AALBORG UNIVERSITY

FOSTERING INNOVATION IN EMERGING SOLAR TECHNOLOGIES IN EUROPE

POLICY LEVERS TO OVERCOME BARRIERS IN EMERGING SOLAR CELL TECHNOLOGY DEVELOPMENT AND COMMERCIALIZATION

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Abstract

The European Union aims to recover its leadership in solar photovoltaic technology while reducing its strategic dependence on non-European countries. Among emerging technologies, perovskite-based solar cells (PSCs) are an attractive alternative to silicon-based cells due to their high efficiency potential, low production costs, and compatibility with tandem architectures. However, despite Europe's strong research base, PSCs remain at an intermediate stage of development (TRL 5–7) and face significant systemic barriers to commercialization.

This thesis investigates can support firms in innovating and commercializing emerging solar cell technologies such as PSCs in Europe. Using the Technological Innovation System framework, complemented by the Technology Readiness Levels and Valley of Death concepts, the study identifies critical weaknesses in three TIS functions: market formation, legitimation, and resource mobilization. The analysis is based on secondary data, including policy reports, academic literature, and strategic roadmaps.

Findings show that current policies insufficiently address the specific needs of PSC technologies. Market formation is constrained by limited early demand and procurement frameworks favoring mature technologies. Legitimation suffers from policy uncertainty and risk aversion among investors and public buyers. Resource mobilization is weakened by fragmented funding, lack of manufacturing infrastructure, and grid bottlenecks. This thesis highlights the need for tailored policy mixes that combine technology-specific support instruments with broader innovation and industrial strategies.

In conclusion, strengthening Europe's position in the global PV industry requires coordinated policy action across national and EU levels. Creating protected niche markets, aligning public investment with technology development stages, and fostering institutional legitimacy are essential to unlock the full potential of PSCs and achieve European energy sovereignty.

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Introduction

Recent geopolitical and economic events, notably the Russia-Ukraine war and rising tariff tensions, have intensified concerns over Europe's technological and energy sovereignty (Chatzipanagi et al., 2023; European Parliament & Council, 2023). At the same time, growing climate change urgency has pushed the EU to set ambitious goals: 42.5% renewable energy in gross final consumption by 2030 and climate neutrality by 2050 (European Parliament & Council, 2023). Among available solutions, photovoltaics attracts increasing attention from European policymakers (Chatzipanagi et al., 2023; IEA, 2024; European Parliament & Council, 2023). Once a global leader in crystalline silicon (c-Si) solar technology, Europe now relies heavily on China, which dominates the global PV market and controls nearly the entire silicon supply chain (Chatzipanagi et al., 2023; IEA, 2024). This dependence not only raises economic and industrial competitiveness concerns but also exposes the European Union to significant geopolitical and material risks.

China's advantage is not limited to manufacturing scale, it also increasingly invests in R&D, including in next-generation PV technologies (Chatzipanagi et al., 2023; IEA, 2024). In parallel, the United States is fostering innovation through policy encouraging industrial development (Chatzipanagi et al., 2023; IEA, 2024). In contrast, most European companies are limited to the downstream segment of the silicon value chain or to early-stage research activities (Chatzipanagi et al., 2023; IEA, 2024). However, Silicon-based PV modules, which have historically driven the growth of the solar industry, are now approaching their theorical efficiency limits. As a result, scientific and industrial attention is turning toward alternative solar cell technologies that offer higher efficiencies, reduced material usage, and potentially lower production costs (Ghosh and Yadav, 2021).

Among the most promising candidates are perovskite-based solar cells (PSCs), including single-junction and tandem configurations (perovskite/Si tandem) (Alami, 2023; Chatzipanagi et al., 2023; Ghosh & Yadav, 2021; Lameirinhas et al., 2022). These technologies have the potential to achieve higher efficiency and low-cost, low-energy manufacturing processes (Anzolin & Righetto, 2018; Giannouli, 2021). The European Commission has identified PSCs as a key strategic area for maintaining EU leadership in solar technology (Chatzipanagi et al., 2023). However, according to the European Perovskite Research Group, these technologies remain at a critical stage between lab-scale validation and commercial viability (PEPPERONI, n.d.-a). Meanwhile, international competitors such as China and the United States are accelerating their own developments, with China already establishing pilot-scale production lines (Chatzipanagi et al., 2023).

Given this context, the EU must not only catch up in terms of production capacity but also ensure that promising technologies such as PSCs can be successfully developed and commercialized. However, Europe's previous experience with silicon PV, where early leadership was ultimately lost due to inconsistent support and global competition, demonstrates the need for a more coordinated and forward-looking approach to innovation and commercialization policy (Chatzipanagi et al., 2023, Fichtner, 2024; Métayer, 2024; NorSun, 2024).

This thesis seeks to contribute to this conversation by addressing the following central research question:

How can public policy effectively support firms in innovating and commercializing emerging solar cell technologies in Europe?

To answer this question, the study focuses on the specific case of perovskite-based solar cells, using them to explore the key technological and market-related challenges associated with the development and commercialization of emerging PV technologies in Europe. This study also discusses policy responses required to overcome them. More precisely, the study answers the main research question by addressing the following sub-questions:

1 – What are the key challenges faced by stakeholders in the development and commercialization of emerging solar cell technologies?

2 - What policy interventions can mitigate systemic barriers to facilitate technology and innovation development in the European solar cell sector?

By focusing on perovskite technologies, an area still underexplored in terms of systemic commercialization challenges, this thesis aims to provide initial thoughts for policymakers, industry stakeholders, and researchers about how to address barriers to innovation and avoid repeating the mistakes made in the past with silicon PV.

Methodology and data collection

Purpose of this study and research design

This thesis examines how public policy can support firms in innovating and commercializing emerging solar cell technologies in Europe. Due to their promising results and strategic relevance, perovskite-based cells (i.e., single junction and perovskite/Si tandem) are chosen as a case study to explore challenges facing emerging

PV cells and potential challenges to large-scale commercialization. The role of policy is then discussed considering these challenges and their implications for firms and innovation management. This thesis is structured in five parts, in addition to introduction, methodology and conclusion: 1) A literature review on technological innovation system, technology readiness levels and Valley of Death; 2) a contextualization of the European PV industry, including PV technology generations and innovation drivers; 3) the analysis of the first sub-question; 4) the analysis of the second sub-question; 5) the discussion. A more detailed description of the two analytical parts is provided below. Additionally, a list of abbreviations is provided in Appendix 1.

The third part of this thesis addresses the following sub question "*What are the key challenges faced by stakeholders in the development and commercialization of emerging solar cell technologies?"*. The question is answered by focusing on assessing the development stage of the perovskite solar cell industry not only from a technical standpoint, but also from a systemic perspective. The analysis is based on the Technological Innovation System (TIS) concept and the related six-step scheme developed by Bergek et al. (2008) as well as some insights from the *Guide for Technological Innovation System Analysis for Building-Integrated Photovoltaics* written by IEA PVPS, which is an application of Bergek et al. (2008) scheme (Van Noord et al., 2023). The TIS of analysis, referred to as the focal TIS, is the European emerging perovskite-based PV cell technological innovation system (or PSC TIS). This choice is justified at the beginning of the analysis section. However, since the technology is just starting to be commercialized for demonstration projects, the market for PSC is still immature. Additionally, as further explained in the data collection section, the study is solely based on secondary data from academic papers and governmental or non-governmental institutions' reports. Therefore, applying consciously the entire six-step scheme of analysis by Bergek et al. (2008) or the guide from IEA PVPS (Van Noord et al., 2023) is not possible due to a lack of detailed information, expert insight and empirical data. The limitations of this study (immature market, lack of data, limited number of papers studying the systemic challenges of this TIS) explain why only some steps have been considered. The analysis is divided into three parts. First, the scope and structural components of the TIS are discussed, which corresponds to step one and two in the six-step scheme. Then, the current development stage of the TIS and its development target are assessed, including a discussion of the knowledge development function. Finally, the third part discusses the needs for the TIS to reach its development target and the associated challenges regarding three functions: Market formation, legitimation and resource mobilization. These functions have been chosen based on the type of

information available online, because they are particularly interrelated and they cover a wide range of topics related to technology and innovation management and policy design. This choice does not imply that other functions are unimportant, and some information may be missing in conducting a TIS analysis with only three functions. In addition, the Technology Readiness Levels (TRLs) framework is introduced within the TIS analysis to assess the readiness level of perovskite technologies and thus to link the technical challenges largely addressed in the literature with the TIS development stage and the related barriers to commercialization. The TRLs are used by European policymakers to assess project proposals but also to develop roadmaps for technology commercialization and to design targeted policies (Directorate-General for Research and Innovation et al., 2017b; Héder, 2017), which directly relate to the purpose of this study. Findings from the literature on the Valley of Death (VoD) concept are also included in the analysis. Since the VoD is a conceptualization of the gap between the development of a prototype and the commercialization of a full-scale technology, perovskite cells could be concerned by the typical challenges technologies face when passing through it.
These frameworks and concepts provide guidance on how to assess the development stage of TIS, what implications it has on the challenges encountered and ultimately what should be done to avoid these challenges and ensure that a promising yet emerging technology, such as PSC, successfully reaches large-scale commercialization. At the end of the analysis, the reader should have a good overview of what is happening in the European emerging perovskite-based PV cell TIS, what are the current challenges and potential issues to watch. The results thus answer the first sub question and set the stage for discussing how policymakers can facilitate the development of technology for firms. However, the TIS analysis is not aimed at providing an exhaustive and factual list of detailed challenges but is only a starting point to address a topic that is overlooked in the literature on perovskite technology commercialization and strategic reports from the European Commission.

The fourth part of the thesis addresses the sub question "*What policy interventions can mitigate systemic barriers to facilitate technology and innovation development in the European solar cell sector?"*. When looking at the silicon industry, the difficulties arose when private firms had to develop large-scale manufacturing processes, manage the deployment and diffusion of the new technology and make profit at the same time. Despite strong policy support, at least at the beginning, the silicon PV module industry weakened in Europe and is now mostly focused on R&D activities and the downstream part of the value chain (Chatzipanagi et al., 2023). Moreover, some of the remaining big players are filing for bankruptcy, delocalizing their activities in the US or in China or complaining about the lack of regulations in Europe, the oversupply of cheap Chinese imports and the lack of effective market protection policies (Fichtner, 2024; Métayer, 2024; NorSun, 2024). To avoid making the same mistakes with perovskite cells and mitigate the challenges identified in the first part, policymakers must assess the right policy issues and solutions. The thesis participates in the discussion by first exploring the different policies and support mechanisms used in a selection of countries and their impact on the three TIS functions analyzed (market formation, legitimation and resource mobilization). Then, based on the type of policies identified and the specific challenges found when answering the first sub-question, potential areas to improve current policy design are discussed. As for the first sub-question, this section does not aim at providing specific recommendations but rather at discussing key areas of interest for policymakers and further studies on the subject.

Methodology and data collection

This work is based on a qualitative, exploratory, and interpretive research design grounded in secondary data sources. The term exploratory research is used in its most general meaning, which is "to study, examine, analyze, or investigate something" (Stebbins, 2001). The research is exploratory as it explores what may hinder technological development and the role of policies at the system level, without predefined expectations. It also addresses a relatively underexplored academic and policy area: systemic failures in Europe's innovation system for emerging solar technologies. Such research suits situations where scientific knowledge is limited, helping clarify problems and generate hypotheses (Stebbins, 2001). Given the urgency of the energy transition and the emergence of new PV technologies, such as perovskite and tandem cells, this study seeks to uncover underlying structural bottlenecks and gaps not yet extensively documented. This study is also interpretive, seeking to understand how innovation phenomena are shaped within a socio-technical system. The objective is not to test hypotheses or to provide statistical generalization, but instead to develop a broad understanding of how innovation system dynamics shape technology development and commercialization of emerging PV cells.

This study relies exclusively on secondary sources, including academic literature, policy documents, strategic reports, market analyses, and technological roadmaps. These sources offer a broad and multi-perspective understanding of the systemic challenges faced by emerging PV technologies in Europe and the policy role in addressing them. Initial research was conducted without strict criteria to gain general knowledge of renewable energy, photovoltaics, and related innovation policies. Then, academic literature was gathered primarily via databases such as Google Scholar and AAU's university library webpage. Preference was given to recent publications (post-2010), and those that made substantial theoretical or empirical contributions to the understanding of innovation systems and technology development in the energy sector. Policy documents and strategic reports come from EU institutions, intergovernmental agencies, and reputable think tanks. They were selected for their authority, relevance, and insights into innovation dynamics and policy landscapes. Focus was placed on sources covering European photovoltaics, emerging technologies, and innovation barriers. Most selected documents were published after 2020, to ensure that the strategic and quantitative results are as relevant as possible in 2025. Section IV.1 presents a cross-country policy analysis in Austria, Denmark, France, Germany, Italy, Netherlands, Spain, and Sweden, based on the IEA policy database and PVPS national reports. Only renewable energy and solar PV policies active since 2015 are considered unless otherwise noted.

This secondary data approach enables the integration of diverse insights and the construction of a holistic picture of the technological and institutional environment. Relying on existing sources also reveals how stakeholders frame innovation challenges, central to interpretive analysis. However, as previously discussed, this approach also presents limitations. Without primary data and interviews, findings reflect existing sources' framing and may miss actors' nuance, experience and tacit knowledge. Finally, policy documents and strategic reports may be biased by authors' political, economic or societal interests and institutional agendas, influencing how challenges are presented, and which solutions are emphasized. These limitations are acknowledged and considered when drawing conclusions and offering policy recommendations.

I – Literature review

I.1 – The concept of Technological innovation system (TIS)

Scholars studying innovation, industrial transformation and economic growth emphasized that technological development must be analyzed within broader innovation system (IS) rather than in isolation (Johnson, 2001; Bergek et al., 2008a). The IS concept serves as an analytical tool to describe the dynamics and performance of a defined system, whether or not it exists in reality (Bergek et al., 2008a). Bergek (2008) describes an innovation system as a set of actors, networks and institutions working toward the overall function of developing, diffusing and utilizing new products and processes. System components may not interact intentionally, and conflicts are as integral to their dynamics as collaboration (Bergek et al., 2008a). In their paper, Hekkert et al. (2007)

underlines the role of public and private sectors in initiating, modifying and diffusing new technologies. Innovation systems have gained in popularity in the literature on technological change, innovation process and associated policymaking, as they offer a holistic perspective that integrates the technology with the system in which it evolves (Hekkert et al., 2007). Consequently, IS has been adopted by regional, national, and international bodies to guide policy design (Bergek et al., 2008a; Bergek et al., 2015). This perspective is particularly relevant to explore how public policies can be designed to better support the development and commercialization of photovoltaic technologies by strengthening the functions of the innovation system and addressing the structural barriers that hinder progress. From the IS concept, several system-based approaches emerged, including national, regional, socio-technical, and technological innovation systems (Johnson, 2001; Bergek et al., 2008a). The Technological Innovation System (TIS) approach focuses on how innovation systems function around a specific technology. As this thesis focuses on solar cell development, the technology-centered TIS approach is deemed most appropriate. This choice is supported by Bergek (2019) and Hekkert et al. (2007), who see TIS as well-suited to sustainability transitions, especially in renewable energy.

