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BIPV Market Development: International Technological Innovation System Analysis

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Abstract

Building-integrated photovoltaics (BIPV) is expected to play a relevant role in decarbonising our cities, both in new buildings and retrofit projects, making them more sustainable, resilient and pleasant. However, BIPV remains a niche market. To understand the reasons and help boost its development, this paper provides insights into BIPV through a holistic and systematic analysis that considers BIPV's dual nature as both photovoltaic and building product. The methodology is based on the analyses of several BIPV technological innovation systems (TISs) developed in six countries, as well as extensive comparative assessments and investigations to identify key global features of BIPV. Social aspects, market status and forecast, perspectives from the photovoltaic and building sectors, and related regulations and standardisation are key aspects analysed to develop recommendations for policymakers. Outcome examples are low to moderate acceptance of BIPV among building owners, who give cost reasons for choosing building-added photovoltaics (BAPV) over BIPV, as well as a need for information, official guidance, skilled personnel, improved cross-sector collaboration, availability of BIPV products, proper digital tools and specific regulation to improve BIPV's legitimacy in the construction sector. Essential is developing policies that encourage the adoption of BIPV, including standardisation, promotion and financing.

Keywords: building-integrated photovoltaics; BIPV; technological innovation system; BIPV social acceptance; BIPV market; renewable energy policies

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1. Introduction

Installing photovoltaic (PV) energy systems in buildings is one of the most competitive and efficient ways to generate renewable electricity on site, making cities more sustainable and resilient to climate change and energy and economic uncertainties. PV modules can be added to the building's envelope (building-added photovoltaics, BAPV) or integrated into it as building components (building-integrated photovoltaics, BIPV) (see Figure 1). In the BIPV case, PV modules are considered construction products because they must fulfil the requirements of building products and are referred to as BIPV modules [1]. Their designs seek suitable integration into construction systems such as ventilated façades, curtain walls, awnings or roofs. They should fulfil the electrical and construction requirements, complying with the proper standards and regulations [2], which include safety and performance aspects and energy-related demands [3].

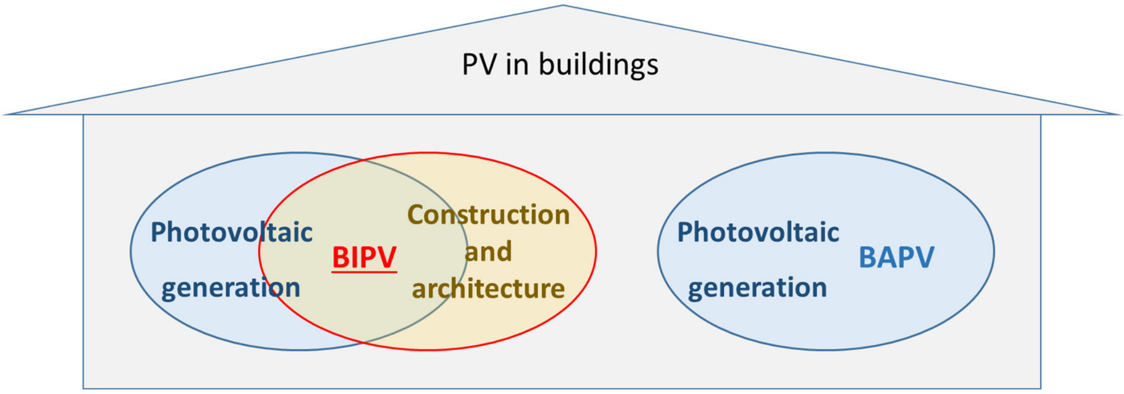


Figure 1. In BIPV, BIPV modules become construction elements of the envelope, while in BAPV, PV modules are attached to the building without any construction function.

Although BIPV offers advantages over BAPV, such as saving construction materials and achieving aesthetic results, which are valuable aspects for architects, urban planners and citizens [4], it faces significant challenges that make it underrated. Vroon et al. [5] applied the technological innovation system (TIS) methodology to analyse the historical development of the Dutch BIPV innovation system, providing a comprehensive overview of the systemic problems that hinder further diffusion of BIPV in the Netherlands. A former multi-criteria analysis of the BIPV ecosystem in various European countries [6] showed the specific country differences but recognised the need for an international perspective to analyse BIPV. The present work provides for the first time an international holistic approach to BIPV challenges and opportunities, focusing on the TISs of five European countries and Australia.

The paper is structured in sections: after the introduction, the second section presents the methodology, the third section develops the main results of the work organised by items, the fourth section discusses the main outcomes and gives recommendations to policymakers, and, finally, the fifth section includes the main conclusions of the work.

2. Methodology

2.1. General Approach

This work builds on a collaborative analysis of the technological innovation systems (TISs) for building-integrated photovoltaics (BIPV) across six countries. BIPV experts from these countries employed the TIS methodology outlined by van Noord et al. [7], as part of Task 15 of the Photovoltaic Power Systems Programme of the International Energy Agency (IEA-PVPS Task 15, iea-pvps.org/research-tasks/enabling-framework-for-the-development-of-bipv). The individual TIS analyses conducted for Sweden, the Netherlands, Austria, Italy, Spain and Australia [8–13] serve as the foundation for this study. A detailed comparative analysis of these national case studies has enabled the development of a comprehensive overview of the BIPV technological landscape.

While the initial goal was to include as many TIS analyses as possible from a variety of countries, not all task participants chose to contribute to this specific initiative. These engagements made the authors aware that many of the findings reflect global common patterns and shared challenges. A repeat of the TIS analyses in a few years and the inclusion of other countries, such as China and India, could significantly change the results.

2.2. Brief Introduction to Technological Innovation System (TIS) Theory and Analysis

A technological innovation system (TIS) is the set of actors, networks of actors and institutions that interact within a specific technological domain, contributing to the generation, creation, diffusion and use of variants of a new technology or product [14]. Actors and institutions interact at different levels, corresponding to functions about knowledge development, dissemination, regulation and use of the technology.

In the context of building-integrated photovoltaics, the TIS analysis aims to identify the key stakeholders, institutions and functions involved in BIPV technology and study how they have interacted. As a result, and after considering the current and expected contexts, new ideas and solutions can arise to help develop the technology.

