV-related innovation projects [49].

found in Table 4.

4.1.4. 2016–2019: the stagnation of the Dutch BIPV innovation system

In this period, a shift of focus can be observed in the PV industry. Whereas in previous years, BIPV was a major focus of the PV industry, more parties are now focusing on other technologies that can be paired with PV systems (e.g., energy storage systems and heat pumps) (-F4). This trend is also reflected in the yearly national conferences (e.g., Solar Solutions) and the National Solar Trend Report of 2016 [47,50]. During this period, the number of articles published in industry magazine Solar Magazine that raise positive expectations on BIPV decline as well. The shift of focus of the PV industry also influences other system functions, as fewer subsidies are being allocated to BIPV-related innovation projects than in the previous period (see Fig. 6) (-F6). Nevertheless, due to the (multi-annual) innovation projects that were initiated in previous periods, the number of *running* projects reaches a peak in 2017 with a total of 32 running projects. From 2017 onwards, the number of *starting* subsidized projects remains relatively stable (7–10 projects per year). When looking at the type of projects that are being initiated, a clear increase can be seen in the number of projects on façade-integrated BIPV solutions (opposed to roof-integrated BIPV) between 2016 and 2019 (+F1).

In contrast to the decrease in nationally subsidized innovation projects that are being initiated, multiple EU funded projects are initiated to further progress the Dutch BIPV innovation system (+F1, +F6) In 2016, SEAC publishes a price study on BIPV that shows that BIPV products are 20–80% more expensive than regular BAPV products [51]. This report also reveals that from 2014 until 2016 the price of roof-integrated BIPV products has only slightly decreased (e.g., the price for solar tiles has decreased from 2.70 €/Wp to 2.65 €/Wp). A positive exception to this are prefabricated BIPV systems, with which a PV system can be integrated for an additional cost of only 1.20 €/Wp.

In 2018, branch association BIPV Nederland is established to intensify collaborative knowledge diffusion and marketing efforts towards the construction industry (+F3) as well as gain favorable policy support for the BIPV innovation system (+F7). However, this does not result (yet) in more collaboration with the construction industry and the (expected) exponential growth of the BIPV market. A network analysis [52] (see Fig. 7) shows that building component manufacturers (dark green nodes) and other important stakeholders from the construction industry do not play an active role within the BIPV network (i.e., they can be found in the periphery of the network). Research institutes (yellow nodes) remain dominant in the BIPV network. Furthermore, negative publications regarding the fire safety of BIPV decrease the legitimacy of the technology [53] (-F7). In 2019, the Dutch government announces that it will be scaling down the netting arrangements, which will have significant effects on the payback time of (BI)PV (-F5) [54]. In addition, limited financial instruments and regulations are put in place to support further industrialization and commercialization of BIPV (-F4, -F6).

From 2017 until 2019, the Dutch PV market shows tremendous growth (see Fig. 8), making the Netherlands one of the fastest-growing countries in the EU in terms of installed PV [5]. However, according to interviewees, the BIPV market is not able to gain a higher percentage of the total PV market during this time period, thereby remaining a niche market. One of the reasons for this is that the prices of BIPV products remain relatively high. The only companies that experience significant growth are firms that offer the lower-priced in-roof mounting systems (e.g., GSE and Viridian Solar) or that offer more integral solutions, where BIPV is combined with other solutions such as energy management systems (e.g., solar glazing products of Physee). In 2019, 29 MWp BIPV was installed of which almost 60% was realized by in-roof mounting BIPV systems [56,57].

Table 4
Top 5 Residential and non-residential BIPV projects up to 2015 [32].

Residential		Non-residential	
Project name	Installed capacity	Project name	Installed capacity
1. Stad van de Zon (Heerhugowaard, Alkmaar en Langedijk)	5000 kWp	1. Expo Haarlemmermeer	2287 kWp
2. Nieuwland (Amersfoort)	1351 kWp	2. Rotterdam Central Station	500 kWp
3. Columbuskwartier (Almere)	550 kWp	3. Utrecht Central Station	100 kWp
4. Vogeltjesbuurt (Tilburg)	450 kWp	4. The Edge (Amsterdam)	100 kWp
5. Woudhuis (Apeldoorn)	218.8 kWp	5. ECN (Petten)	70 kWp

4.2. Current state of the Dutch BIPV innovation system

Following the historical development of the Dutch BIPV innovation system, this subsection provides deeper insights into the current fulfillment of the system functions. To gain these deeper insights, 29 semi-structured interviews were conducted. The outcome of these interviews is described below and the current fulfillment of every system function is scored using a 5-tier Likert scale scoring system of absent (1),