Studying interactions within a TIS and its broader context requires clearly defined system boundaries. TIS analyses typically begin with the technology itself, allowing for non-geographic boundaries that better capture knowledge and infrastructure (Bergek, 2015; Hekkert et al., 2007). For instance, a geographical limit may overlook national specificities, influence from international innovation areas and shifts in the importance of different scales over time. Still, in some empirical analyses, using geographical delimitation is common (Bergek, 2015). Bergek et al. (2008) argue that, while having an international component is crucial to completely understand TIS, a spatial focus can be applied to capture specific aspects of a country or region.

The dynamics between a TIS and contextual structures are difficult to fully analyze. Bergek (2015) identifies two types of TIS-context interactions. First, “external links” refer to contextual factors (e.g., policy shifts, infrastructure, market conditions) shaping TIS development without direct influence from TIS processes. Second, “structural couplings” involve shared components between a TIS and its context, as actors often engage in multiple domains and objectives beyond the focal technology. Beyond firms, institutions and networks can act as structural coupling elements, like feed-in tariffs affecting different renewable energy stakeholders (Bergek, 2015). A TIS with several strong structural couplings can face more strategic challenges and constraints because of conflicting or synergic relationships constraining alliances, institutional rigidity favorizing dominant technologies and ill-developed infrastructures for emerging technologies (Bergek, 2015). On the other hand, it can also facilitate access to crucial assets for technology development (Bergek, 2015).

I.2 - Technological innovation system (TIS) framework

While TIS is a concept aimed at illustrating the complexity of interactions, actors and structures involved in the process of developing, diffusing and utilizing new technologies, it does not provide a common framework for mapping the dynamics of the system. To address this, Johnson (2001) identified common "functions", defined as "the contribution of a component or a set of components to the goal", which offer a shared analytical lens across TIS literature (Bergek, 2019; Johnson, 2001). These functions facilitate the setting of boundaries of a system and the combination of different levels of analysis. They provide a structure to study both the present state of the TIS, the dynamics that have led to it and its performances and ensure that the focus is on the system functionality rather than its structure which allows for a fairer comparison between TIS. Additionally, this functional perspective is useful when analyzing influences on the technological (e.g., subsidies), sectoral (e.g., industry norms), and national (e.g., societal values) levels (Johnson, 2001). Over time, several sets of functions have been developed and used but two lists seem to dominate in the literature: the one by Hekkert et al. (2007) and the one by Bergek et al. (2008). The functions of the innovation system framework from Bergek et al. (2008) are selected because of the importance of policies in the analysis design and the clarity of the step-by-step description. Indeed, the authors have introduced a six-step scheme to evaluate functions, to identify the key policy issues and systemic weaknesses that hinder technology development and diffusion, and to guide intervention in any TIS. Their approach emphasizes the identification of inducement and blocking mechanisms and associated policy issues.

In this thesis, Bergek et al.'s (2008) framework is used as a guiding tool to identify and analyze systemic challenges faced by emerging solar cell technologies in Europe and discuss potential policy levers to overcome them. To do so, the first step involves defining the boundaries of the TIS, including the technology in question, the geographical scope, and sectoral dimensions. The second step maps the structural components of the system, such as key actors, networks, and institutions. The third step assesses system dynamics via the performance of seven functions: 1) knowledge development, 2) guidance of search, 3) entrepreneurial experimentation, 4) market formation, 5) legitimation, 6) resource mobilization, and 7) positive externalities. However, as explained in the methodology section, only *market formation, legitimation* and *resource* *mobilization* are discussed in this thesis. The fourth step, *assessing the functionality of the TIS and setting process goals*, and the fifth step, *identify inducement and blocking mechanisms*, are combined and included in the function analysis. Lastly, the sixth step aimed at identifying key policy issues is adapted to answer the second sub-question and is conducted in a separate section, in accordance with the methodology.

I.3 – Complementary tool and concept: TRLs framework and Valley of Death

Originally developed by NASA in the 1980s to assess space technology readiness, the Technology Readiness Levels framework has evolved and been adapted for use across a variety of sectors, including photovoltaics. This framework breaks down the development of a technology into nine levels from basic concept to system ready for commercialization. Progressing through TRLs requires meeting specific criteria, from lab validation to system integration and full-scale demonstration. Figure 1 outlines this nine-level model adapted from NASA. Its efficiency in managing risk, guiding development phase and strategic planning has made it a popular tool in the management of new technologies (Héder, 2017; Mankins, 2009). The understanding of the nine different levels helps decision-making in research, development, and innovation actions (Salazar & Russi-Vigoya, 2021). It is also used to align stakeholders (e.g., researchers, firms, investors, and policymakers) around a shared understanding of development stages and commercialization timelines. (Chatzipanagi et al., 2023; ETIP-PV, 2024; Directorate-General for Research and Innovation et al., 2017a). In sectors like solar PV, where technological advancements and validation are crucial to keeping pace with multiple developments, TRLs help set milestones, manage timelines, and reduce uncertainty before commercialization (Chatzipanagi et al., 2023; ETIP-PV, 2024; Directorate-General for Research and Innovation et al., 2017a).

	TRL	DEFINITION
Early-stage R&D	1	Basic Principals Observed and Reported
	2	Technology Concept and/or Application Formulated
	3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
Validation and demonstration	4	Component and/or Breadboard Validation in Laboratory Environment
	5	Component and/or Breadboard Validation in Relevant Environment
	6	System/Subsystem Model or Prototype Demonstration in Relevant Environment
Demonstration and commercialization	7	System Prototype Demonstration in Relevant Environment
	8	Actual System Completed and Qualified Through Test and Demonstration
	9	Actual System Proven Through Successful Mission Operations

Figure 1 - Technology Readiness Levels (Adapted from Mankins, 2009)

Nevertheless, TRLs overlook the evolving capabilities required to manage technologies across stages, from managing a basic technology (TRLs 1 to 4), to a full-scale technology (TRLs 5 to 7) and finally an entire system (TRLs 8 to 9). As a result, when public institutions and governments use TRLs to evaluate project proposals, like in Europe, but overlook the evolving needs for funding, they tend to reduce their investment for intermediate to high TRLs (Héder, 2017). However, these levels usually require more resources than lower levels, but the private sector can find it too risky to invest a substantial amount of money during the demonstration phases (Héder, 2017; Mankins, 2002; Mankins, 2009). As a result, a funding gap is created between TRL 4 and TRLs 8 and hinders the commercialization of new technologies.

The TRL 5 to 7 phase is commonly known as the "Valley of Death", where technologies struggle to transition from demonstration to market (Muscio et al., 2023). It is marked by increasing development costs, difficulties gaining investors' interest, uncertain returns and inadequate structural supports that hinder the transition from lab-scale success to market-ready innovation (Muscio et al., 2023; Tassey, 2014; Teece, 1986). Moreover, the challenges faced during this phase are receiving growing attention for their impact on innovation policy and business R&D management (Muscio et al., 2023).

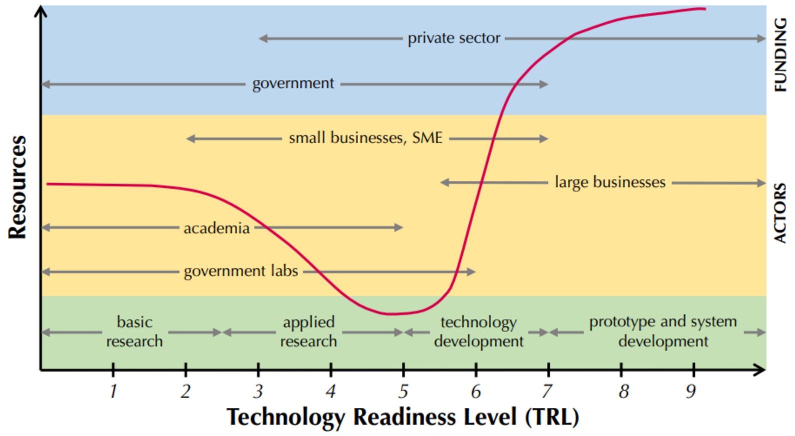

Figure 2 - Availability of resources for new product development at various TRLs. The gap in the middle is referred to as "The Valley of Death" (Hensen et al., 2015)

Beyond funding, the VoD is rooted in structural misalignments between public and private sector roles. Indeed, small and large firms, manufacturing supply chains, research, education and financial infrastructure are becoming increasingly interdependent (Tassey, 2014). As a result, the alignment of public-private dynamics is crucial to prevent promising advances in basic science from falling into a VoD and ensure they evolve into advanced technologies ready for commercialization. According to Tassey (2014), TRLs 1 to 3 correspond to basic scientific research, a phase mostly supported by public institutions due to its non-commercial value and characteristics close to public good. However, as technologies advance into TRLs 4 to 7, they become more applied and include proof-of-concept research and the creation of technology platforms (TRLs 4-5), applied R&D (TRLs 5-7) and the development of infratechnologies (TRLs 4-7). These intermediate stages typically combine both public and private good characteristics and benefit from public-private co-investment. However, these platforms and supporting systems are often underdeveloped, making firms reluctant to invest alone (Tassey, 2014). As governments reduce support prematurely, assuming private actors will fill the gap, they inadvertently deepen the VoD and limit the emergence of competitive innovations (Tassey, 2014). Tassey (2014) stresses that addressing this gap requires more than just increasing the level of funding. Efficient R&D strategy and organizations require a well-structured approach that considers the portfolio of technologies needed to develop the full technological system and align investment with the different roles and needs of basic research, proof-of-concept and technology platforms, and applied R&D at each stage. This structure should also optimize who participates (universities, industry, governments etc.), how they collaborate and the supporting infrastructures and resources (skills and knowledge).

This approach is echoed in Teece's (1986) perspective on the importance of complementary assets, such as supply chain infrastructures, for successful commercialization. Firms without control over these resources are unlikely to reap the benefits of their innovation (Teece, 1986), especially in sectors like photovoltaics, where advanced manufacturing capabilities are essential for producing more efficient modules and scaling-up next-generation cell technologies. Competitive manufacturing is complementary to technological innovation, so a decline of the former threatens the development of the latter (Teece, 1986). From a broader standpoint, foreign manufacturers and suppliers are likely to benefit from R&D activities performed across borders and, if a country does not want to see its technological innovation absorbed by foreign companies, then it must sustain a well-developed value chain. By viewing the VoD through the lens of an innovation system, it becomes possible to identify and address not only funding shortages, but also systemic weaknesses, such as poor coordination, missing infrastructure, or misaligned incentives, that prevent emerging technologies from reaching the market.

II - Technological landscape of the European PV industry

This section explores the different generations of solar cell technologies, focusing on their current progress and the technical barriers they face. It also examines the structure of the innovation system by identifying key actors and their roles in technological development. This analysis provides essential context for understanding the challenges faced by European PV firms in commercializing emerging technologies and sets the stage for the deeper analysis in the next section.

II.1 Generations of solar cell technologies

PV technologies are typically categorized into three generations, based on the materials, manufacturing techniques and their historical stage of development (Lameirinhas et al., 2022; Pastuszk & Wegierek, 2022). Each successive generation aims to reduce costs and improve efficiency compared to its predecessor (Suman et al., 2020). Figure 3 illustrates the key innovations in materials, cells, and modules, along with their chronological development. The emergence of each technology corresponds to the public disclosure of its initial concept or cell development. These dates serve as indicators to visualize the evolution of photovoltaic technologies over time, though they may vary by a few years in reality.

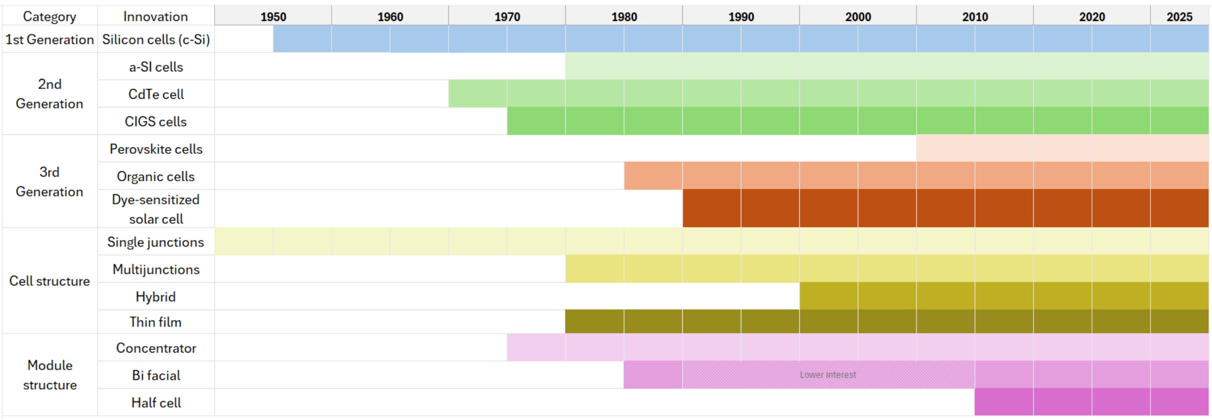

Figure 3 - Timeline of major cell and module innovations[1]

II.1.1 First generation: Silicon based modules

The first generation of photovoltaic cells is primarily based on silicon wafers and was developed upon the raw materials and techniques already used for microelectronic systems (Lameirinhas et al., 2022; Pastuszk & Wegierek, 2022). Silicon’s favorable

[1] Based on Akshay VR (2025), Bosio et al. (2020), Chandrasekaran et al. (2010), Eguren et al. (2022), Fraas (2014), Green & Ho-Baillie (2017), Kopecek et Libal (2021), Lee & Ebong (2016), Solar & Irmak (2023)

bandgap, natural abundance and developed supply chain thanks to the microelectronic industry have been determinant factors in the success of silicon-based PV cells, which now account for 95% of the global PV cell production (Chatzipanagi et al., 2023). Silicon-based PV cells are categorized into monocrystalline silicon (m-si) and polycrystalline silicon (p-si). While polycrystalline cells are less expensive to produce and assemble, monocrystalline cells have higher efficiency. Innovations in production and assembly processes have enabled monocrystalline cells to increase their global market share from 25% in 2010 to over 90% in 2022 (Fraunhofer ISE, 2024; Smith et al., 2021). However, silicon technology's efficiency is approaching the saturation curve and researchers are working on alternative materials, new manufacturing methods and advanced metrology to enhance efficiency and reduce costs (Ghosh and Yadav, 2021). Although GaAs wafers also belong to this generation, their high production cost restrict them to niche applications, mainly in the aerospace and defense industry (Papež et al., 2021).