Importantly, a TIS analysis spans both technical and social dimensions. Social studies of technologies should address their social shaping rather than their effect on society [15]. This interdependency between social and technical aspects highlights the importance of approaching innovation as a socio-technical process, rather than as a purely technical phenomenon.

The TIS analysis can accelerate the diffusion of a technology by helping policymakers understand the innovation system that supports its development, along with the structural issues it faces. This enables the design of systemic instruments to overcome those problems and, eventually, the formulation of technology-specific policies.

The TIS framework was developed by Swedish scholars in the late 80 s and early 90 s [16] in response to an initiative by Swedish policymakers [17]. In the last years, the dominating approach within TIS analysis is the functions framework [18]. The lists of functions proposed by Hekkert et al. [19] and the modified version by Bergek et al. [20], have been the most used.

Several energy transitions' TIS analyses based on the functions framework, often combined with additional contextual factors, are found in the literature. For instance, the TIS approach was applied to assess the offshore wind innovation system in Poland, aiming to identify key deployment challenges. These included unpredictable public policies, limited grid infrastructure, poor research quality and weak interactions between science and business sectors [21]. The study also highlighted the importance of entrepreneurial experimentation and cross-border knowledge exchange—particularly for so-called "follower" countries—in enhancing the performance of the innovation system.

The biodiesel innovation system in Taiwan was analysed by Chung [22], who concluded that international institutions could play a role in the guidance of search, while national governments should ensure consistent policies that support the domestic TISs' functions.

The assessment of the biofuel innovation system in the Netherlands and its evolution from 1990 to 2007 was used in [23] to illustrate the 'event history analysis' of the interactions between system functions and their development over time to identify forms of positive feedback, i.e., cumulative causation.

Edsand [24] analysed the slow diffusion of wind energy in Colombia throughout the TIS analysis, along with what he called the landscape factors or wider context. By combining expert evaluations (structured and semi-structured interviews) and history event analysis, the study revealed the weaknesses in the TIS functions and the influence of the wider context.

The technology's history has been also identified as a fundamental source of information to understand its evolution, status and expectations. In [25], the authors analysed the interplay of techno-economic, political and socio-technical processes to explain the different energy transition paths in Germany and Japan. An ambitious study across thirty provinces in China, from 2008 to 2022, empirically analysed the effects of technological innovation on the energy transition process [26], finding that contextual guidance, knowledge development and phased legitimisation were relevant functions.

2.3. Common Principles of the Developed TIS Analysis

This work builds upon TIS analyses conducted in six countries for the BIPV technology, followed by a comparative assessment and further investigation to identify the main global challenges hindering BIPV deployment. Each national TIS analysis followed the common methodological framework outlined in [7]. which uses the list of functions developed in [27], drawn from earlier work by Bergek et al. [20] and complemented with the additional function of social capital development, as in [28]. Table 1 presents the set of functions considered, along with their primary focus areas for supporting BIPV market growth.

Table 1. TIS functions used in the BIPV TIS analyses and the main assessment focus.

TIS Function	**Main Questions for the Analysis**
Knowledge development	Is the appropriate knowledge available or being developed?
Knowledge dissemination	Is that knowledge reaching the right actors, including feedback from demonstration projects to academics?
Entrepreneurial experimentation	Do enough actors try new technologies or applications (startups and diversification)?
Resource mobilisation	Can actors find sufficient and appropriate. . . (1) . . . skilled professionals? (2) . . . financing? (3) . . . related products, services and infrastructure?
Development of social capital	Are social relations between people good enough, and is there sufficient mutual trust and understanding?
Legitimation	Is there sufficient acceptance of BIPV technologies, actors and regulations amongst relevant stakeholders? Is BIPV a trusted solution?
Guidance of the search	Is there enough market promise to guide industry actors towards (a variety of) BIPV solutions? Also, compared to other adjacent innovation systems?
Market formation	Do the following actors sufficiently contribute to market creation? (1) government (regulations, tax rules, support schemes), (2) entrepreneurs (market push), (3) lead customers (market pull)

Before conducting the TIS analysis, the historical development of BIPV technology—such as solutions, products and materials—as well as the historical evolution of the innovation system—including the actors, networks and institutions involved—was reviewed in each participating country. This first data collection mainly corresponded to secondary data gathered from scientific and grey literature, project and patent databases, national technical building codes and regulations, industry platforms, companies' reports and websites, and social media.

The analysis of this information allowed the identification of relevant stakeholders by groups: BIPV product manufacturers and suppliers, users and consumers, architects, promoters, property owners, public and financial institutions, PV industry, NGOs, industry associations, research and academia, and policymakers. For the second round of data collection, we conducted extended, semi-structured personal interviews with representatives of each group and sent surveys to a broader audience (see Appendix A in [7]).

Based on a comprehensive analysis of all collected data, the fulfilment of each TIS function was evaluated and scored on a scale from 1 to 5. The process began with each group of national experts (i.e., the co-authors of the TIS reports) independently assessing their own country's performance, keeping their evaluations confidential. These preliminary qualitative assessments were then presented during a series of country-specific "benchmarking meetings," where experts from other countries provided feedback on each function's evaluation. Following this, a blind poll was conducted to collect scores from all participating experts. The results were then reviewed, justified and, if necessary, re-scored. The final score for each function was calculated by averaging all individual scores, including the national expert group's input. This collaborative approach enhances consistency across countries and enables more accurate and meaningful comparisons between different TISs.

Systemic problems and opportunities were subsequently extracted from the identified functional strengths and weaknesses. The analysis focused on the functions most relevant to the current national market development, as suggested in [19]. Based on this, recommendations on policy instruments and industry actions that could impact the structure of the national BIPV TIS to overcome systemic problems and exploit opportunities were drawn up. Guidance on relevant instruments was found in [29].

The authors have focused on those aspects that national TIS assessments identified as most relevant. Still, given the complexity and national differences in the structures and functioning of the TISs, it is likely that some variations would also occur if a single group wrote all national analyses. The authors assume that comparing the major existing challenges identified in each country is highly relevant, even if some major challenges in some countries were not considered in others and have appeared while writing this paper, although as minor challenges or weaknesses.