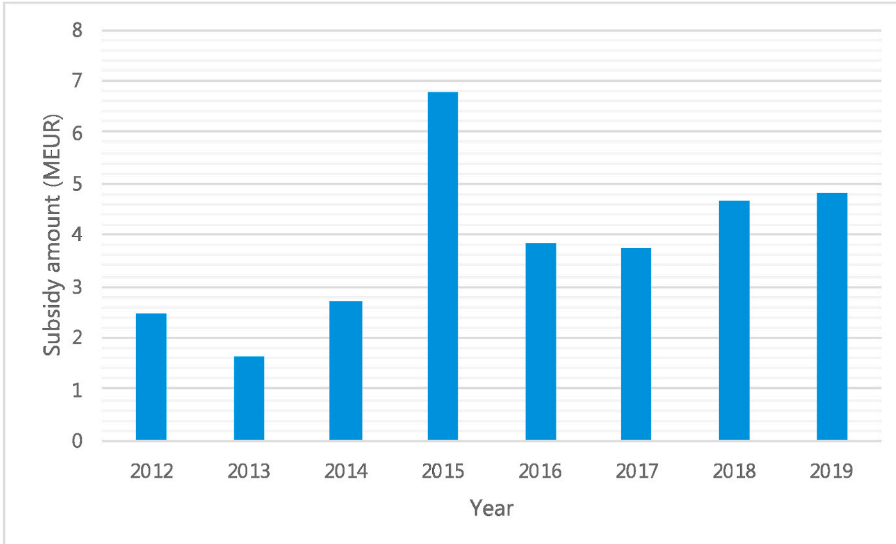

Fig. 6. The amount of nationally allocated subsidy to BIPV-related innovation projects [49].

weak (2), moderate (3), strong (4), and excellent (5) (see Fig. 9).

The function knowledge development (F2) is strongly fulfilled, as most interviewees argue that there is sufficient knowledge on BIPV and related disciplines (i.e., construction and electrical engineering) to scale up the BIPV market. There is a strong knowledge base on PV in general (e.g., on PV cell technologies) and PV manufacturing in specific.

The functions entrepreneurial activities (F1), guidance of the search (F4), and creation of legitimacy (F7) are moderately fulfilled. The function entrepreneurial activities (F1) is moderately fulfilled, as many (subsidized) innovation projects have led to a plurality of first- and second-generation products and a large number of startups and SMEs that have entered the BIPV market. However, there are not many large firms from the construction industry (and other adjacent industries such as the chemical manufacturing and steel industry) active within the BIPV sector. More collaborative innovation projects with these firms could be initiated to accelerate the build-up of industrial capacities. The function guidance of the search (F4) is also moderately fulfilled as it can be observed that the Dutch government has specific targets and requirements regarding renewable energy generation and the energy performance of buildings. However, the government could focus more on societal acceptance as a criterion to direct the market toward technologies like BIPV. The function creation of legitimacy (F7) is also moderately fulfilled, as the establishment of the branch association BIPV Nederland has led to a growing voice of the industry. However, it can be observed the legitimacy of BIPV is under threat due to concerns regarding the fire safety of BIPV products.