II.1.2 Second generation: Thin-film technology

The second generation was developed with the aim of reducing the costs associated with the first generation, improving their characteristics and reducing reliance on traditional semiconductor materials (Lameirinhas et al., 2022; Pastuszk & Wegierek, 2022). This generation utilizes new materials such as amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) to build thinner cells and to make modules more flexible, lightweight and less demanding in materials. Additionally, these cells and modules are more cost-effective to produce, as they can be manufactured using a roll-to-roll process (Solak & Irmak, 2023). Thin-film modules are particularly promising for applications in building-integrated photovoltaics (BIPV) and portable and lightweight solar panels for outdoor activities (Solar & Irmak, 2023). Despite growing interest and some advantages, more research is conducted to ensure stability and durability over time and to reduce manufacturing costs for large-scale production. The International Energy Agency (IEA, 2024) characterizes thin-film technology as a "niche market" and, in 2023, thin-film technology contributed to 2.5-5% of the global PV market (Chatzipanagi et al., 2023; Fraunhofer ISE, 2024), making it the second most widely produced PV technology after silicon-based wafers.

II.1.3 Third generation: Emerging technologies

The definition of third-generation photovoltaic technologies can be ambiguous, as it sometimes includes only new materials like perovskites or organic photovoltaics, while in other cases it extends to advanced cell designs such as multi-junction and hybrid cells. Nevertheless, the literature broadly agrees that perovskite, organic and dye-sensitized

(DSSC) cells represent the most promising options for developing low-cost and efficient modules in this generation (Alami, 2023; Chatzipanagi et al., 2023; Ghosh & Yadav, 2021; Lameirinhas et al., 2022).

The main advantage of perovskites lies in their tunability, since they can be synthesized across a wide range of bandgap energies, making them ideal for tandem cell applications and for optimizing photon absorption. Organic cells are lightweight and flexible, making them suitable for small-scale applications and portable devices and are easy to recycle (Solak & Irmak, 2023). DSSCs are flexible, semi-transparent, and are promising for building-integrated photovoltaics and low-power applications (Solak & Irmak, 2022). Overall, cells from the third generation rely on low-cost, earth-abundant and less toxic materials, and they benefit from potentially low-cost manufacturing processes (Solar & Irmak, 2022). However, from an innovation and commercialization perspective, major barriers remain, particularly in terms of scalability, long-term durability, and operational stability, factors that contribute to delaying the market readiness of these technologies.

II.1.4 Cell and module structures

New materials from the 2nd and 3rd generations have been developed with the objective of reducing costs and increasing efficiency. However, they are traditionally used in single-junction cells (solar cells that are made from a single layer of semiconductor material) and their efficiency is limited by the Shockley-Queisser limit, which is approximately 30% for common photovoltaic materials (Ehrler et al., 2020). To overcome this theoretical limit and drive technological performance gains, innovation is increasingly directed toward the architecture of cells and modules. Multijunction cells (including tandem), which stack layers with varying band gaps to capture a broader portion of the solar spectrum, are seen as promising and projected to reach a 5% market share by 2030 (Chatzipanagi et al., 2023). Hybrid cells are a combination of different types of materials, often organic and inorganic, to take advantage of their complementary strengths (Solak & Irmak, 2023). Thin film cells consist of producing thinner and lighter modules (Chatzipanagi et al., 2023).

At the module level, several innovations aim to enhance performance without changing the cell materials. One example is the bifacial module, where cells are mounted on both sides of the panel to capture not only direct sunlight but also reflected irradiance from the environment (De B Mesquita et al., 2019). A second innovation is half-cell technology, in which 120 to 144 half-cells are used instead of 60 to 72 full cells in traditional modules (De B Mesquita et al., 2019). By cutting each cell in half, the current per cell is reduced, which in turn reduces resistive losses. As a result, two half-cells can produce slightly more current than one full cell (De B Mesquita et al., 2019). Lastly, concentrator photovoltaics use lenses or mirrors to focus the light onto a small area of the solar cells (Solak & Irmak, 2023).

II.2 Research focus and areas of innovation in photovoltaics

When looking at the technological development of the past decades, several innovation areas stand out: efficiency, cost, stability, durability and application potential. The first three parameters are considered pillars in the development of competitive and commercially viable technological products and often referred to as the "golden triangle" of solar cells development (Chalkias et al., 2022; Raman et al., 2021; Tang et al., 2024).

As shown in Figure 2, any photovoltaic technology is considered commercially viable if it achieves high initial performance (efficiency), minimal system cost, and minimal performance loss over its operational lifetime (Raman et al., 2021).

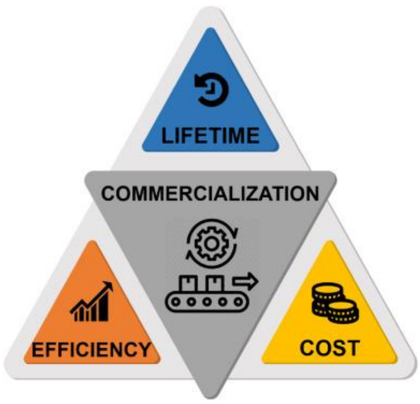

Figure 4 - The golden triangle for photovoltaic technology leading to commercialization (Raman et al., 2021)

However, while this golden triangle captures core performance requirements, it tends to overlook critical dimensions such as environmental sustainability and manufacturability, both of which are essential for ensuring the broad diffusion and long-term acceptance of solar technologies (Martulli et al., 2023). Today, cost, efficiency, lifetime, environmental sustainability and (easy and low-cost) manufacturability criteria are typically used to assess the potential of a photovoltaic innovation. The benchmark for each of these criteria is largely set by crystalline silicon (c-Si) technologies, which remain the global standard. Consequently, to be deemed interesting, a new technology must demonstrate superiority in one or two dimensions (e.g., higher efficiency that offsets a higher cost, as in bifacial modules), or at least incremental improvements across several. Lifetime performance is currently a key area of concern, especially for perovskite-based technologies, including tandems, thin films, and multijunction cells. Firms are also investing in industrial-scale process innovation, aiming to reduce the gap between laboratory cell efficiency and large-scale module performance, and to improve the scalability and cost-competitiveness of alternatives to silicon. These challenges are particularly salient for innovation and technology managers, who must align emerging technologies with existing capabilities and market expectations.

III - Analysis of development challenges in the European perovskite solar cell TIS

III.1 - Scope and structural foundations of the focal TIS

III.1.1 – Defining the TIS in focus

The first step of a technological innovation system analysis is to define the TIS in focus, called the focal TIS. This step is crucial, although complex. The chosen starting point has a major influence on the rest of the study and the way the situation is depicted. According to Bergek et al. (2008), at least three choices must be made to define a clear focal TIS: (1) the choice between knowledge field or product as a focusing device, (2) the choice between breadth and depth, and (3) the choice of spatial domain. The first choice is straightforward, the focusing device is clearly a technological product: solar (or PV) cells. The second choice is more complicated as there is a wide range of cell technologies and different applications possible (building-integrated, space, utility-scale, rooftop, etc.). As the purpose of the study is to analyze the development and commercialization challenges, the first generation of cells is out of scope. Then, because perovskite is considered as a very promising material in Europe (Chatzipanagi et al., 2023), the focus will be on emerging perovskite-based cells, i.e. perovskite thin-film cells and tandem perovskite/Si cells. There is no real focus on a particular application, except that very niche ones like military or space are too specific to be included in the TIS. The willingness to not consider a single application is coherent with the uncertainty involved in the analysis of emerging TIS, for which clear applications are not yet defined, and the lack of field knowledge that reduces the possibility for an in-depth case study (Bergek et al., 2008a). Third, the choice of a spatial domain is optional but is applied in this thesis (Bergek et al., 2008a). Indeed, the first motivations for conducting the analysis are the growing geopolitical tensions around the globe, the increasing dependence of Europe on the global supply chain for renewable energy due to deindustrialization and the increasing demand for energy that requires a minimal level of energy sovereignty. Therefore, while an innovation system is often global, this study focuses on the European context. However, international components are considered for comparison points or for their influential interactions with the focal TIS.

Finally, the focal TIS is the following: the European emerging perovskite-based PV cell Technological Innovation System (shorten to PSC TIS). To shorten the reference to perovskite based emerging cells, the abbreviation PSC is used, in accordance with the literature.

III.1.2 – Identification of the structural components of the TIS

The structural components of the TIS are divided into three categories: actors (e.g., firms, research institutes, etc.), networks (e.g., technology platforms, public-private partnership, etc.) and institutions (e.g., culture, norms, laws, etc.). A good starting point is to consider the value chain (VC) of emerging solar cells, identifying all actors downstream and upstream. Without insight from experts, the value chain composition is based on reports and papers on PSC manufacturing processes and c-Si photovoltaic VC analysis. The huge complexity and diversity of raw materials, manufacturing techniques and cell structures associated with the early development stages of the PSC add a layer of difficulty in the identification process. Therefore, it is challenging to determine precisely the structural components of the focal TIS and only the main actors within the system are identified. This is sufficient to discuss TIS interaction and potential systemic challenges, but it is not enough to provide in-depth knowledge and actions without further studies.

The photovoltaic value chain usually involves many different stages, from raw materials fabrication to recycling through module production and deployment, that are common to all PV technologies regardless of the materials. However, thanks to easier manufacturing processes and lower energy requirements, the PSC VC is expected to be much shorter than the c-Si PV value chain (Anzolin & Righetto, 2018). The fabrication of perovskite-cells involves a series of steps (Alami, 2023; Kajal et al., 2017):

1. Substrate preparation (often FTO[2]-coated glass)
2. Electron Transporting Layer (ETL) deposition to help with electrons mobility
3. Perovskite-based absorber layer deposition to convert sunlight into electricity
4. Hole transporting layer (HTL) deposition to help with positive charges mobility
5. Metal electrode, often gold, to collect the generated current.

[2] Fluorine-doped tin oxide (FTO)-coated glass

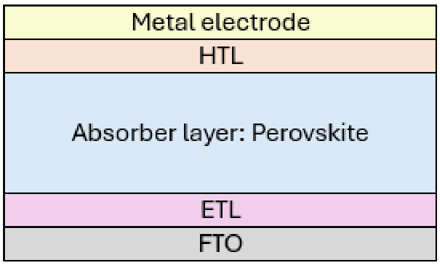

Figure 5- PSC structure, adapted from Kajal et al. (2017)

The value chain can be divided into three parts: upstream, midstream, and downstream. The upstream part is primarily focusing on raw materials and substrates technologies that enable the production of perovskite-based products (Anzolin & Righetto, 2018). This involves the extraction and purification of elements that are essential for synthesizing perovskite crystals (Alami, 2023). Additionally, the development of technologies for synthesizing perovskite materials also falls under the upstream category. This part of the value chain is not necessarily specific to perovskite cells, as perovskite can also be used in LEDs for instance (Xiao et al., 2018). The midstream part focuses on the processing and manufacturing of perovskite layers and assembly of solar cells according to the process described above (Anzolin & Righetto, 2018). Finally, the downstream sector encompasses the assembly of perovskite cells into modules and support devices (Anzolin & Righetto, 2018). It also includes the production of BoS components[3] (inverters, wires, batteries, etc.), the deployment of solar panels (Wholesalers, installers, project planners), after-sales services and recycling of modules (Chatzipanagi et al., 2023; Franco & Groesser, 2021). Although the downstream part for PSC does not exist yet, it will probably be similar to the one existing for silicon PV cells, as these activities are not specific to any particular technology (Anzolin & Righetto, 2018).

While PSCs technologies are still in the intermediate development stages (PEPPERONI, n.d.-a), several companies are working on it. Appendix 2 shows a non-exhaustive list of European firms currently working along the upstream and midstream perovskite cells value chain segments. Some companies operate worldwide but only their country of origin is listed. England and Switzerland are included because they collaborate with European countries and participate in cross-country project.

Dyenamo (Sweden) is the only European firms among the approximately twenty global material providers but SolarOnix, a Swiss company, is also conducting successful research on perovskite materials (SolarOnix, n.d.). The EU is a leader in equipment manufacturing for the perovskite technology with 7 major companies (Chatzipanagi et al.,

[3] The balance of system (BOS) encompasses all components of a photovoltaic system other than the photovoltaic panels. This includes wiring, switches, a mounting system, one or many solar inverters, a battery bank and battery charger.

2023): MBRAUN, Aixtron and Bergfeld Lasertech in Germany, FOM Technologies and infinityPV in Denmark, SparkNano in the Netherlands and JACOMEX in France. The USA and China dominate the market for module production, Enel Green Power in Italy being the only European company with Evolar (Swedish company acquired by the American giant First Solar) among the twenty global market players for the perovskite technology (Chatzipanagi et al., 2023). However, Saule technologies, which focuses on producing perovskite solar cells printed on thin, flexible substrates for building applied and small electronic devices application, is showing very promising results (Saule Technologies, 2025). Finally, Oxford PV is an England-based company but is also very important in the European landscape (Chatzipanagi et al., 2023).
Regarding the downstream value chain, the market is highly fragmented with big players in the deployment segment (i.e., Enel Green Power, Engie and BayWa), the recycling segment (i.e., Envaris, Reiling, Rieger & Kraft Solar and Rinovasol in Germany, La Mia Energia and Yousolar in Italy, Euresi and Solucciona Energia in Spain, etc.) and the monitoring and control segment (i.e., AlsoEnergy, Solar-log and Meteo&Control) (Chatzipanagi et al., 2023).

Apart from firms, other actors are actively shaping the European PSC TIS. Research institutes and innovation centers such as Fraunhofer ISE and CEA-Liten are conducting cutting-edge research on materials, device architectures, upscaling, and stability of perovskite solar cells. Universities are critical in advancing fundamental understanding, training talent, and participating in EU consortia. They can create spin-out that actively participate in the commercial development of cells. Examples are EPFL, Oxford University or Eindhoven University of Technology. EU-Funded Projects & Collaborative Platforms enable transnational R&D and the sharing of infrastructure and knowledge (e.g., Viperlab, Pepperoni, TESTARE). Consortia and Innovation Networks unite academia, research, and industry to facilitate innovation and knowledge exchange (Solliance Solar Research, ETIP PV). Intergovernmental Organizations provide analysis, benchmarking, and policy recommendations relevant to emerging PV technologies (e.g., SolarPower Europe, IEA – PVPS). Lastly, European and national authorities are part of the TIS as they influence or shape the market for technologies, resources allocation, infrastructure and funding availability, target for solar power capacity, incentives for renewable energy, penalties for non-renewable energy, economic and fiscal environment, etc. A more detailed list of these actors is provided in Appendix 3.

The last category of structural components described by Bergek et al. (2008) concerns institutions such as culture, norms, laws, regulations and routines. Mapping this part is very complex, especially at the European level, since European laws, norms and regulations coexist with national institutions. Only some of the most influential formal institutions at the European level are identified. In addition, instead of considering policies implemented within each country, a summary of the main types of policies and regulations implemented nationally is made based on the IEA policy database (IEA, n.d.), IEA analysis on the PV industry (IEA, 2024) and national reports from IEA PVPS (Austrian Technology Platform Photovoltaic & Fechner, 2022; Bernsen, 2023; De L'Epine, 2023; Donoso et Behar, 2022; Oller Westerberg et Lindahl, 2022; Tilli et al., 2022). A deeper analysis of national and European policies is conducted in section IV.