3. Results

3.1. Social Aspects of BIPV

According to the IEA's recent forecast [30], utility-scale and distributed solar PV are expected to account for nearly 80% of renewable electricity expansion worldwide by 2030. In particular, distributed applications constitute nearly 40% of the overall PV expansion. Photovoltaic self-consumption has positively impacted the domestic economy and increased societal awareness of the energy transition and the need for more sustainable and resilient cities. However, with the growing number of PV installations, public acceptance is becoming more complex. While resistance is most commonly directed at ground-mounted systems, there is also occasional opposition to BAPV [31]. In general, key stakeholders perceive BIPV as better integrated with the environment, although other important societal aspects should also be considered when evaluating BIPV acceptance.

Socio-political acceptance of BIPV is one consequence of soft institutions' development. It is about the non-legal, intangible norms, practices and social conventions that shape behaviour and interaction within a society or a particular cultural group regarding BIPV technology [7]. The national BIPV TIS analyses examined various soft institutions, such as public awareness and acceptance, aesthetic preferences, non-formalised public procurement practices, and the stakeholders' conduct and practices.

Overall, social acceptance of renewable energies, and photovoltaics in particular, is strong in the six countries. Homeowners are increasingly seeking greater energy self-sufficiency and lower electricity costs through self-generation. Simultaneously, there is growing concern about the environmental and visual impact of utility-scale PV plants, leading to increased interest in integrating solar power into existing structures and buildings.

These evolving cultural institutions and societal attitudes collectively contribute to BIPV adoption. While socio-political acceptance of BIPV is generally increasing, its acceptance still involves intertwined cross-cutting issues.

A major barrier is the lack of understanding between the construction and solar energy sectors. Different languages and priorities are the main aspects that hinder good cooperation and trust. With BAPV dominating PV in buildings, the step to change wears does not appear easily. Architects and construction professionals typically exclude solar energy expertise in early planning phases, and the construction industry prioritises upfront cost reduction over lower lifetime costs.

Additionally, PV installers often prefer BAPV over BIPV, even when clients initially express interest in BIPV solutions. This is largely to avoid the added complexity of engaging with construction practices, guarantees and building integration requirements. This preference for simplicity aligns with the broader acceptance of BAPV among contractors and property owners, providing little incentive to address the cultural differences between the two sectors.

The TIS analyses revealed weak social capital development in all the studied countries, except Italy, where the BIPV market has been historically stronger. Italy experienced a significant period of innovation in BIPV, largely driven by the former feed-in tariff (FiT) legislation, which supported "totally integrated PV" and "Innovative BIPV" systems [11]. This policy framework contributed to the installation of over 2.5 GW of BIPV capacity, out of a total 18 GW of installed PV capacity nationwide. Following the end of the FiT era, the market declined but showed a slight recovery in 2017. The system typologies incentivised under the previous FiT schemes still dominate the market today, although new products have also begun to emerge.

Weak social capital indicates a lack of mutual trust among stakeholders, a lack of networks and meeting places for BIPV, and poor relationships between the PV and building sectors, reflecting the early development phase of BIPV technology, see Figure 2.

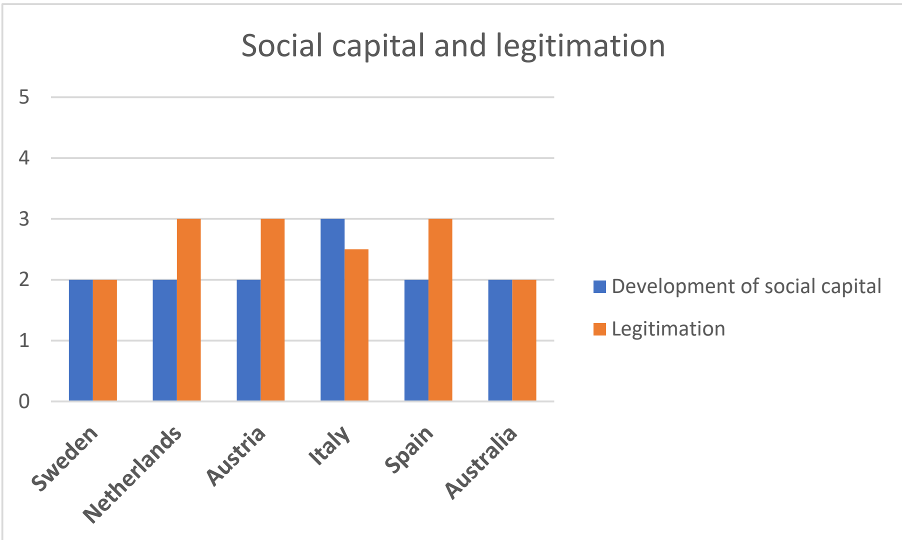


Figure 2. Development of social capital and legitimation of BIPV technology in the six indicated countries. Data are obtained from 160 interviews with stakeholders of the whole value chain. Functions' fulfilment varies from 1 (absent or weak), 2 (weak), 3 (moderate), 4 (strong), to 5 (excellent) [8–13].

In general, there is a weak or moderate legitimation of BIPV technology, another key outcome of the TIS analyses. The reasons relate to the poor knowledge dissemination of this technology informing about its benefits. Additionally, official technical guidance on the BIPV design, installation and operation is lacking. Bad examples and non-involvement of public buildings in BIPV actions do not help legitimation either.

Cost is a main barrier. People willing to include PV in their buildings usually choose BAPV for its lower investment cost. Although adopting semi-standardised solutions can lead to significant cost reduction, the main issue is that the dual value of BIPV modules as PV generator and construction material is commonly ignored. Cost-competitiveness perception can change when considering the costs of the substituted conventional construction materials. Providing cases where BIPV is competitive would help increase the acceptance of BIPV. A clear market opportunity is retrofit actions, where several BIPV solutions can be more advantageous than regular construction ones, e.g., BIPV ventilated façade with many regular equivalent solutions.

Considering an average range price of PV modules of 0.20–0.27 EUR/Wp [32–34], regular PV modules' prices per square meter vary in the range of 31–60 EUR/m^2 for module efficiencies between 15% and 22%. Concerning BIPV modules, a recent survey of 35 European BIPV products shows significant BIPV module price variation based on type and appearance: coloured cladding costs 225–600 EUR/m^2, full-black cladding 150–205 EUR/m^2, and roof tiles 90–470 EUR/m^2 [35]. Data from 54 European BIPV case studies reveal system-level prices ranging from 380 to 980 EUR/m^2 for rainscreen façades, 170 to 970 EUR/m^2 for roof systems and 810 to 1930 EUR/m^2 for curtain walls. In general, PV and BIPV prices tend to decrease [36].