The functions knowledge diffusion (F3), market formation (F5), and resources mobilization are weakly fulfilled. The function knowledge diffusion (F3) is weakly fulfilled, as there is a lack of awareness among key decision makers, including housing corporations, building owners, and owners' associations. Furthermore, additional value chain coordination and collaboration is necessary for the successful large-scale integration of BIPV. As interviewee 10 explains: "*BIPV companies are currently unable to handle large-scale construction projects. Now, BIPV companies are often producing and installing BIPV products by themselves because other parties are often unable to do so. But in the end, this is not the solution because BIPV companies have a limited capacity. Ideally, BIPV companies should only supply their product and installers then should install their products. But in the absence of a well-coordinated value chain, BIPV companies take on the entire value chain by themselves*". To improve value chain coordination, the constructional and electrotechnical components of BIPV products should be made compatible with traditional building components and installations to increase the ease of application (i.e., "plug & play" installation). Moreover, combinations with traditional building components and installations can result in symbiotic interactions between different technologies. When BIPV is complementary to an integral installation system, all installations in that system (including BIPV) benefit from the added value of the whole system. BIPV companies that take a more integral approach, also experience more growth in terms of sales (e.g., Physee). As interviewee 18 states: "*You should not see BIPV as an individual solution that generates electricity, instead it should be part of a building's integral installation system. Because when you combine BIPV with for instance the heat supply and energy storage of a building, stakeholders cannot just say that they want to remove BIPV out of the system to reduce costs. […] If BIPV companies can come up with an integral installation system with other suppliers, then BIPV benefits from the added value of the whole system*". These types of integral systems will most likely prevail in the future, as the Dutch construction industry is moving to prefabricated solutions [58,59] where building components and installations are manufactured and (to a large extent) assembled into large roof or façade elements off-site in a factory to reduce the number of actions and personnel on-site (thereby increasing the efficiency of the entire value chain). The function market formation (F5) is also weakly fulfilled, as it can be observed that both entrepreneur-driven and government-driven market formation processes are currently lacking. Interviewees indicate that the limited growth of the BIPV market can be explained by the fact that many parties in the construction industry believe the advantages of BAPV (low costs, energy performance, and ease of application) currently outweigh the advantages of BIPV (esthetics). This is enhanced by market regulations, as these are primarily focused on the reduction of CO_2 emissions in a cost-efficient manner, and societal acceptance is often underprioritized. As interviewee 24 explains: "*The traditional companies that are active within the construction industry often see PV or BIPV as a necessity to achieve a certain energy performance requirement. […] Very often this results in the most cost-efficient solution being chosen to keep the construction costs as low as possible.*" The function resource mobilization (F6) is also weakly fulfilled, due to the limited availability of financial and human resources as well as the small-scale physical infrastructure that limits further price reduction of BIPV. One of the reasons for this is that the current subsidy landscape primarily supports innovation projects that focus on (new) product development rather than the industrialization of BIPV products.