The institutional landscape shaping the development of PSC in Europe includes both formal and informal institutions. Key formal institutions involve EU-level strategies and regulations such as the European Green Deal, the Net Zero Industry Act, and Horizon Europe, which guide research funding and climate targets. Informal institutions include cultural expectations around environmental sustainability, industry routines favoring established silicon PV technologies, and academic norms emphasizing efficiency, durability, and reproducibility. Additionally, the European culture of collaborative R&D, along with the generally risk-averse and traditional mindset of investors (Tsanova & Havenith, 2019), also shapes the dynamics of the innovation system.
At the national level, a broad range of policies and instruments shape the development and deployment of PV technologies, including PSCs. These measures include economic incentives (e.g., feed-in tariff, capital subsidies), regulatory frameworks (e.g., portfolio standards, building requirements), fiscal incentives (e.g., tax credits, tax deductions, self-consumption schemes) and grid-related instruments (e.g., net-metering, net-billing). In addition, countries implement targeted support for emerging applications, including building-integrated photovoltaics floating solar panels, and promote demand response technologies and complementary systems like battery storage. Governments also establish national PV deployment targets, provide direct subsidies or investment grants, and invest in grid infrastructure upgrades to facilitate the connection of higher shares of PV electricity. To foster innovation, many countries support fundamental research, applied R&D, and industrial development, often through public investment banks or dedicated auction schemes designed to support national or European technology providers. Some financial institutions offer green commercial banking products (e.g., green mortgages) that indirectly stimulate PV adoption. These instruments interact with broader innovation and industrial policy frameworks, shaping the trajectory of the technological innovation system for emerging solar technologies like perovskite cells.

External components can also significantly influence the TIS for emerging European perovskite cells. These include the electricity grid infrastructures, which impact integration and scalability, as well as competing PV technologies and broader renewable energy sources that compete for subsidies, investment resources, and infrastructures. Additionally, sectors such as construction, agriculture, and wind energy compete for limited land availability, affecting the deployment of solar installations. The global perovskite innovation landscape, particularly developments in the United States and China, also shapes European efforts through technological spillovers and competitive pressures. The established silicon-based solar cell value chain remains a critical external factor influencing market dynamics and innovation strategies (especially the low-cost supply chain centered in China). Finally, all fund providers such as private venture capital firms, corporate investors, and multilateral development banks (e.g., EIB) also play a crucial role in shaping the dynamics and direction of the TIS.

Figure 6 summarizes the most relevant structural components that influence the development of the focal TIS.

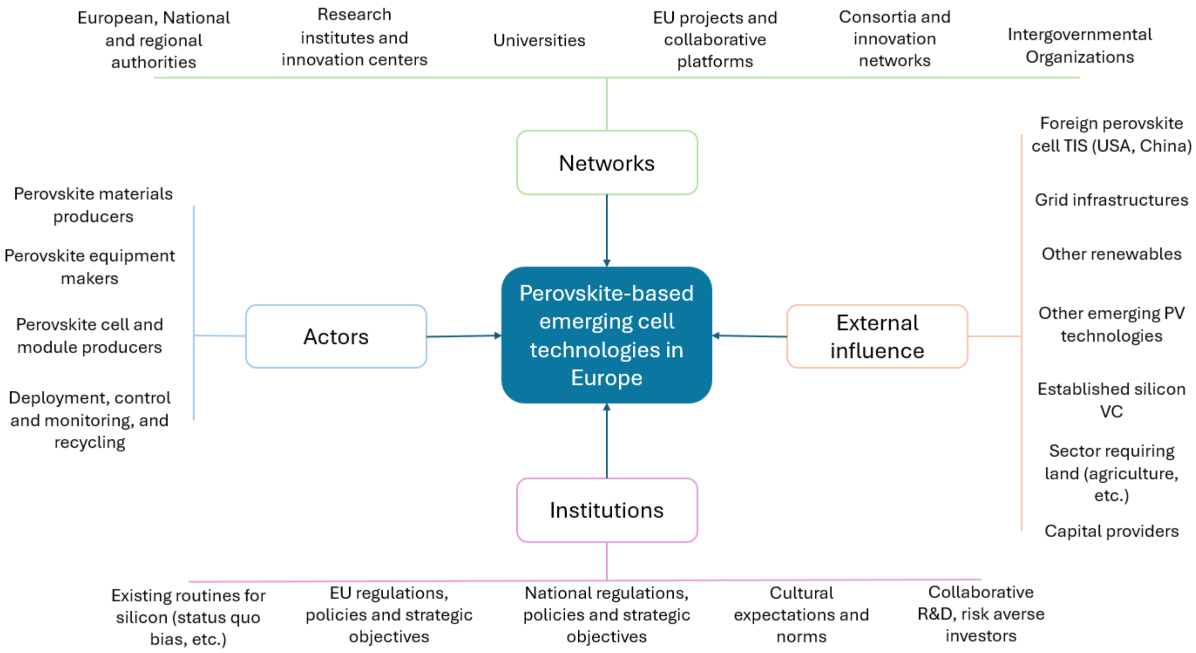

Figure 6 - Summary of the main structural component of the focal TIS

III.2 – Assessment of the TIS development stage and development target

The birth of the solar PV industry occurred with the first Silicon-based PV cell developed in 1954 in Bell Labs and since then, researchers have been looking for new techniques to develop low-cost and more efficient devices (Roy et al., 2020). However, while the natural perovskite mineral was found in 1939, the first solar cell including this material wasn't created until 2009 (Roy et al., 2020). First, the knowledge about perovskite as a PV material was expanded through R&D activities on DSSCs and quantum dot cells (Roy et al., 2020). A few years later, Parker and his coworkers replaced the liquid perovskite in DSSCs with solid perovskite, improving efficiency to almost 10%, its stability and its lifetime, thereby changing the perception of PSCs (Lee et al., 2020; Roy et al, 2020). The following years, many researchers focused on improving the efficiency of the cell using innovative engineering methods (Lee et al., 2020; Roy et al, 2020). Knowledge development was expanding on deposition and solvent engineering process, compositional engineering and interface methods (Lee et al., 2020; Roy et al, 2020). During the period 2012 - 2019, PSC efficiency skyrocketed from 10% to 23,3% thanks to research efforts devoted to optimization of ETL and HTL layers, perovskite composition thickness, manufacturing processes and device structures (Lee et al., 2020; Roy et al, 2020). Today, continuous improvement on these subjects have allowed single-junction PSCs efficiency to reach 27%, which is equivalent to silicon-based cells (Lee et al., 2020; Roy et al, 2020). Now, since the theoretical limit of single-junction cells is around 30%, researchers are trying to address toxicity, stability and area issues (Giannouli, 2021; Lee et al., 2020; Roy et al, 2020). Indeed, high efficiency is only obtained for cells and small modules, but current design and fabrication methods present some limitations in upscaling and must be adapted in scalable processes for commercialization (Giannouli, 2021; Lee et al., 2020; Roy et al, 2020; Figure 7). Moreover, the complex technologies applied to small areas to achieve high efficiency such as composition engineering and antisolvent dripping processes have not been fully upscaled (Giannouli, 2021; Lee et al., 2020; Roy et al, 2020).

In parallel, tandem cells and especially perovskite/Si tandem, have attracted growing attention in the scientific community with a first cell certified by NREL in 2020 (Giannouli, 2021; Figure 8). Tandem cells are either two independent cells, one on top of the other, or a two-terminal device built in series on a single substrate (Giannouli, 2021). Perovskite/Si cells have the potential to overcome the limit of single-junction cells and can capitalize on the mature silicon solar cell industry (Giannouli, 2021).

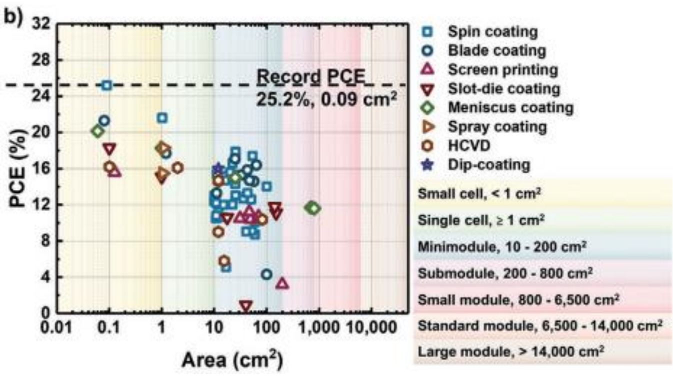

Figure 7 - Efficiency with respect to the area for different fabrication processes. The axis is in logarithmic scale. (Lee et al., 2020)

Figure 8 shows the rapid development of scientific knowledge on perovskite (red and yellow curve) and perovskite/Si tandem cells (brown and yellow curve). Record efficiency for single junction perovskite cells is equivalent to the highest efficiency reached by silicon cells while perovskite/Si tandem cell efficiency is already much higher than any of the other technologies depicted Figure 8. However, these results are for lab cells and Figures 7 and 9 illustrate the knowledge gap between cell and module fabrication. The highest confirmed efficiency for perovskite modules is 21.1% and is achieved by a small module whose size is still far from commercialization standards.

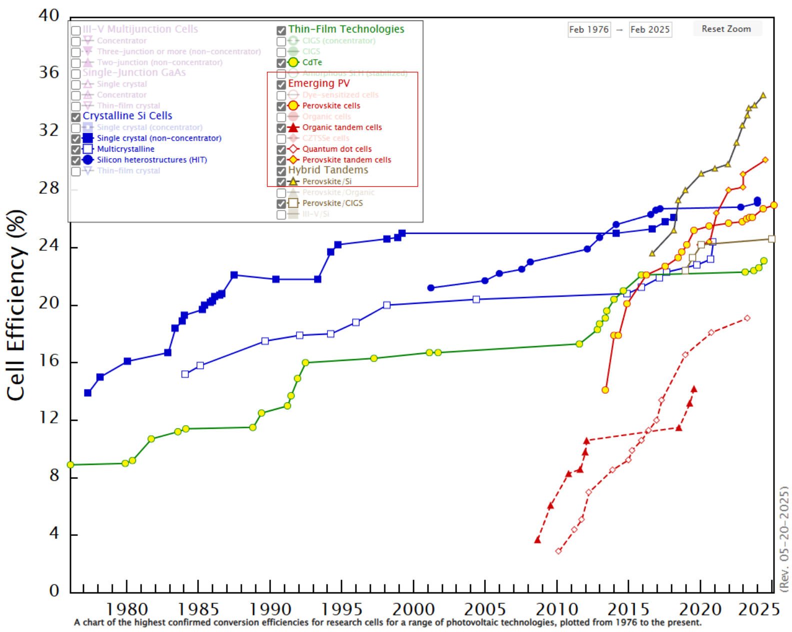

Figure 8 – NREL's Best Research-Cell Efficiency Chart (2025). The two dominant technologies on the market (silicon and CdTe) and some other emerging technologies are included for comparison.

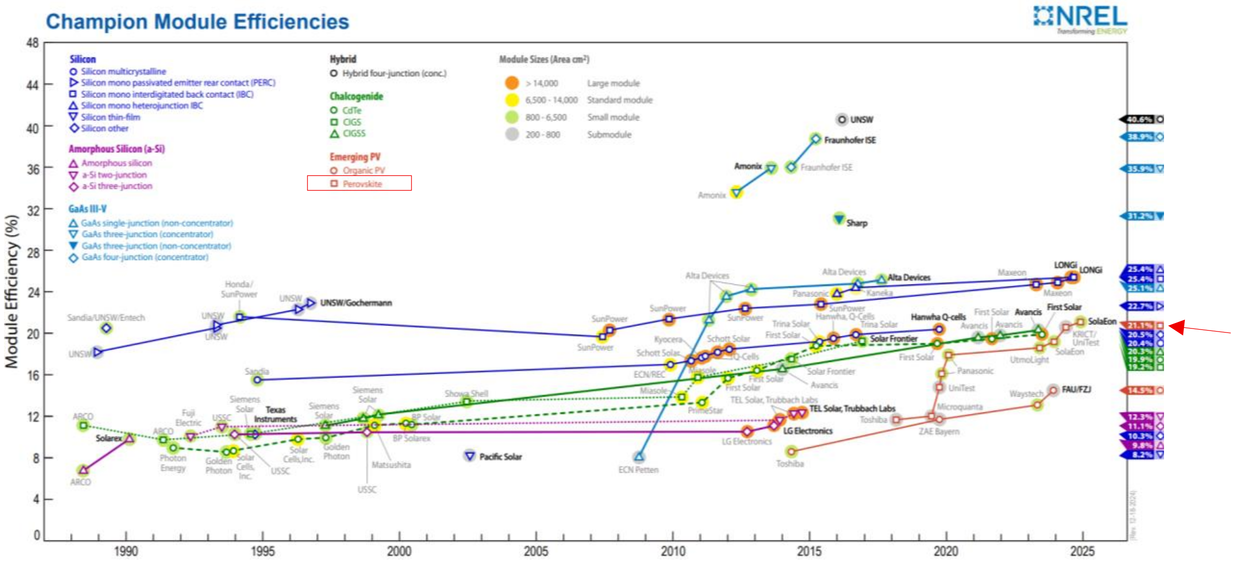

Figure 9 - Highest confirmed conversion efficiencies for champion modules (NREL, 2025)

To reach the objective of large-scale commercialization, PSC need to obtain better performances in the "golden triangle", that is cost, efficiency and lifetime, but also in environmental sustainability and (easy and low-cost) manufacturability. Cost is maybe the best feature of perovskite, with cell efficiency, as PSC use cheap and easy-to-find materials with simple, and therefore less energy consuming and expensive, fabrication processes (Giannouli, 2021). However, to surpass Si-based cells and be deemed interesting for commercialization, manufacturing processes must be developed for large-scale production while ensuring the same high efficiency for modules as for cells. Additionally, deeper knowledge on how to improve long-term stability is crucial. The different actors involved in fundamental research and R&D actively pursue research on novel materials, processing techniques, and device architecture.

To explain the current knowledge on PSCs technology from a technology management perspective, all perovskite-based cells (single-junction or tandem) are in the middle stages of development. According to the European project on perovskite and perovskite/Si tandems (PEPPERONI, n.d.-a), these technologies are at TRL5 and should reach TRL7 by the end of 2026. At TRL 5, these technologies have validated stable and repeatable performance in a relevant environment. By TRL 7, they are expected to demonstrate performances in a relevant environment, including the integration of BoS components into large-scale prototypes. However, progressing beyond level 5 requires overcoming significant technological and economic barriers, such as long-term stability, longer lifetime, and scalable manufacturing processes, that hinder industrial development (PEPPERONI, n.d.-a; ETIP-PV, 2024). As such, coordinated actions are necessary across TRL 2 to 7 to bring these innovations closer to commercialization (Chatzipanagi et al., 2023; Figure 10).