Building owners are starting to invest in BIPV technology, creating demand. The interviewees feel they are part of the innovation process and would appreciate being awarded for choosing BIPV. Some of the incentives they propose are increasing the real estate value of the building or creating a specific "BIPV label". Such actions could make the financial and building sectors more involved in the BIPV market. Besides, some building owners are sometimes concerned about energy performance and waterproofness. Thus, there is a need to work on BIPV's reputation concerning energy and construction roles.

3.2. The BIPV Market Status

3.2.1. A Niche Market

There is consensus in considering BIPV as a niche market. According to a recent report by the International Agency [37], depending on the definition used, the BIPV market in Europe ranged from 250 MW to 450 MW in 2023, indicating either moderate growth or stagnation. Globally, the BIPV market is likely to have surpassed 3 GW. One of the key challenges in estimating these figures lies in the frequent confusion between BIPV and BAPV, especially in certain regulatory contexts (e.g., in some feed-in tariff laws), which can lead to overestimated BIPV data. Additionally, the diversity of BIPV products, the range of manufacturers and the split between custom-made and standardised solutions further complicate efforts to accurately assess the market share and development of BIPV.

Entrepreneurial experimentation is key for niche markets to evolve into commercial growth. In general, higher BIPV entrepreneurial experimentation leads to more diverse and active BIPV markets. Austria, Italy and the Netherlands have shown a moderate fulfilment of this function. Also, the guidance of the search is a crucial function that helps steer the entrepreneurial efforts toward potentially viable BIPV. Half of the studied countries have a weak or fairly weak ability to guide the search for innovation in BIPV. Figure 3 displays the fulfilment of knowledge development and dissemination, entrepreneurial experimentation and guidance of the search, for comparison among the six countries [8–13].

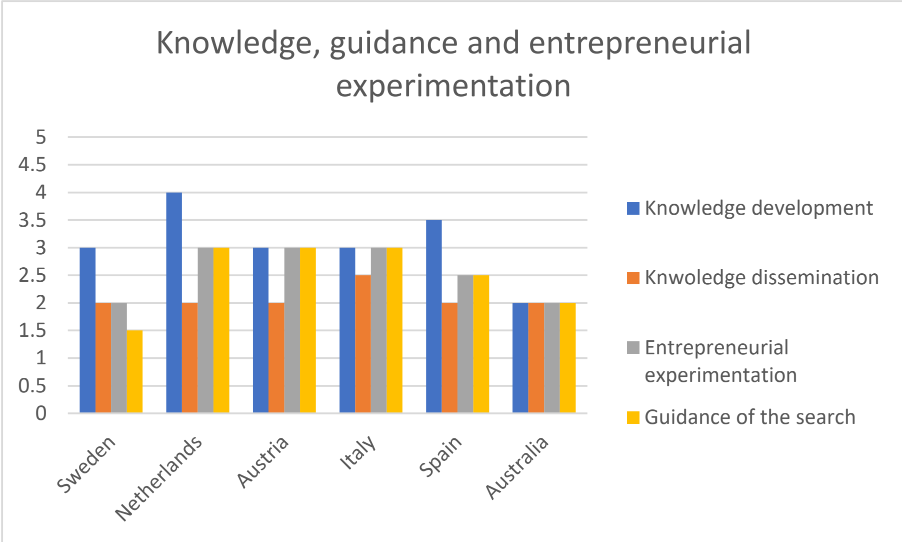


Figure 3. Knowledge development and dissemination, entrepreneurial experimentation and guidance of the search scored in each country from interviews and national and international project, patent and publication databases. Functions' fulfilment varies from 1 (absent or weak), 2 (weak), 3 (moderate), 4 (strong), to 5 (excellent).

Although Europe and the USA have led the BIPV market during the last decades, other countries such as China and Australia have demonstrated a growing interest. In particular, many Chinese PV manufacturers are developing BIPV products [38]; many manufacturers are adding BIPV products to their catalogue, including mainstream manufacturers. However, simplified BIPV, using conventional PV modules with dedicated mounting structures, is still leading the global BIPV market.

Most product market development has corresponded to the PV industry, with glass/glass PV laminate as the main basic element. Alternative laminates result from combining PV cells with ceramic or flexible layers. In general, PV manufacturers offer a variety of designs and sizes for their BIPV products, and sometimes, the possibility of a high degree of customisation.

Regarding BIPV installations, Europe has been the global leader, mainly because of the regional regulations supporting Renewable Energy and Energy Efficiency in Buildings, which help pave the way to near-zero and positive energy buildings. However, most support has focused on PV in buildings, not specifically on BIPV.

3.2.2. Market Segmentation According to the BIPV Application

The BIPV market can be analysed based on the specific application within the building envelope. The BIPV construction, energy, safety and aesthetic requirements of BIPV modules vary depending on the characteristics and requirements of the construction system, such as ventilated façades, curtain walls or roofs.

BIPV roofs are the most widespread BIPV systems, mainly because they occupy the most isolated areas of buildings. BIPV roofing solutions are available in a variety of different formats and colours and can be adapted to both continuous and discontinuous roofs. This last type is the majority BIPV market in countries such as Sweden, Italy and the Netherlands. Manufacturers are actively developing a growing range of designs, colours and dimensions to accommodate the diverse requirements of roofs across different architectural styles and urban contexts (see Figure 4). PV tiles, or PV shingles, are typically small, rectangular solar panels that can be installed alongside conventional tiles or slates using a traditional racking system used for this type of building product [37].

(**a**) (**b**)

Figure 4. (**a**) Innovative BIPV solution for a roof in Badia, Italy. BIPV modules and mounting system (Solar-Fabrik, Laufach, Germany, and Ernst Schweizer AG, Hedingen, Switzerland) ensure a watertight seal. Source: GSE (GSE, 2012). (**b**) BIPV roof in a commercial building in Valtice, Czech Republic, with crystalline silicon terracotta-colour modules (Yingli Gain Solar, Baoding, China) to fit the urban context. Photo credits: Millie Tan.