4.3. Systemic problems within the Dutch BIPV innovation system

Following the assessment of the current functional fulfillment of the

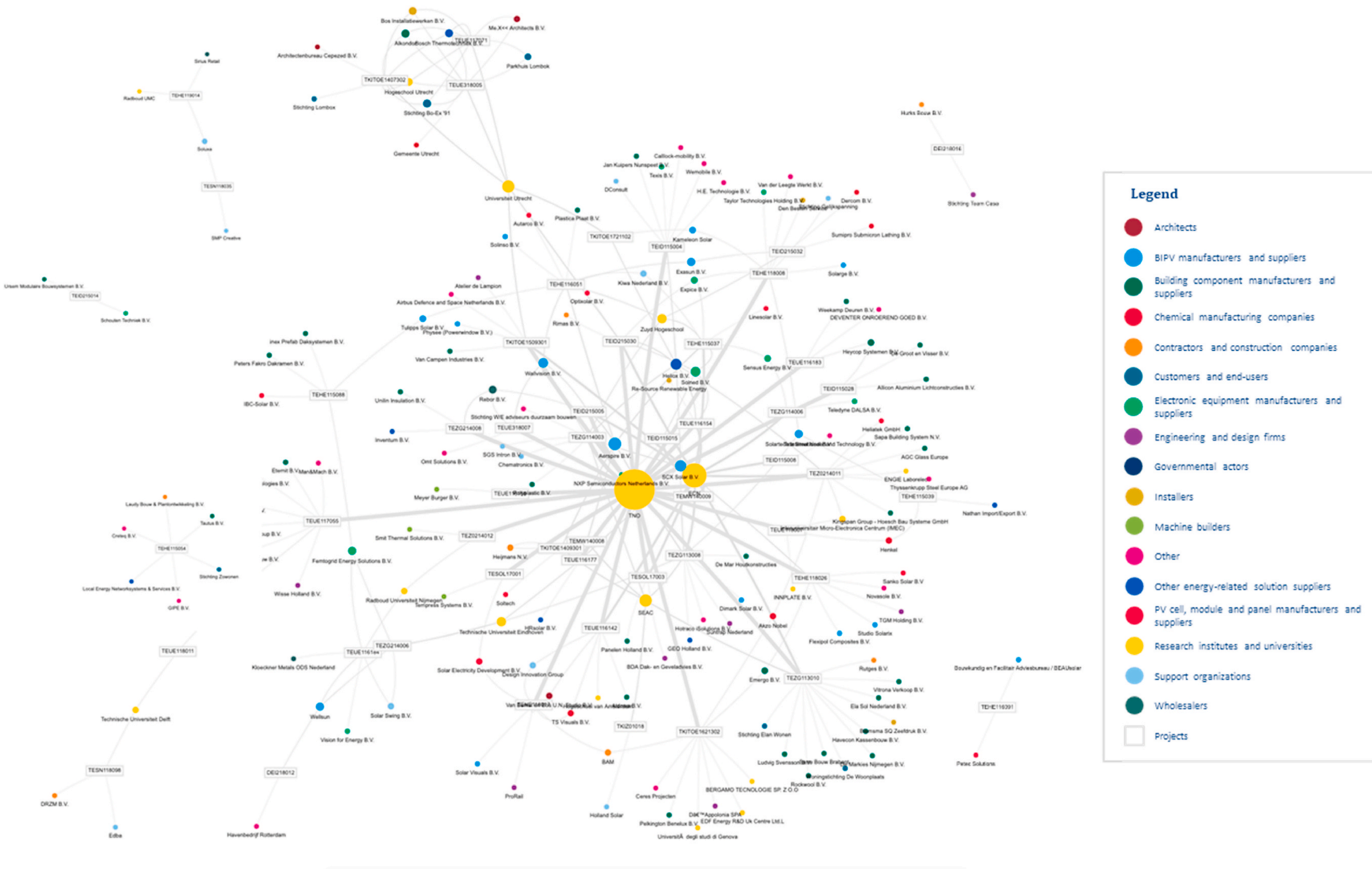

Fig. 7. Overview of the BIPV network 2016–2019 [49].

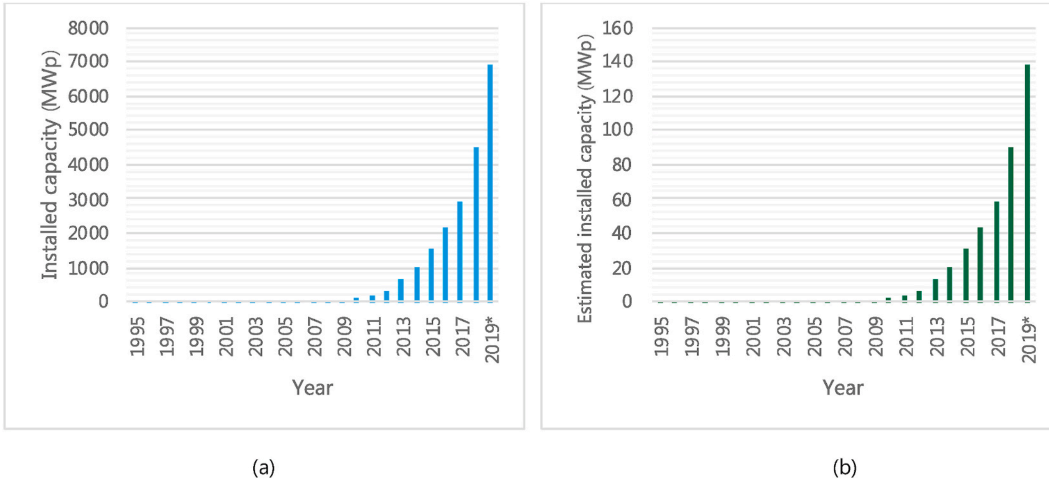

Fig. 8. a) Total installed capacity PV (MWp) [55], and b) estimated installed capacity BIPV (MWp) in the Netherlands according to interviewees (2% of the total PV market). *The installed capacity of 2019 is a preliminary estimate.

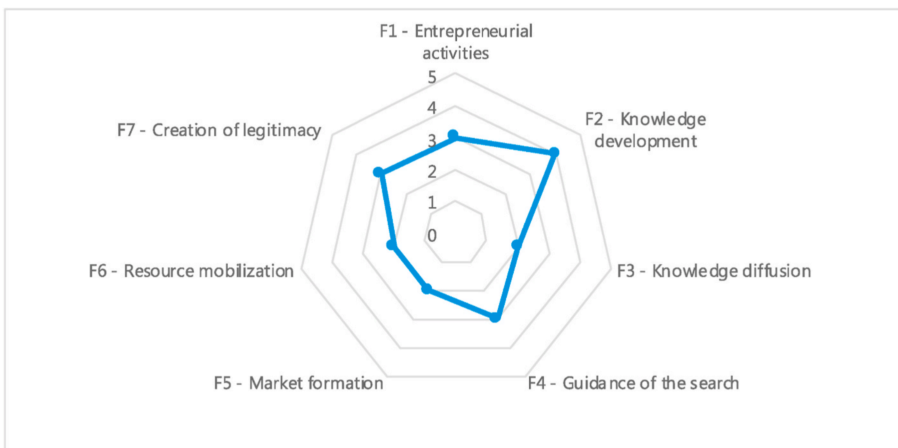

Fig. 9. Current functional fulfillment of the Dutch BIPV innovation system. Based on semi-structured interviews and verified by IEA-PVPS Task 15 members.