TRL	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2-3	Pb-free TF PV absorbers					Recycling strategies for Pk				
	Low-cost highly performant transparent electrodes									
3-5	Module manufacturing									
5-7	Demonstrate at pilot level Pk modules on glass and on foils for various applications									
7-8			Establish EU pilot lines for Pk modules on glass and on foils							

Figure 10 - Technology targets, research priorities and respective TRLs for the perovskite PV modules in the EU (Chatzipanagi et al., 2023)

Various stakeholders are joining efforts to drive knowledge development on stability, manufacturing, scalability and sustainability. The three main programs implemented by the European Commission indicate a continuous implication of both institutions and firms towards PSCs and PV in general (Chatzipanagi et al., 2023; European Commission, 2024a). Under Horizon 2020 (2014-2020), EUR 455 million was allocated for 140 PV projects (Chatzipanagi et al., 2023). Horizon Europe has an estimated budget of EUR 93,5 billion for the period 2021-2027 from which EUR 172 million and EUR 134 million were allocated for PV projects under the 2021-2022 and 2023-2024 work programme respectively (Chatzipanagi et al., 2023). In line with the current needs of PSC, R&I activities focus on stable, high performance and large area perovskite solar cells and modules. More generally, the areas covered by R&D on PV technologies are novel concepts at cell and module level, alternative equipment and processes for PV manufacturing (including pilot lines for innovative technologies), operation, performance and maintenance of PV systems, recycling of PV modules, resource efficiency in production, and penetration of PV in renewable energy communities (Chatzipanagi et al., 2023). The innovation fund is also participating in bringing to the market industrial solutions to decarbonize Europe but among the 8 current PV projects participating, none of them are focused on PSC. However, they are mostly aiming at developing large-scale manufacturing and new applications (agrivolatics, BIPV, floating), two complementary components that can help the local production of PSC (retention of benefits from innovations) and create a demand for a flexible and lightweight technology like perovskite-based cells (Chatzipanagi et al., 2023).

Thanks to these R&D efforts, and contrary to all the other PV technologies, the number of publications on PSC have known an important growth in Europe between 2012 and 2022 (Figure 11). The same trend can be observed in the rest of the world, which is both positive and negative for the focal TIS. On one hand, if the global scientific community is focusing on PSC, then the chances of improving the knowledge on the technology are higher because of the potential information sharing and knowledge spillovers. On the other hand, the purpose of the TIS is to ultimately become a competitive, strategic and economic advantage for the European Union and local firms. Thus, if other countries find ways to manufacture more efficient and stable PSC before Europe and protect them through IP mechanisms, European firms could struggle to compete (Teece, 1986). Because production costs are usually higher in Europe than in China or in the US, the EU must capitalize on its innovation capabilities to be the first mover and to try to keep the benefits within its borders, as explained by Teece (1986).

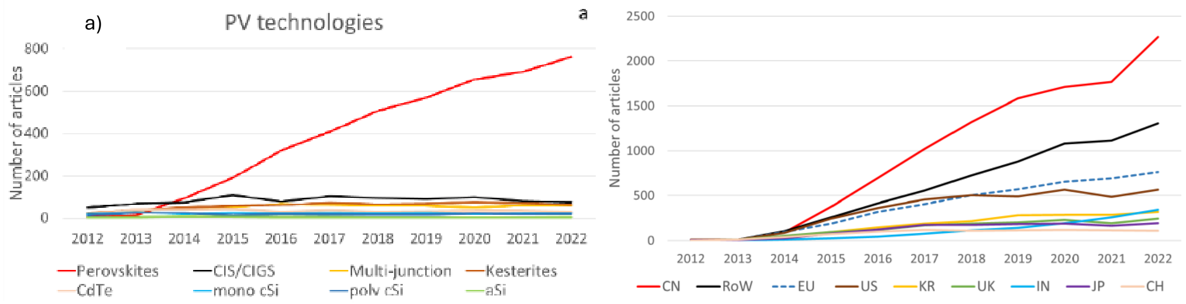

Figure 11 – a) EU publications b) global publications, on PV technologies between 2012 and 2022 (Chatzipanagi et al., 2023)

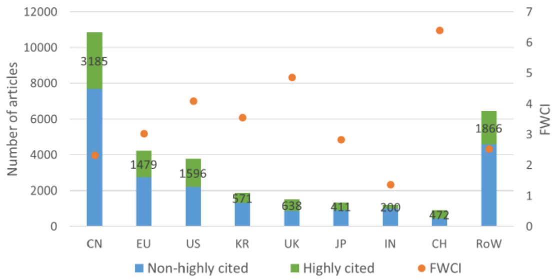

Figure 12 - Global highly cited publication on perovskites and EU position for the period 2012 - 2022 (Chatzipanagi et al., 2023)

The road towards commercialization and market formation is well engaged, with several European companies already preparing demonstration projects and pilot production lines. In 2016, Solaronix (Switzerland) came up with an all printed 500 cm2 perovskite module with 12% efficiency (Solaronix, 2016). In 2016, they collaborated with EPFL and Grätzel group to produce fully printed 100 cm2 PV panels stable over a year (Roy et al., 2020). In 2018, Oxford PV beat the record of efficiency with a perovskite/Si tandem cell reaching an efficiency of 28% (Roy et al., 2020). According to the research team, their tandem cells are efficient, stable and have passed heat and damp reliability tests in line with IEC 61215 standards (Roy et al., 2020). This exploit has attracted bigger players to the PSC market, such as Meyer Burger, the leading European PV equipment and Si modules supplier (Roy et al., 2020). Together with Oxford PV, they have developed a manufacturing line comprising all adaptations required to improve the production of tandem technology (Roy et al., 2020). While their collaboration ended in 2021, Meyer Burger pursues its investment in perovskite/Si cells and capitalize on its established vertically integrated module production chain with a large portfolio of processes, production techniques and machinery to commercialize at an industrial scale this technology (Enkhardt, 2022). Thanks to collaboration with innovation centers, universities and research institutes, they have access to highly skilled workforce and the latest discoveries (Enkhardt, 2022). In the Netherland, the well-established research institute Solliance has developed a large area coating process to scale up the active area of PSC devices without performance loss (Perovskite-info, n.d.). They also collaborated with IMEC (independent nanoelectronics R&D hub) to manufacture 4x4 cm^2 PSC and with Panasonic for the development of roll-to-roll manufacturing processes for large-scale production of flexible PSC (IMEC, n.d.; Roy et al., 2020). Lastly, Saule technologies have been able to print PSCs with lightweight, flexible and semi-transparent single-junction PV modules with 10% efficiency (Roy et al., 2020). Recent achievements of Saule Technologies include an expansion of their line printing capacity from 40,000 m^2/annum to 200,000 m^2/annum and a collaboration with Skanska commercial business unit to cover office buildings with PSCs over commercial scale. This collaboration successfully led to the installation of a commercial prototype composed of 72 encapsulated PSC modules (Perovskite-info, n.d.; Roy et al., 2020; Saule Technologies, 2018). However, in May 2025, Saule Technology apparently faced financial difficulties that might trigger internal changes or even bankruptcy (PolskieRadio, 2025).

PSCs present many particularities, such as its flexibility and suitability for vertical facade, the possibility to be produced in different colors and on various surfaces, to work under artificial and low-scattered light or to be made semi-transparent, that create opportunities for specialized applications. Consequently, the building-integrated PV industry is particularly interested in this technology for windows, roofs, architecture and PV materials applications (Solak & Irmak, 2022; Wojciechowski et al., 2019). PSC's light weight combined with its flexibility leave room for other applications such as vehicles and wearable devices (Solak & Irmak, 2022) but these markets are not as developed as BIPV (Chatzipanagi et al., 2023).

In summary, the development of perovskite cells is marked by rapid knowledge development, extensive R&D activities conducted by research institutes, startups and established PV firms, and a growing interest from formal institutions (i.e., national governments and the EU). Despite impressive laboratory-scale progress in terms of efficiency, the system remains constrained by persistent challenges, particularly regarding long-term stability, toxicity, and the lack of scalable manufacturing solutions. As illustrated in Figure 13, the perovskite-based solar cell (PSC) Technological Innovation System (TIS) in Europe is currently in the demonstration phase, supported by pilot production lines and small-scale deployment projects. However, commercial uptake remains very limited, and no mass-market products are yet available. Due to technical hurdles and the limited feedback from recently launched pilot projects, the system has not yet reached the niche market phase. Advancing to that stage will require continuous R&D, further demonstration efforts, and progress on several fronts: improving stability, reducing toxicity, optimizing industrial-scale manufacturing, and producing commercial-size modules with competitive efficiency.

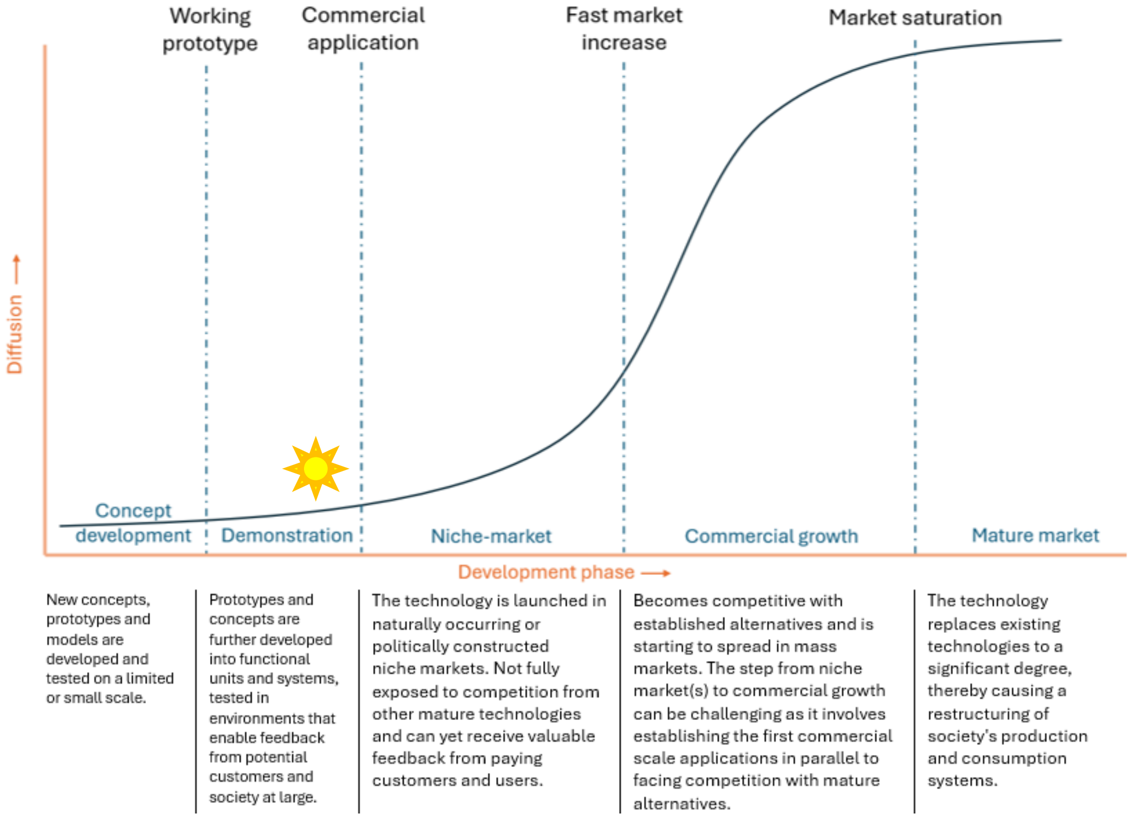

Figure 13 - Development phases for the focal TIS, the current stage is represented by the sun (adapted from Van Noord et al., 2023)

This analysis provides the necessary context to understand where the system stands in terms of technological readiness and commercial maturity. It also lays the groundwork for the next section, which will examine what future developments are needed to reach commercialization targets and what systemic challenges the TIS might face, especially those where public policy can play a decisive role in supporting the transition from demonstration to niche market adoption.

III.3 – Future development needed to achieve the target and associated challenges

While technical improvements and knowledge development are necessary to bring PSCs to market, strengthening the TIS functionality is also crucial (Bergek et al., 2008). In this section, three functions are particularly discussed: Market formation, legitimation and resource mobilization.

III.3.1 – Market formation

The focal TIS is in the demonstration phase, which means that the next development stage is the niche market creation. Therefore, the question of what market and how to facilitate its formation must be addressed to anticipate potential blocking mechanisms. The emergence of a market for PSCs is shaped by intense competition from the dominating c-Si technology, which accounted for approximately 95% of global PV market share in 2023 (Chatzipanagi et al., 2023). Over several decades, c-Si has benefited from continuous process innovation, large-scale industrialization, and a steep learning curve, which have driven down costs dramatically (IRENA, 2024). According to IRENA (2024), the global weighted-average LCOE[4] from utility-scale solar PV fell by 90% between 2010 and 2023, from USD 0.460/kWh to USD 0.044/kWh. This reduction is primarily due to declining module prices, which dropped from USD 0.568/W to USD 0.145/W in Europe, followed by decreases in balance-of-system (BoS) and installation costs (IRENA, 2024). This aggressive cost decline has tightened margins across the value chain, threatening the re-building of PV manufacturing in Europe and the survival of the few European companies left (Chatzipanagi et al., 2023). Ultimately, it also raises the entry requirements for emerging technologies like PSCs, which must match or surpass not only the cost-efficiency of c-Si, but also its proven reliability and bankability. While PSCs offer theoretical advantages such as high efficiency potential, low-cost materials, and compatibility with flexible or tandem applications, their commercial scalability remains limited.

Reese et al. (2018) suggest that an investment of $0.2-1 billion is required to incubate a new entrant and to reach 1 GW of production for a new PV technology like perovskite.

[4] The Levelized Cost of Energy is a metric for gauging the average cost of electricity generation over the lifetime of an energy asset. LCOE can be determined by dividing an energy asset's total lifetime costs by the asset's total energy generation over its life cycle (Gomstyn & Jonker, 2024).

However, this assumes the most optimistic scenario, with rapid scalability, minimal learning costs, low capital expenditure, low energy expenditure, and 75% of all costs attributed to materials. Mathews et al. (2020) have analyzed potential growth paths for perovskite manufacturing. The cost model for roll-to-roll perovskite manufacturing indicates module costs ranging from $3.30/W at a very small scale (0.3 MW/year) down to $0.53/W at 1 GW/year. Due to technological risks like stability and Pb toxicity, entering the mainstream utility-scale market requires a large upfront investment to establish a profitable manufacturing facility (over $1 billion for a target selling price of around $0.40/W). However, they also provide solutions to lower the entry barriers: 1) finding disruptive, lower-cost materials, reducing initial investments to about $40 million at 1 GW/year scale, or 2) focusing on niche markets such as IoT devices, building-integrated photovoltaics, and vehicle integration, where higher selling prices allow initial investments as low as ~$1 million. For tandem modules, existing silicon manufacturers could accelerate growth by co-investing in perovskite tandems, assuming successful scale-up with high efficiency and manageable degradation and toxicity issues (Mathews et al., 2020).

Furthermore, the utility-scale PV market is particularly competitive. Procurement decisions are mostly based on proven cost-efficiency and performance metrics under competitive auctions (IEA, 2024). With c-Si module prices continuing to decline due to economies of scale in China and global supply chain optimization, PSC developers might struggle to offer a compelling value proposition without significant support through public procurement, demonstration projects, or green premium mechanisms. Consequently, creating and niche a market for PSCs will require a mix of targeted subsidies, regulatory clarity, and risk-mitigation instruments that can help de-risk early investments and allow the technology to mature alongside established PV solutions. This challenging market environment highlights the importance of achieving strong legitimacy, both technical and institutional, among different stakeholders to obtain the necessary support mechanisms for PSC commercialization.