BIPV modules for skylights (Figure 5a) and curtain walls (Figure 5b) are based on PV glass laminates, most commonly featuring a double or triple glazing structure. These modules are often semi-transparent and use crystalline silicon (c-Si), although thin-film PV technologies achieve more homogeneous light transmittance. The colour of the transmitted light can be easily adjusted by colouring the back glass, allowing for greater design flexibility.

The market for curtain walls and skylights has gained more traction in countries that have actively promoted BIPV in commercial buildings. This is the case in Spain, where one domestic BIPV has emerged as a key player. By recognising the potential of this emerging niche, glass manufacturers in several countries have started to develop "PV glass" or "PV glazings". The challenge is to convince their customers to adopt it instead of the equivalent regular one. However, a significant challenge remains: persuading customers to choose PV glass over its conventional counterpart, which often requires overcoming different concerns.

(**a**) (**b**)

Figure 5. (**a**) Skylight with PV insulated glazing (Onyx Solar, Avila, Spain) covering San Anton market in Madrid, Spain, designed by studio ATARIA (Madrid, Spain). (**b**) Curtain wall with BIPV insulated coloured semi-transparent glazing in the Art Centre of Alcobendas, Spain, designed by Fernando Parrilla and M. Isabel Muñoz. Photo credits: N. Martín-Chivelet.

BIPV modules used in ventilated façades and double-skin façades are typically based on laminated PV glass (Figure 6a), or they may combine a front glass with substrates made from various materials, such as ceramics, metals and others. These combinations result in aesthetically appealing solutions. The market for opaque-coloured BIPV modules is currently booming, driven by the development of innovative colouring techniques. Photovoltaic module manufacturers have introduced BIPV products with a wide range of surface finishes and colours—particularly in countries like Switzerland and Austria. BIPV ventilated façades also present significant opportunities for retrofitting existing buildings, offering a compelling solution for improving energy efficiency [39,40].

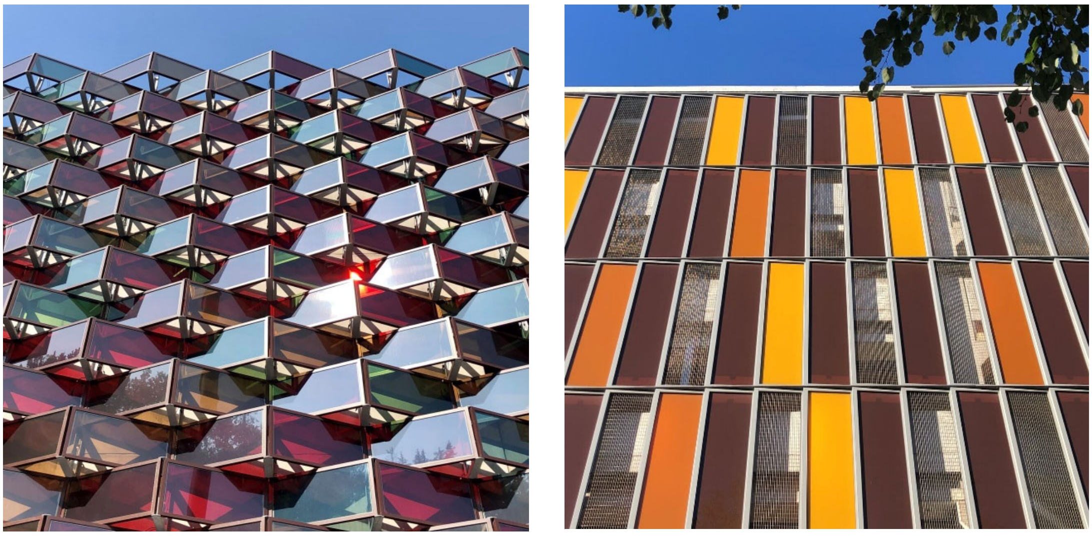
(**a**) (**b**)

Figure 6. (**a**) BIPV double-skin façade in a research centre in Granada, Spain, with semi-transparent PV glazing in different tones (Onyx Solar, Avila Spain). Architects: E. Vallecillos and E. Rodríguez. Photo credits: Eva Ruiz. (**b**) Photovoltaic pergola with crystalline silicon glazing having 18% light transmittance (Onyx Solar) at the Olympic Port in Barcelona, Spain. Photo credits: Carmen Martín.

Other BIPV applications, such as shading elements, are increasingly in demand, both for buildings and other infrastructures, such as carports, railway station canopies and street pergolas (Figure 6b). For these uses, BIPV modules are typically frameless glass/glass laminates, which are commonly developed by PV module companies.

3.2.3. Trends

Research and development in new materials, manufacturing processes and integrated construction solutions for PV modules is advancing rapidly. In any case, crystalline silicon-based BIPV products will continue dominating the market in the next years. Emerging colouring techniques and advanced materials are expanding the design possibilities for both opaque and semi-transparent BIPV modules, enabling a greater variety of colours and patterns [41] (see Figure 7), combining aesthetics, daylighting performance and PV efficiency [42]. Among the various design parameters, the lightness of the colour has been identified as the most critical factor influencing the efficiency of opaque BIPV modules [43,44].



(a) (b)

Figure 7. (**a**) Coloured semi-transparent cadmium telluride PV glazing (Soltech Energy Solutions, Stockholm, Sweden and Fasadsystem, Stenkullen, Sweden) in a car park façade in Gothenburg, Sweden, designed by Liljewall Arkitekter. (**b**) Coloured opaque crystalline Si BIPV façade elements in a car park in Borås, Sweden, designed by Tengbom, Borås, Sweden. Source: Instagram@solarcellsarkitektur.

New regulations and standards specific to BIPV are expected to boost the BIPV industry. In particular, the next edition of the European standard EN 50583-1, which will address BIPV modules having at least one glass pane, will include further and more adequate tests and requirements. Additionally, to reduce costs and gain trust among stakeholders, standard products in sizes and characteristics are starting to gain relevance in the market.

3.3. The PV Industry Role and Perspective

The PV industry focuses on developing higher-efficiency PV modules and lowering costs. The most widespread technology is monocrystalline silicon (m-Si); high-efficiency PV cells with back contacts and advanced rear-side passivation techniques [45] result in commercial silicon PV modules with more than 24% efficiency [46]. Advances in perovskite–silicon tandem cells and triple-junction devices have also shown great potential, pushing efficiency further and progressing in stability and reliability [47,48]. Perovskite-based and tunnel oxide passivated contact photovoltaic technologies will increase the offer and efficiency of BIPV products.