Dutch BIPV system, this section identifies the systemic problems that cause low fulfillment of certain system functions by performing a coupled structural-functional analysis. The focus of this subsection is primarily on the systemic problems that cause low fulfillment of the functions knowledge diffusion, market formation, and resources mobilization, as these functions are least fulfilled within the BIPV innovation system.

4.3.1. Actors' problems

Both presence-related and capacity-related actor's problems are present within the Dutch BIPV system. A presence-related problem is that there is a general lack of involvement of large firms from the construction industry and other adjacent industries (e.g., chemical manufacturing and steel industry). The absence of these firms negatively affects the fulfillment of the functions knowledge diffusion (F3), market formation (F5), and resource mobilization (F6). Especially building component manufacturers could be more active within the BIPV sector, as these actors generally have established links with the executing parties in the construction industry, making them an important vehicle to increase knowledge diffusion and market formation processes. Additionally, more involvement of large firms (with industrial capacities) could enable further industrialization and price reduction of BIPV products, since BIPV companies themselves lack the industrial capacities in order to do so (i.e., a capacity-related problem).

4.3.2. Institutional problems

When it comes to institutional problems, both presence-related and capacity-related institutional problems are present within the Dutch BIPV innovation system. Presence-related institutional problems are present due to the lack of policy support for the industrialization and commercialization of BIPV as well as the absence of a harmonized standard for BIPV products. The current subsidy infrastructure mostly supports innovation projects that focus on (new) product development and other R&D-related activities rather than projects that focus on the industrialization and commercialization of BIPV. This negatively affects the function resources mobilization (F6) and limits the build-up of industrial capacities and the overall price reduction of BIPV products through economies of scale. Furthermore, market regulations negatively affect the function market formation (F5), as these are primarily focused on the reduction of CO_2 emissions in a cost-efficient manner, whereas societal acceptance is underprioritized. This results in the construction industry choosing the most cost-efficient solutions to realize the required energy performance, which results in companies choosing BAPV over BIPV. Additionally, there is currently no harmonized standard available to properly certify (specific) BIPV products. Consequently, it is often unclear which specific standards regarding construction components and PV systems apply to BIPV products. This affects the fulfillment of the functions creation of legitimacy (F7) and market formation (F5) as certifications increase trust among customers and implementors. Besides, standards help to facilitate the decoding of complex information, which in turn enables successful inter-organizational collaboration and knowledge sharing (i.e., the function knowledge diffusion, F3) [60,61].

Capacity-related institutional problems include the lack of sufficient fire tests under the available standards to test the fire safety of BIPV products. This also negatively affects the legitimacy of BIPV (F7) as actors are not able to prove sufficiently that their products are fire-resistant.

4.3.3. Interaction problems

Both presence-related and quality-related interaction problems can be observed in the Dutch BIPV innovation system. Currently, the BIPV network is primarily dominated by research institutes and universities as well as startups and SMEs. In contrast, there are not enough links with companies from the construction industry and currently established links are generally weak. One of the reasons for this is that some BIPV companies are spin-offs from previous research projects and thus originate from scientific research networks. These types of firms often encounter structural holes between their scientific research networks and industry networks and thus face challenges in building social capital and initiating inter-organizational collaboration [62]. Ultimately, this negatively affects the fulfillment of the function's knowledge diffusion (F3), market formation (F5), and resources mobilization (F6).

The function knowledge diffusion (F3) is affected because the lack of interaction with the construction industry hampers knowledge diffusion towards key decision makers and executing parties. Furthermore, it hampers the ability of BIPV companies to improve the constructional and electrotechnical compatibility and complementarity of BIPV products with other (traditional) building components (e.g., windows and roof tiles) and installations (e.g., energy storage solutions). The limited amount of established connections with companies from the construction industry also hampers the function market formation (F5), as BIPV solutions are often not even considered in (new) construction projects. The function resources mobilization (F6) is affected because, BIPV companies can benefit from the industrial capacities of large firms form adjacent industries.