III.3.2 – Legitimation

According to Bergek et al. (2008), the process of legitimation is crucial for the formation of a new industry or a new TIS. In this context, legitimacy is defined as the extent to which the technology is perceived as appropriate and desirable by relevant actors and is a matter of both social acceptance and compliance with relevant institutions. Technology has to be considered legitimate for resources to be mobilized, for demand to form and for actors in the new TIS to acquire political strength (Bergek et al., 2008a). In the light of the development stage and target of the European PSC TIS, the perceived legitimacy of this technology by industries, society and formal institutions will play an important role in the success of its transition from demonstration to niche market and eventually mass-market adoption. As a starting point, PSC can leverage the established legitimacy of c-Si cells since their massive deployment has demonstrated the benefits of photovoltaic as an energy production source. As illustrated by Figure 14, the EU PV cumulative installed capacity is growing in all countries. This trend shows that photovoltaic is an attractive source of energy and has the support of governments for their deployment.

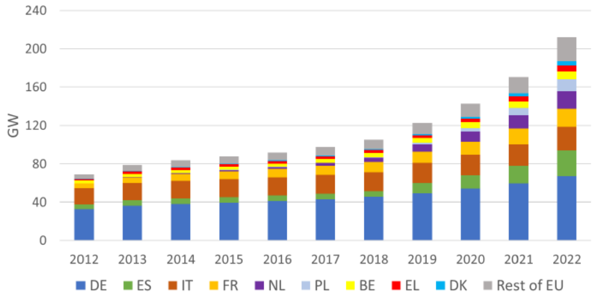

Figure 14 - EU PV cumulative installed capacity per country for the period 2012 – 2022

In particular, the REpowerEU plan implemented in 2022 by the European Union aims at reducing its dependence on foreign fossils fuels, decarbonizing the industry and accelerating the deployment of renewable energy sources (European Council, 2025). Governments are receiving subventions to invest in RES[5] and the related infrastructure and to implement regulations and measures that support the deployment of RES (European Council, 2025). Additionally, REpowerEU sets targets for RES installed capacity to reach 1 236 GW, including at least 592 GW of solar, by 2030 (IEA, 2024). National and European objectives for solar PV, associated with strategic plans, regulations and investments, accentuate the legitimation of PV technology. However, newly added solar capacity is dropping (Figure 15), and projections for the next 5 years are following the same path (Figure 16). This decline may suggest a lack of incentives to invest in PV technologies, which could in turn hinder the deployment of emerging perovskite cells. Investors may be particularly hesitant to invest in new technologies in a market that appears to be losing its momentum. The reasons behind this phenomenon should be carefully investigated to understand why photovoltaic is not as attractive as it has been and if new technology is the solution to re-dynamize the industry.

If the legitimacy of photovoltaics is established, demonstrating the legitimacy of perovskite and perovskite/Si tandem cells as an alternative to c-Si cells is crucial and must be enhanced to secure investments required for its commercialization. As argued

[5] Renewable Energy Sources

in section II, PSC must be perceived as more legitimate than other solar technologies, especially Silicon-based cells. The main criteria that make a solar cell desirable are efficiency, costs, lifetime, manufacturability and environmental sustainability (Chalkias et al., 2022; Martulli et al., 2023; Raman et al., 2021; Tang et al., 2024). The legitimacy of perovskite is assessed based on those criteria for different groups of stakeholders that influence the TIS development: Formal institutions, PV firms, businesses and individuals.

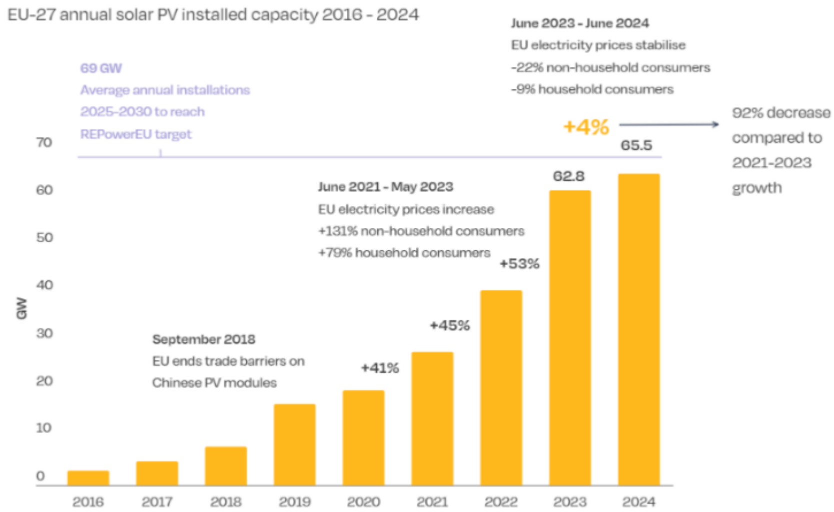

Figure 15 - EU annual solar PV installed capacity 2016-2024 (SolarPower Europe, 2024)

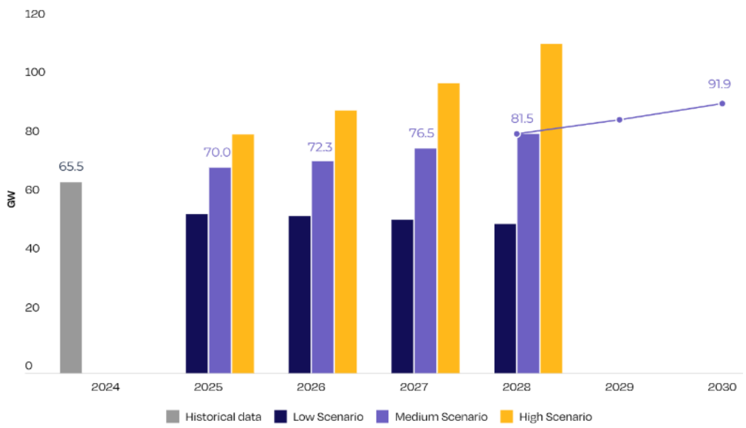

Figure 16 - EU-27 annual solar PV installed capacity scenarios 2024-2030 SolarPower Europe, 2024)

Businesses and homeowners are the end customers of solar modules so their attitude towards the technology is a significant parameter for successful commercialization. The literature review and survey of European stakeholders conducted by Peñazola et al. (2022) highlight potential adoption enablers and barriers for solar PV panels and heat pump. Economic concerns are the main barriers to PV adoption and in particular high investment costs, the long and uncertain payback period, the lack of government support and the inadequate subsidies. However, people are generally curious about new renewable technologies and can be sensitive to the associated environmental and social benefits. A well-developed market, well-designed policies and the availability of relevant information are determinant factors for PV technology to be perceived as legitimate. According to Van Opstal & Smeets (2022), many studies indeed stress the importance of economic factors, government policies and the perception of benefits solar PV brings for the residential market. Additionally, peer effects and environmental norms influence the adoption of solar panels (Van Opstal & Smeets, 2022). For commercial and public infrastructures, self-sufficiency, the development of electric cars and green energy loans are parameters taken into consideration before investing in PV (Van Opstal & Smeets, 2022).

Beyond end-user perceptions, the legitimacy of perovskite PV technologies also critically depends on how they are perceived within the business ecosystem, particularly by firms operating in the photovoltaic sector. For these firms, legitimacy relates not only to the technological feasibility and market potential of perovskite solar cells but also to the alignment of the technology with existing business models, value chains, and regulatory expectations (Bergek et al., 2008a; Pero et al., 2010; Teece, 1986). Firms are unlikely to commit significant resources to a technology that lacks proven performance, predictable policy support, or broad social acceptance. Teece (1986), emphasized that, for firms to benefit from innovation, they must be able to access complementary assets such manufacturing capacity, distribution networks, and supply chain infrastructure. If a new technology does not integrate well into these existing structures, or if the assets needed to support it are lacking or controlled by incumbents, firms may hesitate to invest. In this context, PSC technologies must align with existing infrastructure and supply chains and comply, create or manipulate informal institutions (Bergek et al., 2008a; Teece, 1986). On one hand, PSC offers an attractive value proposition compared to incumbent c-Si technologies. For instance, whereas silicon solar cells require energy-intensive production of pure silicon, complex and costly manufacturing processes, special facilities and emit important amounts of greenhouse gases, perovskite materials can be solution processed using low-embedded energy manufacturing techniques (Bati et al., 2023). However, the current lack of well-developed complementary assets and the limited integration of PSCs into the existing PV value chain not only slows down the diffusion of the technology but also weakens its perceived legitimacy among industrial actors. Additionally, the current state of the c-Si technology industry in Europe illustrates how sensitive this sector can be to the economic, political and global context (Chatzipanagi et al., 2023; Fichtner, 2024; Métayer, 2024; NorSun, 2024). For example, because they couldn’t compete with Chinese importation of low-cost c-Si modules, many companies in the upstream and middle stream of the silicon VC downscaled or to filed for bankruptcy (Chatzipanagi et al., 2023, Fichtner, 2024; Métayer, 2024; NorSun, 2024). Besides, firms are hesitant to make large capital investments in technologies that have uncertain or fluctuating policy support, limited standardization, or ambiguous market signals (Blind, 2016; Gulen & Ion, 2016; Kang et al., 2013). This means that the institutional context, such as the presence of clear incentives or public procurement support, plays a vital role in fostering the legitimacy of PSCs among firms. Without a stable and credible policy framework and a clear path to market alignment, perovskite technologies may be perceived as too risky or premature, even if they hold long-term promises. Overall, coordinated efforts to develop and diffuse complementary technologies, encourage vertical and horizontal collaboration, and provide policy and financial support are required for the formation of an integrated perovskite innovation system.

In the European context, the legitimacy of PSC technology is not only a matter of market or technical performance but also depends on whether the technology aligns with expectations, priorities, and standards of formal institutions at both EU and national levels. These institutions, such as governments, the European Commission, national energy regulators and funding agencies, assess the legitimacy of technology based on its contribution to strategic objectives, including energy sovereignty, industrial competitiveness, local employment, local employment, resource efficiency and climate neutrality (Chatzipanagi et al., 2023; European Commission, 2024b; Strategic Technologies for Europe Platform, n.d.). For PSCs to be institutionally accepted, they must demonstrate alignment with key policy frameworks such as the European Green Deal, REPowerEU, the Critical Raw Materials Act and the Net Zero Industry Act. By enabling low energy and low-cost manufacturing, using less rare materials while offering higher efficiency, lightweight and flexible devices, they align with EU strategic goals. Nevertheless, current concerns such as toxicity or limited field-tested stability question their compatibility with existing environmental and safety regulations. The positive attitude of the scientific community towards the potential of PSCs, along with the various possibilities to overcome their drawbacks, seems to be currently sufficient to attract investment from the EU. However, as technology approaches commercialization, it must overcome regulatory uncertainties and present robust, transparent evidence of its safety, sustainability, and scalability.

In summary, establishing the legitimacy of perovskite solar cell technology among diverse stakeholders, ranging from end users and businesses to formal institutions, is a critical prerequisite for its successful development and diffusion within the European photovoltaic innovation system. Legitimacy shapes perceptions of risk, desirability, and alignment with broader strategic goals, thereby influencing the willingness of actors to support and engage with PSCs. As legitimacy consolidates, it lays the essential foundation for resource mobilization, enabling the acquisition of financial, human, and organizational resources necessary to advance PSCs beyond demonstration and niche markets toward large-scale commercial deployment.

III.3.3 – Resource mobilization

Going from the demonstration phase to the niche market phase requires the mobilization of different resources (Bergek et al., 2008a). Bergek et al. (2008) mention the mobilization of human, financial and complementary assets resources as critical for the development of a TIS (Bergek et al., 2008a). The availability of human resources is left out because of the complexity of finding relevant data. The capacity of mobilizing financial resources requires a deep analysis of the source of capital available for the different actors in the TIS, which is a subject on its own and an area of research in the academic community and within national and European institutions. Therefore, it is only addressed in a superficial manner, including current public and private investment trends in PV technologies, and should be further studied. Due to the novelty of the system, the level of complementary assets is lower than what is necessary for the commercialization of the technology. The supply chain, manufacturing capacities and fabrication processes challenges related to PSCs have already been covered, at least partially, in the previous sections. Therefore, potential issues related to poor complementary assets infrastructure concerns specific details (i.e., PV glass supply, grid integration and development, permit granting and queue, land availability) to illustrate the complexity of the environment in which the TIS is developed.

Financial resources

It has been previously determined that perovskite cells are currently between TRLs 5 and 7, which correspond to the Valley of Death phase as described in the literature review. During this phase, technology usually faces a funding and coordination gap between public and private actors that hinder the transition from a prototype to a commercial technology (Tassey, 2014). This issue arises when governments reduce support prematurely, assuming private actors will fill the gap, but the commercial viability and competitive benefits of the technology are not sufficiently proven to attract private investments (Tassey, 2014). Muscio et al. (2023) found that this problem is widely observed for renewable energy technologies but less for the specific case of photovoltaic as silicon-based modules have proven the benefits PV. For example, Horizon 2020, a European program aimed at fostering green innovation, was supposed to expand funding opportunities for renewable projects, but it has been shown that resources were mainly allocated to low TRLs projects and scarce for intermediate to high readiness levels (Héder, 2017; Muscio et al., 2023). Firms also criticize the absence of connection and synergies between the different public funding sources and are in favor of a strong and coordinated European funding network to ensure coherence from basic research to deployment of innovative technologies (Muscio et al., 2023). The resulting fragmentation and inefficiencies limit commercialization and production scale-up prospects.

Between 2010 and 2019, R&D funding in the European Union for all photovoltaic technologies was heavily dominated by private investments, which accounted for approximately 82-89% of total funding (EUR 0.8 to 1.8 billion annually), while public investments made up only 11-18% (EUR 173 to 233 million annually) (Chatzipanagi et al., 2023). Figure 17 and Figure 18 illustrate the evolution of EU public investment and cumulative private investment during the period 2010-2021 and 2010-2019 respectively. Figure 19 shows the evolution of annual private investment in the EU and globally.

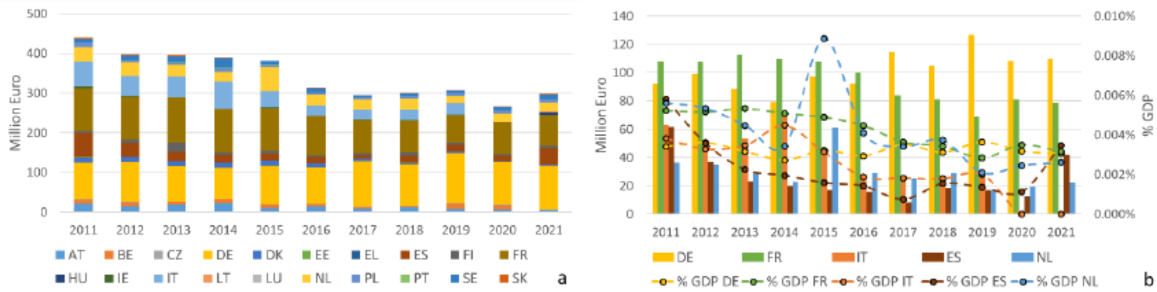

Figure 17 - (a) EU public investment per Member States (MS) and (b) EU public investment and % of GDP in Solar and R&D for the top five MS (Chatzipanagi et al., 2023).