In parallel, cadmium telluride (CdTe) stands off among PV thin-film materials since it reaches competitive efficiencies at lower costs. Other commercial thin-film technologies are indium–gallium–copper selenide (CIGS) with similar efficiencies as cadmium telluride and hydrogenated amorphous silicon (H:a-Si), now scarcely used alone because of its low efficiency, although it plays a role in silicon heterojunction modules.

Although all current PV technologies are suitable for manufacturing BIPV modules, their designs should be adapted to the construction and aesthetic needs. Consequently, the BIPV module's efficiency remains one of the main targets, but not the only one. Special production lines have been developed for BIPV manufacturing at the PV factories, although not as automated as regular PV module ones. From the electrical design point of view, a main concern for BIPV modules is good performance against partial shading, a more frequent issue in BIPV installations than in PV plants. Several solutions address this subject in the literature, e.g., [49–51].

The IEC technical committee in charge of the photovoltaic standards (IEC TC82) recently developed the first two international standards devoted to BIPV products and systems (IEC 63092-1 and IEC 63092-2, respectively). This has been a relevant milestone, although it has not met all expectations; the particular features of BIPV products have not yet been addressed. The PV industry is approaching the construction industry to combine their products and develop smart and aesthetic BIPV modules that fulfil the construction requirements. However, more interrelationship is still needed.

3.4. The Building Sector Perspective: Concerns and Needs

As a multifunctional solution, a BIPV product serves both as a building material and an electricity-generating system. Therefore, the involvement of the building sector is essential. Their expertise and practical input are crucial for the adoption, implementation and standardisation of BIPV technologies.

From the perspective of the building sector, the following aspects—identified through the TIS analyses—reflect key views, concerns and expectations regarding BIPV integration (see Figure 8).

Figure 8. Construction sector concerns and needs for the adoption of BIPV.

Building element requirements: For BIPV modules to gain widespread acceptance within the building sector, they must meet the rigorous standards of conventional building materials. These include fire safety, wind resistance, watertightness, noise protection and other essential building performance requirements, many of which remain uncertain for building professionals [52,53]. Fire safety, in particular, has emerged as a significant concern for building engineers, especially when BIPV modules are used on vertical façades [54]. Furthermore, BIPV modules must demonstrate structural suitability for each particular building function, ensuring compatibility with architectural design, load-bearing requirements and long-term durability.

National building codes: Building codes set out technical requirements for the design and construction of new and retrofit buildings, and strict adherence to these codes is a high priority within construction sector. However, national building codes have not included specific references to BIPV products, solutions or standards. While first editions of the BIPV

European standards, i.e., EN 50583-1 and EN 50583-2 [55,56], represent an important step forward, they are not yet harmonised, which means their fulfilment is not compulsory in the European Union nor formally embedded in national building codes. Their international equivalents, i.e., IEC 63092-1 and IEC 63092-2 [2,57], are used as reference documents in several countries outside Europe, such as Canada and Australia. Although these standards do not yet fully meet the needs of the building sector, they combine the dual electrical and constructional functions of BIPV modules for the first time.

Availability in the conventional market: BIPV modules are currently marketed primarily by PV manufacturers, limiting their visibility and accessibility within the traditional construction materials market. Making BIPV solutions more readily available—ideally through conventional distribution channels, accompanied by simple installation instructions—would help bridge the gap between BIPV and traditional building materials.

If BIPV products were positioned to compete directly with conventional materials, it would broaden their market reach. However, increased promotion, greater familiarity and confidence in BIPV are needed for this transition to occur [58,59].

Confidence in the technology: It is not only that the building sector is inherently conservative or slow to adopt new technologies, but a significant barrier is the lack of confidence in the technology among architects, builders and sustainability engineers. One effective approach to address this is through the active dissemination of knowledge, including case studies and examples of successful BIPV projects. Furthermore, BIPV products shall be introduced with sufficient specifications and skilled professionals ready to implement them. Since the expertise in BIPV remains concentrated within a small circle of specialists in each country, it is crucial to broaden awareness among general building professionals to unveil myths build a more robust understanding of BIPV's potential and applications.

Cost competitiveness: Cost remains a major consideration for the construction sector. BIPV modules are often perceived as luxury items, especially when compared to lower-cost traditional materials. However, this perception does not always reflect reality. A more accurate evaluation of BIPV's economic value should not only consider the initial capital cost but also consider the whole lifecycle costs, including both direct and indirect benefits.

While higher maintenance and replacement costs are also concerns, there is potential for repurposing BIPV modules—for example, using them solely as a building material once their electrical efficiency declines—thereby supporting circular economy principles.

Architectural suitability: Aesthetic integration is a major factor influencing BIPV adoption, particularly in historic districts and rural contexts. While BIPV modules are now available in a variety of colours, patterns, shapes and transparency levels, overall acceptance remains limited [60,61]. Moreover, module designs with a focus on aesthetic and certain optical and solar properties, such as daylighting or solar heat gain, can compromise the PV efficiency [43,44]. This trade-off presents a challenge when balancing performance with design requirements.

Cross-sector collaboration: Many different stakeholders from the construction sector are involved throughout the BIPV value chain. For instance, when an architect designs and proposes a BIPV system, the collaboration of a PV consultant is essential to optimise the system's energy performance. Builders must also engage skilled professionals, such as roofers, plumbers, façade specialists and certified electricians [62].

Furthermore, proper operation and maintenance of BIPV systems requires trained personnel to ensure long-term performance. However, such cross-sector collaboration between the construction and PV industries is still rare. Strengthening coordination is essential to unlock the full potential of BIPV technology.

Practical implementation guides: A lack of accessible and detailed implementation guidelines is another key barrier. Due to the hybrid nature of BIPV systems—which involve both construction and electrical components—comprehensive installation manuals and technical documentation are crucial.

Architects and engineers need clear guidance not only on installation procedures, but also on how to design BIPV systems that maximise energy generation while preserving the structural integrity and functionality of the building. Despite this need, such resources remain scarce. The construction sector is actively seeking well-structured, widely accessible technical guides to support broader adoption.