4.3.4. Infrastructural problems

Infrastructural problems in the BIPV innovation system are considered to be primarily presence-related. There is a general lack of financial and (well-educated) human resources to further industrialize BIPV, negatively affecting the function resources mobilization (F6). This is largely due to the fact that the subsidy infrastructure does not support industrialization-oriented projects and the lack of collaboration with large firms that already possess the industrial capacities. As a result, the current production capacity of BIPV is not scaled up enough (yet) for large market demand.

5. Discussion

First, this research shows that there is a lack of policy support for the industrialization and commercialization of BIPV. The current subsidy infrastructure mostly supports innovation projects that focus on (new) product development and other R&D-related activities rather than projects that focus on the industrialization and commercialization of BIPV products. However, when a technology is in the niche market phase, R&D subsidies are still important but regulations that are designed specifically for industrialization and market formation are even more important [22]. Subsequently, when industrial capacities are established and favorable conditions are created for large-scale diffusion, the technology moves to the commercial growth phase. This can be realized by creating favorable conditions for companies to raise long-term loans or stimulate financial organizations to provide favorable financial instruments for BIPV companies to be able to develop industrial capacities [22]. This should preferably be realized in collaboration with established firms from the construction industry such as building component manufacturers that already have significant industrial capacities. In addition, the "technology neutral" policy of the Dutch government is primarily focused on the reduction of CO_2 emissions in a cost-efficient manner, and societal acceptance is often underprioritized. Ultimately, this results in a situation where cost-effective technologies prevail and more expensive technologies that take into account wider societal aspects such as BIPV are often undervalued and rejected by parties from the construction industry. However, by doing so, there is a risk that the focus of society on cost-efficient solutions for meeting short-term targets might lead to negative interactions that cause the discontinuation of more advanced technologies (such as BIPV) that are needed to meet long-term targets [63]. To avoid this from happening, incentives can be implemented to stimulate construction companies to choose BIPV over BAPV [22,64]. In addition, a clear framework regarding standards and certifications for BIPV products can also help to enhance market trust.

Second, the findings show that there is a lack of awareness and knowledge among key decision makers (e.g., housing corporations, building owners, and owners' associations) and decision influencers (e.g., architects, building consultants). To improve this, it is recommended that BIPV companies, preferably in collaboration with each other, create clear frameworks regarding the applicability for different market segments, energy yield, installation practices, and costs and benefits. Branch associations also play a key role in raising awareness, as collaborative marketing efforts are found to be more effective than individual efforts [64]. In addition, the integration of product information in digital tools such as Building Information Modelling (BIM) libraries can help foster knowledge diffusion towards the parties involved in the architecture, engineering, construction, and operations of buildings [65]. Knowledge diffusion can also be enhanced by organizing educative workshops and increasing the visibility on conferences [18].

Third, the findings show that better value chain coordination and collaboration is necessary. Currently, many BIPV companies take on the entire value chain (from product design until installation) due to the lack of well-trained installers that are able to install BIPV products, making it harder to scale up. To improve value chain coordination, value chain actors are suggested to improve the constructional and electrotechnical compatibility and complementarity of BIPV products with other (traditional) building components and installations. *Compatibility* with building components and installations is important as this improves the ease of application of BIPV and offers flexibility to both designing and executing parties. To improve compatibility, standardization is needed regarding the sizing, type of mounting systems, and electrotechnical components and interfaces of BIPV products. *Complementarity* with other (upcoming) technologies can lead to a symbiotic relationship, as the diffusion of one technology may catalyze further development and diffusion of another technology [66,67]. In the case of BIPV, examples of such technologies include energy storage technologies and technologies that accelerate the electrification of energy demand such as heat pumps or electrical vehicles. This is especially important because BIPV companies that have experienced significant growth, either offer products that can compete on price with BAPV (e.g., in-roof mounting systems) or more integral systems (e.g., solar glazing in combination with an energy management system). Furthermore, as the construction industry is moving toward prefabricated solutions, coordination with parties further up the value chain becomes even more important. This trend offers significant opportunities for integrated solutions such as BIPV, as BIPV companies can become the suppliers of "system integrators" (i.e., the organization that manufactures the prefabricated element) (see Fig. 10). In addition, BIPV companies can benefit from collaborating with (large) companies from the construction industry, such as building component manufacturers, as these types of firms often have a broader knowledge base and the (financial) resources to exploit and industrialize new technologies [68]. Collaboration with building component manufacturers might also result in increased market formation, as these firms have established links with the executing