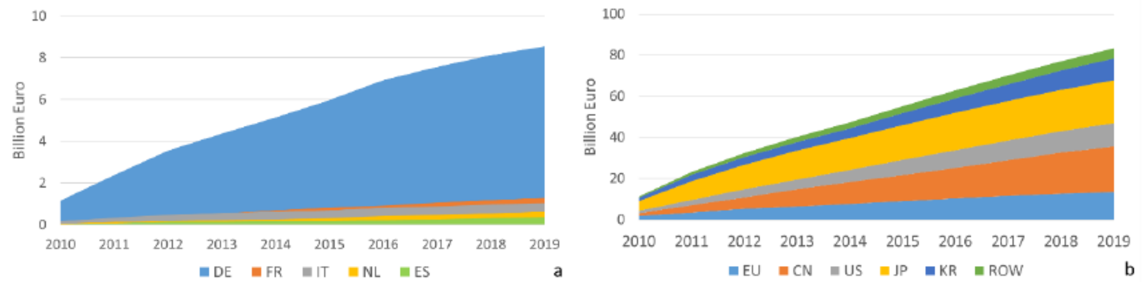

Figure 18 - (a) EU cumulative private investment in PV per MS and (b) global cumulative private investment in PV EU and top five countries for the period 2010-2019 (Chatzipanagi et al., 2023).

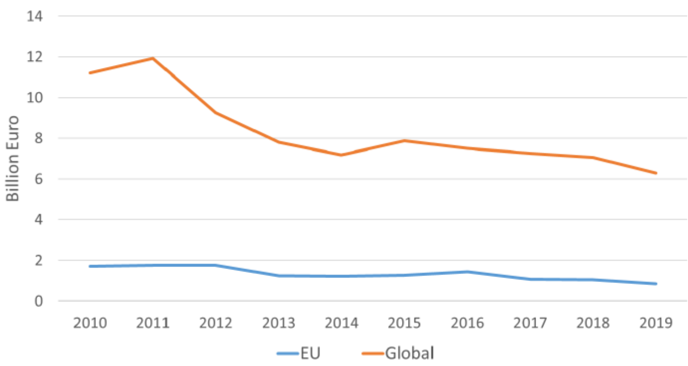

Figure 19 - EU and global private investment in PV for the period 2010-2019 (Chatzipanagi et al., 2023)

These figures show a decline in private investments in the EU of 53% between 2010 and 2019, far outpacing the 8% drop in public funding (Chatzipanagi et al., 2023). Globally, the pattern was reversed, with private investments decreasing less sharply than public ones (Chatzipanagi et al., 2023). This decline in EU private funding is particularly concerning for PSC development across the mid-to-high TRL stages where financing gaps can be dramatic for new technology. To prove that a VoD phenomenon is occurring, more research needs to be done to determine toward which stage of development the remaining public and private investments are made. If the general statement about the Valley of Death is accurate, that public funding tends to focus on early-stage research with social and environmental benefits while private investors prioritize later-stage projects with clearer economic returns, PSC technology might struggle to secure sufficient capital to progress from lab-scale validation to market-ready products. Furthermore, public investments are very unequal across Member States (MS), with Germany, France, Italy, Spain and the Netherlands accounting for most national spending in PV technologies. While France and Germany have a relatively stable PV energy public investment in terms of percentage of their GDP (0.003 – 0.004%), Spain, Italy and the Netherlands' spendings are more unstable. Because R&D investment involves a long-term commitment, uncertainty in public R&D spending has a negative impact on the R&D activities of firms and therefore the development of technology (Guellec and Van Pottelsberghe de la Potterie, 2000). Moreover, past instability is taken by firms as a signal of likely future change (Guellec and Van Pottelsberghe de la Potterie, 2000), which discourages them from investing in the development of technology. The legitimacy of PSCs and their commercialization can suffer from this pattern, especially since improving performance, stability and developing manufacturing capacities require long-term investment from all stakeholders.

As illustrated by Figure 20, venture capital (vc) investments offer a recent signal of shifting dynamics. The period 2014 – 2017 was characterized by low to negative growth in vc investment, but recently, global vc funding in photovoltaic companies increased to reach EUR 2.2 billion in 2022 (Chatzipanagi et al., 2023). However, this growth is largely driven by Chinese firms, which captured 62% of global early-stage and 39% of later-stage investments during the 2017-2022 period, totaling EUR 2 691 million (Chatzipanagi et al., 2023). In comparison, European early-stage venture capital investments have reached EUR 135 million over the same period and, by capturing only 9% of global share (vs 15.5% over 2016-2021), its position in global investment has further weakened (Chatzipanagi et al., 2023). Late-stage investments in Europe totaled EUR 910 million over 2017-2022, concentrated in Germany and Sweden, and accounting for 21% of global share (vs 16% over 2016 – 2021), but the EU still lags behind the US and China (Chatzipanagi et al., 2023).

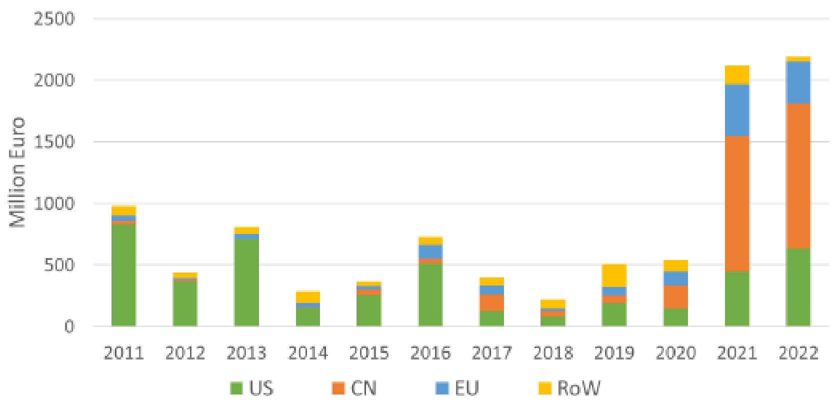

Figure 20 - EU and global total Venture Capital investments for the period 2011-2022

This underperformance reflects a structural weakness in the EU capital market (ESMA, 2024) that reduces the ability of the TIS to mobilize capital toward scaling PSC technologies. Additionally, while public grant funding remains a key support mechanism, if private and VC investments do not keep up then these funds will become insufficient to compensate for financial resources shortage or to overcome the systemic funding gap in intermediate TRLs.

Complementary assets

While securing financial resources is crucial for innovation, the successful commercialization and upscaling of PSCs also depend on the availability of well-developed complementary assets, resources and infrastructures that support production, deployment, and system integration (Bergek et al., 2008; Teece, 1986).

Reducing the dependency on critical and rare materials is one of the strategic objectives of the European Union (Chatzipanagi et al., 2023). Therefore, Jean et al. (2015) state that ambitious targets of PV deployment must be accompanied by the consideration of scaling of materials. They have estimated the amount of raw materials required if one PV technology had to supply 5%, 50% and 100% of 2050 global electricity demand. When considering the last scenario, the equivalent of a few years of global silicon production is required for c-Si cells, 34 years of global cadmium production and 1500 years of global tellurium production for CdTe thin-film, and a few days of global perovskite production for PSC. Regarding glass, a material needed in all PV technologies, they estimate that the equivalent of more than 10 years of production is needed to reach 100% of 2050 global electricity demand with PV. While they do not consider the latter as a major commodity constraint, their conclusions overlook the geopolitical and economic challenges. Indeed, PV glass is lacking in the EU and must be imported in large volumes from China, a strategy that increases the EU dependence on foreign countries and the costs because of customs duties (Chatzipanagi et al., 2023). Moreover, manufacturing glass is very energy-intensive and therefore costly. This last point may limit investment initiatives from companies already in the sector or new players attempting to enter the market (Chatzipanagi et al., 2023). PSCs might be less demanding in critical raw materials, but glass remains essential to module production and for the encapsulation techniques required to preserve the stability and lifetime of this technology (Emery et al., 2022; Giannouli, 2021; Jean et al., 2015; Raman et al., 2021). Building up domestic manufacturing capacity for PV glass is thus a strategic necessity to enable the competitive scaling of perovskite and tandem solar modules in Europe (Chatzipanagi et al., 2023).

Regarding complementary infrastructures, Teece (1986) highlights the necessity of establishing a robust value chain to capture the benefits of innovation. In the case of PSCs and tandem solar cells, this aspect is critical due to the need for specialized production processes. However, Europe's fragmented and mostly offshore Silicon value chain limits domestic firms' ability to scale PV innovations, leaving them dependent on foreign suppliers (Chatzipanagi et al., 2023). The importance of increasing manufacturing capacities has been discussed throughout the analysis, so they are not further discussed here. However, grid-related factors have not been discussed while they constitute a set of crucial complementary assets (IEA, 2023; IEA, 2024). The development of PSCs is tied to the development of photovoltaic in general, which is in turn dependent on the ability of grid infrastructure to integrate high shares of intermittent energy (IEA, 2024). According to IEA (2023, 2024), the expansion of renewable energy in Europe is slowed down by lengthy permitting waiting times, a lack of long-term planning leading to inadequate grid infrastructure that delays solar PV plant connections and insufficient system flexibility to cost-effectively integrate RES. Solar PV remains the dominant technology waiting for grid connection requests (more than 60%) because of its fast development the past years (IEA, 2024).

Grid connection requests have reached 1 500 GW for advanced stage PV and wind projects in the United States, Spain, Brazil, Italy, Japan, the United Kingdom, Germany, Australia, Mexico, Chile, India and Colombia combined, which represent 5 times the capacity additions of solar PV and wind in 2022 (IEA, 2023). The need for grid development is hindering the deployment of PV projects because developers face an increasingly long process and financial burden to get their grid integration permit (IEA, 2023). For instance, in the Netherlands, grid congestion due to high solar PV and wind capacity additions has made some regions unable to accept new capacity during the period 2021-2029, with grid upgrades planned for 2026-2029 (IEA, 2023). On top of longer approval processes, grid congestion can result in the curtailment of renewable energy (i.e., intentional reduction of instantaneous power from generation resources or demand consumption to help balance supply and demand on the grid). When the supply of solar power surpasses the demand, operators cannot further integrate the available power and, in the absence of storage, export possibility or demand-side participation, they curtail. Curtailment is a cost-effective alternative to network expansion when installing VRE[6], but too much curtailment reduces economic benefits, limits VRE contribution to the energy mix and therefore the decarbonization of the grid (IEA, 2024). In the current context of fast PV deployment combined with infrastructure and system integration that are unable to keep pace, the number of curtailment situations is increasing (IEA, 2023; IEA, 2024). In summary, the current grid congestion can lead to increasing connection queues or to the curtailment of current installed PV capacity (IEA, 2023; IEA, 2024). These two situations might result in project developers cancelling plans if they deem their investment too risky (IEA, 2023). IEA (2023) concludes by arguing that slower progress in grid infrastructure development significantly restrains the scale-up of solar PV across all regions. So, if investments in renewable energy continue to outpace grid investments in Europe, PSCs might face additional challenges to both attract investment and reach commercialization.

[6] Variable Renewable Energies, such as wind and solar power.

III.3.4 - Summary

The following figure summarizes the challenges associated with each function and the overall risks for the development of the TIS.

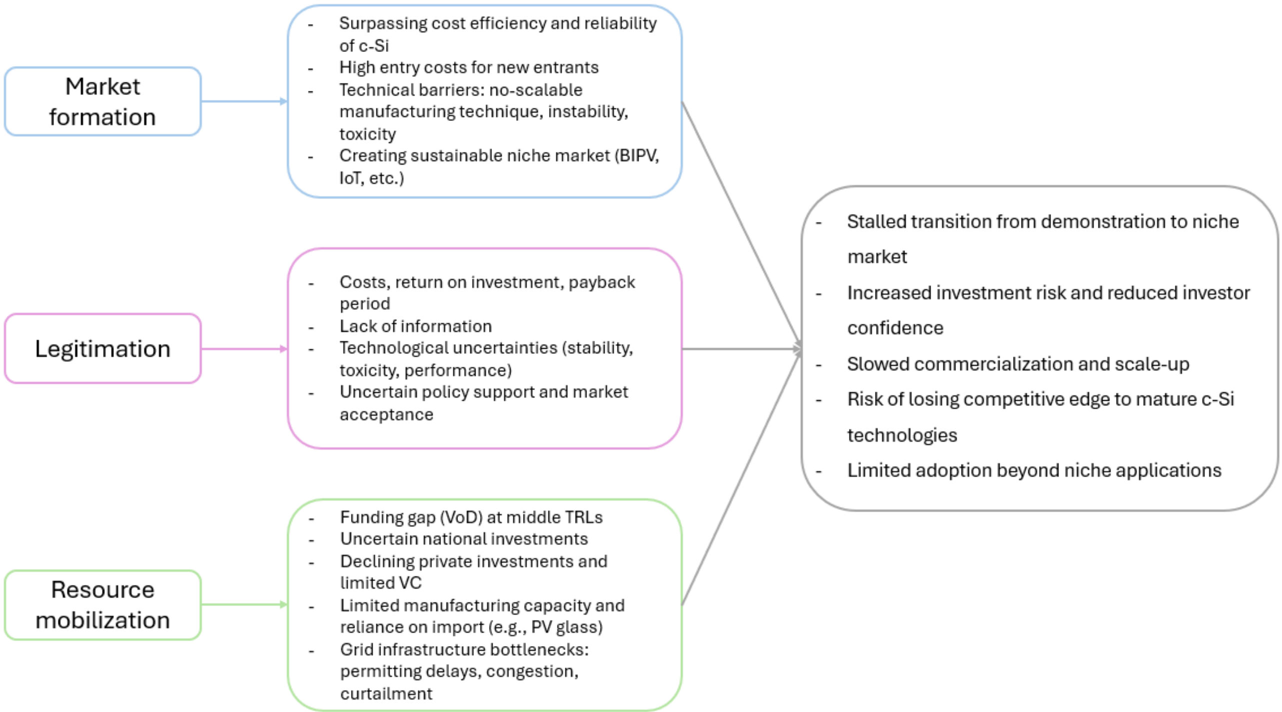

Figure 21 - Summary of challenges in the European emerging perovskite-based PV cell TIS

IV – Key focus areas for policymakers to enable solar cell innovation and commercialization

The literature agrees that technological innovation is highly impacted by policies and regulations, and particularly renewable energy expansion (Amber et al, 2011; Shafiullah et al., 2022; Lund, 2008; Oduro et al, 2024; Peters et al, 2012; Wen et al., 2020). According to IEA (2024), renewable energies are becoming more competitive, but policies remain a key factor for investment and deployment of PV technology. Globally, 84% of renewables utility-scale capacity growth is expected to be stimulated by policy schemes for the period 2024-2030 (IEA, 2024). For the specific case of PV capacity growth, IEA (2024) anticipates that around 75% will be policy driven while 20% will be market-driven during the next 6 years. Policy-driven deployment refers to the capacity for which government policy is the primary driver for investment decisions. The most popular policies are administratively set tariffs and premiums (2/3), competitive auctions (1/5) and tax credits (15%) (IEA, 2024). Market-driven deployment refers to PV capacity for which market forces, such as cost competitiveness, supply and demand dynamics, and technological innovation, are the primary drivers for investment decisions. It mainly encompasses bilaterally negotiated contracts between independent power producers and consumers (40%), green certificates (40%), unsolicited bilateral contracts with utilities (16%) and merchant projects (4%) (IEA, 2024). In Europe, 77% of renewable capacity growth will be policy-based during the period 2024-2030, with competitive auctions accounting for ¾ of utility-scale growth, followed by corporate PPAs[7] to a lesser extent (IEA, 2024).