Digitalisation and cyber-physical environment: Digital transformation is becoming increasingly important across the building industry, and BIPV should not miss the opportunity to be part of this evolution. However, the construction sector continues to face challenges in adopting BIM-based digital design, and progress in digitalising BIPV remains limited. One major barrier is the lack of a BIPV-specific data structure within the Industry Foundation Classes (IFC) [63].

Widely used digital tools, such as Autodesk Revit (https://www.autodesk.com), lack BIPV-specific attributes, limiting their effectiveness in fully supporting BIPV integration. While specialised software like BIPV Enabler (https://www.rmit.edu.au/about/schools-colleges/property-construction-and-project-management/research/research-centres-and-groups/solar-energy-application-laboratory/projects/bipv-enabler (accessed on 19 August 2025)) can assist with design optimisation, it falls short when it comes to automation and the digitalisation of operation and maintenance processes. Overall, the industry is lagging in the adoption of advanced technologies such as digital twins and the Internet of Things (IoT) for remote control and monitoring of BIPV systems.

In addition, digital technologies like virtual reality (VR) and augmented reality (AR) offer promising potential to enhance both the design experience and operational management of BIPV installations. Within the broader context of Industry 4.0, the creation of a cyber-physical environment for designing, installing and maintaining BIPV systems could unlock advanced capabilities and maximise their performance. However, only a limited number of BIPV systems currently operate within such highly digitalised environments.

Environmental performance assessment: Environmental impacts, especially global warming ones, are increasingly gaining importance for the building sector; lifecycle assessment and environmental product declarations are common tools in the industry, e.g., [64,65]. However, the availability of representative, up-to-date lifecycle inventory data is a challenge for PV in general, but even more for BIPV, given the specifics of a niche market with often small production facilities and product batches. This creates uncertainty regarding the carbon footprint assessment of BIPV products compared to other building materials.

Additional uncertainties exist regarding the impact of power electronics in BIPV systems [66] and the effects of BIPV electricity production when replacing other generation sources in the larger-energy system. Altogether, limited data availability, poor data quality and limited scope of comparisons create uncertainty regarding the climate benefits of BIPV, leading to certain scepticism towards the technology in the building sector. More focus on BIPV's environmental performance and optimisation seems necessary to overcome this lack of trust.

3.5. Institutions and Policymakers' Role

3.5.1. Legislation Impact

PV history has demonstrated the importance of legislation in its evolution. While rapid policy changes are often a reaction to evolving module prices, project profitability and trade deficits, structural policy changes depend on energy transition goals, the cost of support mechanisms and local manufacturing stimulus [67]. The economic support in most countries over the last few decades, combined with technological progress, has made photovoltaic energy highly competitive, making it one of the main drivers of decarbonisation. Significant goals in terms of PV installed capacity have led to a record of 600 GW of new installed PV power last year, with rooftop and utility-scale segments growing at different rates, depending on the country [67]. However, rooftop figures do not differentiate between BAPV and BIPV projects, being the last a minority.

Although the first BIPV examples correspond to Europe in the early nineties, the scenario shows scattered BIPV economic support since then, mainly in the 2000s, when BIPV was identified in some countries as an innovative PV application for resource mobilisation and demonstration purposes. For instance, the BIPV market in Italy has benefited from technological innovation support through subsidies for innovative technologies [11]. In Spain, from 2006 to 2019, including PV power in new or retrofit projects of non-residential buildings was compulsory, and the law allowed BIPV façades but not BAPV ones [12].

Some other countries not involved in the TIS analyses of this work also had specific support for BIPV. For instance, in 2003, Germany's law revision after the 100,000 Roofs Program favoured BIPV roofs over BAPV roofs and included a bonus for façade installations in the feed-in law 2004 [68]. In 2006, France also started supporting BIPV over BAPV in the feed-in tariff and continued promoting and supporting good BIPV examples for years [69]. Otherwise, BIPV has been in general competing with BAPV, a cheaper and simpler technology.

It is worth underlining that the concept of support in the past was more related to capital support or feed-in tariff schemes, while today, tax deductions, low-cost loans, self-consumption and energy communities' incentives, energy income schemes are more frequent.

3.5.2. BIPV-Specific Support

BIPV TIS analyses showed similar institutional frameworks for hard and soft institutions in all countries. Regarding hard institutions, i.e., regulations, standards, codes, etc., the existing ones neither support nor regulate the BIPV innovation process. Moreover, BIPV is not considered a construction material by any national or international regulation; thus, BIPV products are not included in building technical codes, which makes the construction sector reluctant to implement BIPV in buildings. Another important consequence is that BIPV materials are not eligible for funding in energy renovation actions.

The TIS analyses revealed resistance from the construction industry to embrace this new challenge related to BIPV as a building material based on an approach to avoiding risk and minimising costs. One reason for not having BIPV materials and solutions in the national building codes is that BIPV-related standards are not harmonised, which would make standards provide a technical basis to assess the performance of construction products, enabling manufacturers to draw up a declaration of performance.

Furthermore, since BIPV standards are not harmonised, they are not mandatory, although recommended. In Europe, the new EN 50583-1 edition, currently under revision, seeks to align with the European Construction Product Regulation and Low Voltage Directive to become harmonised. Besides, further standards and annexes should be developed to characterise BIPV products and systems fully. Steps are being taken towards a more correct and complete standardisation of BIPV [70,71].

All countries analysed showed similar topics to those mentioned above (lack of BIPV-specific support and appropriate standards and building codes). Local authorities and architects have claimed to have difficulties in including BIPV in the early design stage mainly due to the lack of information, understanding and or trust about the technology (this links to the previous analysis on soft institutions and the knowledge dissemination function).

4. Discussion of Results and Recommendations to Policymakers

In this scenario, policymakers should align with broader climate and energy policies to support and promote BIPV technology. Notably, the European Union has recently issued directives related to energy efficiency [72], the promotion of renewable energy [73] and the Energy Performance of Buildings Directive (EPBD) [74]. These directives must be transposed into national legislation, creating opportunities for the integration and advancement of BIPV solutions.

According to the EPBD, EU countries shall ensure the deployment of appropriate solar energy installations in buildings; policies and measures should be developed to that end. EPBD also aims to help increase the renovation rate in the EU, particularly for the worst-performing buildings. In this context, BIPV represents a significant opportunity for energy retrofitting and solar energy integration in buildings. This applies globally.