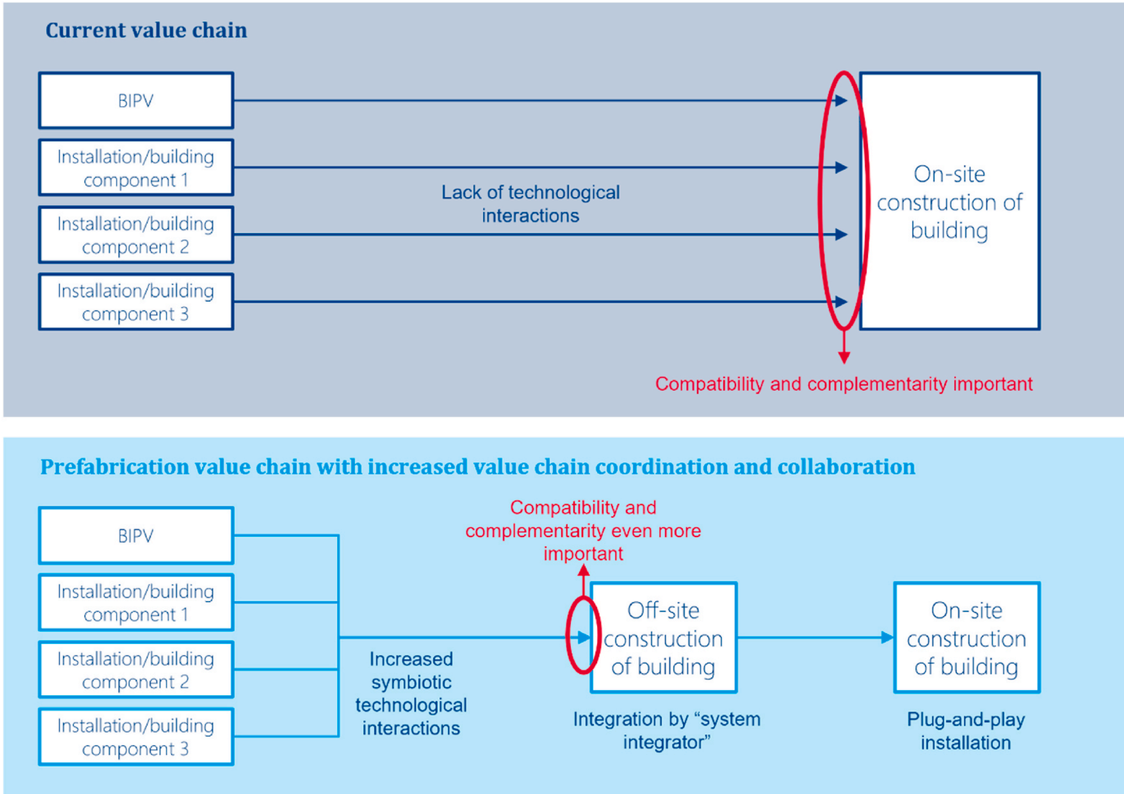

Fig. 10. Current value chain (top) versus prefabrication value chain (bottom) with new forms of value chain coordination and collaboration.

parties in the construction industry.

Finally, a few limitations of this research must be pointed out. First, the implications and recommendations are only applicable to the context of the Netherlands. Nevertheless, certain findings point to problems that require attention on a European level. The lack of industrial capacities is not only a problem for the Dutch (BI)PV sector, but also for other European countries that have a strong (BI)PV sector [1]. Second, the practical implications and recommendations that were provided with this research are tailored to the specific technological development phase of BIPV (i.e., the niche market phase). As such, it cannot be assured that the recommendations that are provided are effective in the technological phases that follow. These phases require different types of activities (e.g., incremental innovation) and policy support (e.g., diffusion policies) [22].

6. Conclusion

The historical analysis of the Dutch BIPV innovation system has shown that, from 1995 to 2016, a strong knowledge infrastructure has been developed around BIPV. Many (subsidized) innovation projects have led to many startups and SMEs entering the market and multiple first- and second-generation BIPV products being launched onto the market. In this period, system functions entrepreneurial activities (F1), knowledge development (F2) and knowledge diffusion (F3) are well fulfilled and reinforce each other. However, due to a shift of focus of the PV industry around 2016, more parties started focusing on other technologies that can be paired with PV systems (e.g., energy storage systems and heat pumps). This led to a decrease in the number of nationally subsidized BIPV-related innovation projects being initiated, leading to a stagnation of the development of the Dutch BIPV innovation system. Also, increased knowledge diffusion and marketing efforts towards the construction industry, as well as the appeal for favorable policy support by BIPV companies and branch association BIPV Nederland, have not resulted (yet) in more uptake of BIPV products. As a result, the Dutch BIPV market remained a niche market.