Examples to follow are the simplification or removal of permit requirements for BIPV occurring in some countries, public administrations leading examples of sustainability and innovative solutions and the development of BIPV guidebooks (e.g., [40,58]) and other technical documents that help in the decision-making process of BIPV systems.

Recommended actions for policymakers in TIS reports focus on the need to include BIPV in the national building codes as building products, the BIPV requirement for public buildings, the development of market potential reports and official dissemination among the main stakeholders to increase their trust in BIPV technology. Also important is the need to grant support to cover part of the product certification costs and patent fees, especially for small producers and niche products. The type of incentives for BIPV solutions should be adapted to each country's market and political framework.

The TIS analyses indicate a lack of networks dedicated to and supporting BIPV in some countries. Policymakers and public administrations, working with local administrations and other institutions, can create a network that includes the different stakeholders to collaborate in renewable energy, energy efficiency in buildings and BIPV deployment. This network could also get involved in BIPV technology training, best practices deployment and assistance with existing incentives. Policymakers and public administrations, moreover, can work with local partners to support the refurbishment plans for the existing building stock, identifying BIPV as one of the main technologies to consider.

Permits in historic districts require special attention. While the BIPV industry seeks product standardisation to reduce costs, local authorities and architects in Italy have advocated for a new architectural language—one that can integrate BIPV into traditional materials, architectural styles and urban planning frameworks. To address this apparent dichotomy, the creation of a dedicated institutional framework is recommended.

Institutions play a crucial role in shaping innovation. They provide guidance through specific rules and define relationships among key actors, such as researchers, industry and other stakeholders. By regulating cooperation and managing potential conflicts, institutions foster mutual trust. They also support innovation by offering incentives and securing property rights for new ideas and knowledge. An important role that has to adapt to technological change over time. Figure 9 summarises the main group of actions proposed to policymakers.

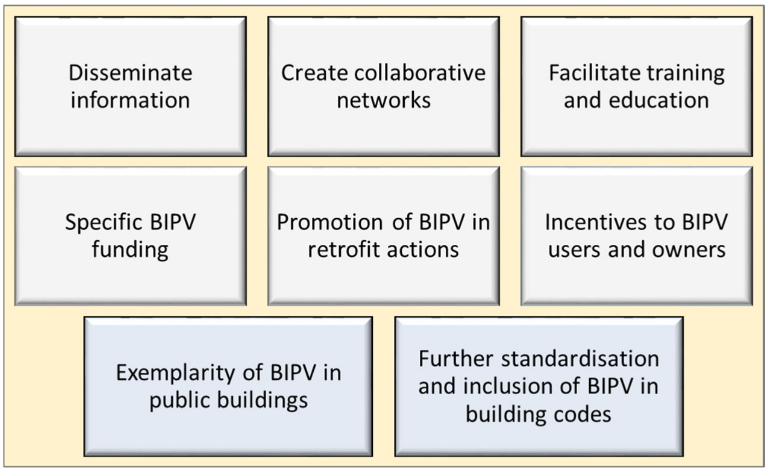


Figure 9. Summary of the main recommendations to policymakers to boost BIPV technology.

5. Conclusions

Climate and energy emergencies are increasing social acceptance of distributed PV, favouring PV self-consumption in buildings. In this context, BIPV emerges as a highly advantageous solution for installing PV in buildings, by serving both as a power generator and a construction material. BIPV contributes to material savings and offers the potential for enhanced architectural aesthetics. Additionally, BIPV can also play a relevant role as an active component in the energy renovation of the building stock.

Despite these advantages, BIPV remains in an early phase of market development due to several persistent weaknesses and barriers. The most fundamental challenge lies in the dual nature of BIPV—as both a photovoltaic and a building product—, which makes the involvement of the building sector essential. This study has identified a range of associated critical barriers and weaknesses that must be addressed to facilitate the wider adoption and mainstreaming of BIPV technology.

The TIS analyses reveal weak to moderate legitimation of BIPV, due to limited knowledge dissemination of this technology. Additionally, official technical guidance on the BIPV design, installation and operation is lacking. Cost is a major barrier, with BAPV often preferred for its lower upfront investment. However, cost-competitiveness perception can change when considering the costs of the substituted conventional construction materials. Standardised BIPV solutions are already proving competitive in both new construction and retrofit projects.

A growing interest among building owners in investing in BIPV. However, the construction sector still lacks confidence in BIPV as a reliable construction material. Greater cross-sector collaboration, wider product availability and improved digital tools for design, installation, operation and maintenance are necessary. Concerns also remain regarding architectural integration and environmental impact assessment.

While crystalline silicon-based BIPV products will continue dominating the market in the next years, additional materials, new manufacturing processes and colouring techniques will appear in the market. However, technological knowledge dissemination is still not sufficient among decision-makers. Information access, adequate official guidance on design and installation, skilled personnel and good examples are necessary to increase BIPV's legitimacy.

The overall outlook highlights great opportunities for BIPV to expand and contribute meaningfully to the decarbonisation of cities, helping make them more sustainable, liveable and resilient to the impacts of climate change. Nevertheless, strong support from policymakers in terms of standardisation, regulation and financing is essential to accelerate the BIPV market. The TIS analyses reveal a lack of networks dedicated to and supporting BIPV in some countries. Policymakers and public administrations, working with local administrations and other institutions, are encouraged to establish a network that brings together key stakeholders to collaborate in renewable energy, energy efficiency in buildings and BIPV deployment, helping to strengthen the innovation ecosystem and drive BIPV market uptake.

This study is based on a collaborative analysis of the technological innovation systems (TISs) for BIPV in six countries. Future updates, and including other countries like China and India, could significantly alter the findings.

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Abbreviations

The following abbreviations are used in this manuscript:

BAPV	Building-Added Photovoltaic(s)
BIM	Building Information Modelling
BIPV	Building-Integrated Photovoltaic(s)
CdTe	Cadmium Telluride
CIGS	Indium–Gallium–Copper Selenide
c-Si	Crystalline Silicon
EU	European Union
EPBD	Energy Performance of Buildings Directive (European Union)
H:a-Si	Hydrogenated Amorphous Silicon
IEA	International Energy Agency
IEA-PVPS	Photovoltaic Power System Programme of the International Energy Agency
IEC	International Electrotechnical Commission
m-Si	Monocrystalline Silicon
TIS	Technological Innovation System

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