The main systemic problems within the BIPV innovation system that cause limited diffusion of BIPV products include actor's problems, institutional problems, network problems, and infrastructural problems. This research shows that there is a lack of policy support for the industrialization and commercialization of BIPV, as the subsidy infrastructure limitedly supports the industrialization of BIPV products. Additionally, market regulations are primarily focused on the reduction of CO_2 emissions in a cost-efficient manner, resulting in a situation where cost-effective technologies like BAPV prevail. Furthermore, the absence of large firms from the construction industry and other adjacent industries, and the fact that the Dutch BIPV innovation system is largely dominated by research institutes and BIPV startups SMEs, hampers the build-up of industrial capacities within the BIPV innovation system. Since some BIPV companies originate from scientific research networks, they often lack the capacity to develop effective network ties with the construction industry. This in turn hampers knowledge diffusion towards the construction industry as well as value chain coordination and collaboration with parties further up the value chain. This is especially critical, because value chain coordination and collaboration can help improve the compatibility and complementarity of BIPV with traditional building components and (electrical) installations, which in turn can improve market formation processes.

To remove these systemic problems, three main recommendations are provided. First, policymakers are recommended to improve the policy support for the industrialization and commercialization of BIPV, thereby providing the necessary conditions to implement the other two recommendations, which focus primarily on actor's, interaction, and infrastructural problems. Policy support for the industrialization and commercialization of BIPV can be improved by creating favorable conditions for companies to acquire financial capital that enables the development of industrial capacities. Furthermore, incentives can be implemented to stimulate construction companies to choose BIPV over BAPV. Second, value chain actors can use the resources that are made available to improve market awareness and knowledge diffusion through collaborative marketing, integrating product information in digital tools such as BIM, visibility on conferences, and providing trainings and workshops. Third, value chain actors can improve value chain coordination and collaboration with parties further up the value chain, by improving compatibility and complementarity of BIPV products with other building components and installations. By collaborating, BIPV companies can also benefit from the industrial capacities possessed by (large) companies from the construction industry and adjacent industries. Additionally, prefabrication offers significant opportunities, as BIPV companies can become the suppliers of "system integrators". The implementation of these systemic instruments should enable the Dutch BIPV innovation system to move further along the technological s-curve from the niche market phase to the commercial growth phase.

Credit author

Tjebbe Vroon: Conceptualization, Methodology, Writing – original draft. Erik Teunissen: Supervision, Funding acquisition. Marlon Drent: Supervision. Simona Negro: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing. Wilfried van Sark: Supervision, Writing- Reviewing and Editing, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: W.G.J.H.M. van Sark reports financial support was provided by European Regional Development Fund.

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Appendix 1. Interviewee list

Interviewee number	Organization type	Date	Length of interview
1	Branch association	27-4-2020	78 min
2	University of Applied Science	28-4-2020	73 min
3	Research institute	28-4-2020	70 min
4	University	30-4-2020	58 min
5	Architect	1-5-2020	75 min
6	Building component manufacturer	1-5-2020	58 min
7	Governmental organization	4-5-2020	49 min
8	Branch association	8-5-2020	56 min
9	Building component manufacturer	8-5-2020	72 min
10	Governmental organization	13-5-2020	41 min
11	Branch association	14-5-2020	66 min
12	Governmental organization	15-5-2020	108 min
13	BAPV/BIPV company	19-5-2020	64 min
14	BIPV company	19-5-2020	66 min
15	Construction company	20-5-2020	67 min
16	BIPV company	22-5-2020	52 min
17	Network organization	25-5-2020	62 min
18	Architect	25-5-2020	57 min
19	Construction company	28-5-2020	56 min
20	Network organization	28-5-2020	47 min
21	Research institute	29-5-2020	50 min
22	Testing and certification organization	29-5-2020	55 min
23	BIPV company	3-6-2020	53 min
24	BIPV company	9-6-2020	63 min
25	Housing corporation	10-6-2020	60 min
26	Building component manufacturer	12-6-2020	63 min
27	Network organization	18-6-2020	54 min
28	BIPV company	19-6-2020	88 min
29	Real estate developer	9-7-2020	60 min

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2021.111912.

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