IV.1 - Description of current policies among a selection of European countries

A non-exhaustive review of policies implemented by different European countries (i.e., Austria, Denmark, France, Germany, Italy, the Netherlands, Spain and Sweden) has been conducted based on IEA policy database (IEA, n.d.) and the national survey reports accessible on the IEA PVPS website and is illustrated in Appendix 4 (Austrian Technology Platform Photovoltaic & Fechner, 2022; Bernsen, 2023; De L'Epine, 2023; Donoso et Behar, 2022; Oller Westerberg et Lindahl, 2022; Tilli et al., 2022). Only policies implemented and/or still in force after 2015, unless otherwise specified, and targeting the development of renewable energy and solar PV are considered.

Policy	Countries	Details
Feed-in tariffs (FiT)	AT, DE, DK, FR, IT	Long-term contracts between producers and governments to guarantee the purchase of energy at a fixed price
Feed-in premium (FiP)	DE, DK, FR, IT, SE	Producers sell their electricity above the market prices
Green certificates	SE, NL	An official record proving that a specified amount of green electricity has been generated. They represent the environmental value of renewable energy production. The certificates can be traded separately from the energy produced.

[7] Corporate power purchase agreement: long-term contract between a corporation (typically a large buyer of electricity) and a renewable energy producer (such as a wind or solar project developer) to purchase electricity at a predetermined price for a fixed period of time, usually 10 to 20 years

Renewable portfolio standard (RPS)	DK, IT, NL (before 2003, no data found after this date)	Obligation on electricity retailers to use a certain amount of electricity from new energy
Self-consumption	AT, DE, DK, ES, FR, IT, NL, SE	Self-consumption authorized, exemption from electricity taxes and other tax-credits, VAT deduction based on the quantity of electricity resold, compensation for electricity trading companies and grid owners, etc.
Net-metering	NL	Allow consumers to offset excess solar production at time *t* against later consumption, valuing both at the same price
Net-billing	ES, FR, IT, NL	Encourages consumers to sell electricity to the grid when prices are high and to consume when prices are low, aligning with supply and demand signals
Collective self-consumption and delocalized net metering	AT, ES, FR, IT, NL, SE	Enables multiple consumers to share solar energy produced on-site or from a remote location within a defined area
Sustainable building requirements	AT, DE, DK, ES, FR, IT, NL, SE	Requirements regarding the percentage of RES used in new buildings
BIPV incentives	AT, FR, IT	Policy instruments tailored to promote building-integrated photovoltaic applications
Procurement procedures	DE, DK, ES, FR, IT	Calls for PV projects, tenders, auction, non-price criteria in auctions (FR, GE)
Guarantee of origin	SE	Producers receive one GO per MWh generated from RES, which can be sold to utilities seeking to label their electricity as renewable

Direct financial support: investments, grants and incentives	AT, DE, DK, ES, FR, IT, NL, SE	Direct investments in upskilling, local manufacturing, R&D, RES innovation projects, etc. include also capital subsidies

Table 1 - Summary of the main types of policies implemented after 2015 in a selection of European countries

Table 1 highlights the diversity of policy instruments adopted across European countries since 2015, revealing both national similarities and specificities in supporting PV deployment. Direct financial support mechanisms, such as grants and subsidies, appear to be one of the most widely used instruments. These investments are used to support different parts of the innovation system, depending on the government's current objectives and perceived needs. For instance, many countries provide R&D support to foster technological development (Figure 13), which contributes directly to knowledge development by facilitating exploratory research and experimentation. Denmark has invested in green upskilling as part of the 2025 *REpowerEU* programme, increasing the human capital available to help companies innovate and scale up (IEA, n.d.). Spain provided direct grants to boost domestic manufacturers through the *Support scheme to support the renewable energy sources act (Solar package I)* in 2024, contributing both to resource mobilization and market formation by strengthening the local supply chain (IEA, n.d.). In 2022, France announced the *France 2030 Investment Plan* that includes €1 billion of investment in renewable energy projects to increase installed renewable energy capacity to 100 GW by 2050 (IEA, n.d.). France's investment shows a strong political commitment to the development of PV technologies, strengthening market formation, long-term resource mobilization and reducing policy uncertainty and perceived investment risk. Austria, Spain, Italy and the Netherlands have also used capital subsidies to reduce initial investment costs for deploying PV technologies, thereby reducing one of the main barriers to commercialization (Austrian Technology Platform Photovoltaic & Fechner, 2022; Bernsen, 2023; Donoso et Behar, 2022; Tilli et al., 2022). This suggests that reducing upfront capital costs for firms remains a central strategy to foster PV technology diffusion. This strategy is aligned with the barriers to legitimation discussed in section III, particularly regarding the perceived risks and uncertainty associated with the high investment costs. Moreover, mixing R&D and capital subsidies help bridge the VoD by providing support during the full technology development process, from early-stage research to later-stage commercialization.

Self-consumption schemes, including collective net-metering and net-billing, are also broadly adopted to foster PV technology adoption among homeowners and firms. Research has shown that these measures have generally a positive effect on the development of residential PV by reducing investment costs and limiting global challenges such as grid energy losses and congestion problems (Bertsch et al., 2017; Ciocia et al., 2021; Escobar et al., 2020; Mateo et al., 2018), which help remove barriers to PSC market formation and legitimation. However, side effects include cross-subsidization (non-PV owners pay for part of the network costs that PV-owners avoid), increased difficulty in grid management and violations of grid thermal and voltage limits (Ciocia et al., 2021; Mateo et al., 2018). Net metering is a specific form of self-consumption policy that is only used by few countries because it overlooks actual electricity market prices and therefore leads to financial losses for the grid operators (ComWatt, 2024).

Traditional support tools like FiT and FiP remain prevalent in several countries to provide continuity and stability for RES investments (Del Río & Gual, 2007). There is not much information on feed-in premiums, but they seem to be used for industries and PV plants as an alternative to FiT and can be included in auctions (Austrian Technology Platform Photovoltaic & Fechner, 2022; Bernsen, 2023; De L'Epine, 2023; Donoso et Behar, 2022; European Environment Agency, 2014; Oller Westerberg et Lindahl, 2022; Tilli et al., 2022). FiT is considered as one of the most successful policies in promoting renewable energy and innovation (Blanco et al., 2022; Shafiullah et al. 2002). They ensure continuity and investment stability, which is particularly effective in stimulating early market formation and knowledge development (Wen et al., 2020; Del Río & Gual, 2007). For instance, they are responsible for the rapid growth of the German PV market and the expansion of PV technology after 2000 (Wen et al., 2020).

Sustainable building requirements are present in nearly all countries studied, underscoring how regulatory measures in the construction sector are increasingly leveraged to promote solar integration, especially in new or renovated buildings. For example, France imposes new buildings to have at least 30% of the roof covered by renewable energy systems or revegetation systems, a percentage that will be increased to 40% in 2026, and 50% in 2027 (Directorate for Legal and Administrative Information, 2025). Since 2021, all new buildings in the Netherlands must comply with *Nearly Energy-Neutral Building* standards, emphasizing the integration of renewable energy systems (Rijksdienst voor Ondernemend Nederland, 2017). In Germany, the GEG 2024 requires new heating systems installed in buildings to be powered by at least 65% renewable energy. These policies can help create a niche market for innovative technology and applications such as PSCs and BIPV, thus creating a synergy between these two that contributes to reinforcing market formation.

In parallel, procurement mechanisms, including tenders and auction designs, are increasingly used to allocate support more efficiently and foster price competition (IEA, 2024). France's *Electricity Production through Renewable* scheme (2021–2026) introduced multiple RES technology-specific and technology-neutral tenders, totaling 3.54 GW for PV technologies, including premiums on top of market electricity prices and supported by a €30.5 billion budget (IEA, n.d.). Spain's *National Recovery and Resilience plan* (2021) includes calls for projects aimed at boosting domestic production and development of RE-related technologies while its *Renewable energy auction* design implemented in 2020 awarded over 3 GW of PV and wind capacity at record-low prices (IEA, n.d.). Germany's *Omnibus Energy Act* (2018) launched additional tenders totaling 4 GW for PV and established innovation auctions to encourage the development and integration of cutting-edge renewable energy technologies (IEA, n.d.). These mechanisms not only stimulate demand but also support industrial learning and system cost reduction, helping structure competitive PV markets.

Less commonly used instruments are green certificates, RPS, guarantees of origin and BIPV incentives. While no concrete national RPS policies were identified, all European countries are legally bound to meet the European target of 42.5% renewable energy in the Union's gross final consumption of energy by 2030, with an ideal goal of 45% (The European Parliament & The European Council, 2023). This overarching directive acts as a supranational-level instrument that indirectly supports national-level market formation and resource allocation. BIPV is attracting growing attention from both the EU and national governments, and support schemes are gradually being implemented (Chatzipanagi et al., 2023), indicating a recognition of its market potential and infrastructural relevance.

On top of national policies, the European Union provides strategic roadmaps, including policies, objectives and resources to encourage the development of renewable energy on the continent. The European Green Deal is the European Union's strategic roadmap for achieving climate neutrality by 2050 (European Commission, n. d.-a). It outlines the long-term vision and policy direction needed to decarbonize the economy while promoting sustainable growth, competitiveness, and social fairness. It serves as a comprehensive policy framework rather than a single policy instrument, encompassing legislative texts, sectoral strategies and financial mechanisms aimed at transforming the European economy and energy system. Within this framework, the Net-Zero Industry Act seeks to scale up the EU's manufacturing capacity for clean technologies (European Commission, n. d.-b). Its main objectives are to improve the investment environment for net-zero industrial projects, foster employment in green sectors, and reduce strategic dependencies. REPowerEU is also embedded within the Green Deal and is the European response to the recent energy crisis. It focuses on accelerating the deployment of RES to reduce the dependency on Russian fossil fuels and improve the energy system resilience through targets for RES share, easier permitting procedures and accelerated infrastructure developments (European Commission, n. d.-c). The European Green Deal is also supported by a range of financial instruments aimed at concretizing the strategic vision of the European Commission and ensuring a fair development between countries. In parallel, Horizon Europe, the EU's research and innovation framework programme for 2021–2027, aligned with the Green Deal ambitions and provides the main vehicle for supporting knowledge development, one of the TIS functions analyzed in this thesis. Horizon Europe funds fundamental and applied research, technology development, and collaborative innovation across the EU to enable technology maturation, interdisciplinary collaboration, and the diffusion of knowledge across firms, research institutions, and public agencies (Polluveer, 2024). The Innovation Fund supports projects aligned with the climate neutrality goal of the EU and particularly projects focusing on demonstrating and commercializing innovative solutions (Polluveer, 2024). These efforts contribute not only to technological progress but also to the systemic coordination required to bridge the gap between research and market uptake, especially for emerging technologies such as perovskite solar cells.

IV.2 – Designing policy to overcome barriers in emerging erovskite PV markets

Building on the cross-country policy identification presented in Table 1, this section discusses how current and emerging policy mechanisms can be designed or adapted to address the systemic barriers to commercialization identified in the European PSC TIS. Bergek et al. (2008) state that policy should be used to solve challenges associated with weak functionality in the TIS by improving inducement mechanisms and removing blocking mechanisms. The TIS analysis has revealed weak functionalities regarding market formation, legitimation and resource mobilization, that are critical for effectively transitioning PSCs from prototypes at the demonstration phase to commercially viable PV technology ready to be deployed on niche markets. To effectively address these challenges, this section uses insights from the concept of technological niche markets, which highlights three essential functions of a successful niche (Smith and Raven, 2012; Smith et al., 2013): shielding (protection from competitive pressures such as price competition, performance standards, supply chain dominance), nurturing (supportive learning, networking and structures), and empowerment (building competitiveness and reshaping selection environments to upscale the technology).

IV.2.1 – Market formation: Enabling early demand and niche market creation

The formation of an initial market for PSCs is hampered by high entry costs, lack of competitiveness in procurement procedures dominated by mature c-Si technologies, and the absence of protected niche markets for early deployment. Policies that create demand or expand market size (e.g., procurements, FiT schemes) are usually implemented to encourage learning-by-doing and increase the cost-competitiveness of renewable energy technologies (Böhringer et al., 2017).

First, regarding shielding, policy instruments should be designed to create protective space where PSCs are not exposed to full market competition. Policymakers have a range of policy options to create a protective space for technology while fostering firms' ability to innovate, including FiT tariffs and procurement policies.
Procurement policies play an important role in creating a demand for technology and are considered an interesting instrument to encourage innovation development (Georghiou et al, 2013;). They are increasingly used in many European countries and will account for 77% of renewable capacity growth during the period 2024-2030, replacing FiT as the most widespread policy instruments (IEA, 2024). Georghiou et al. (2013) have explored the deficiencies in the procurement frameworks used by governments that limit the benefits of innovation. Public procurements tend to focus on immediate results, while innovation is often an incremental process, and to be too prescriptive, focusing on price and measurable criteria rather than functional specifications that allow room for innovation (Georghiou et al., 2013). Moreover, SMEs often struggle to participate in public procurement (Georghiou et al., 2013) despite being a crucial component of the TIS and especially during the niche market phase. Lastly, public buyers tend to be more risk-averse, to lack awareness, commitment or capacity to implement innovation-oriented procurement strategies and to overlook the importance of early engagement mechanisms with suppliers (Georghiou et al., 2013).
These deficiencies discourage long-term partnerships and continuity in R&D investments (Georghiou et al., 2013). Additionally, auctions may favor existing PV technologies over emerging ones such as PSCs and therefore limit firms' incentives to innovate (Blanco et al., 2022; Del r& Kiefer, 2022). Indeed, auctions are typically technology-neutral and based on cost criteria (Del Río & Kiefer, 2022; IEA, 2024), which favor technology such as c-Si that have already achieved economies of scale. However, Del Río & Kiefer (2022) argue that technology-specific auctions targeting less mature technology may spur

innovation, and consequently firms R&D investments. Moreover, predictable and frequent auctions provide a stronger signal to equipment manufacturers on the potential market for their products, thus encouraging technology development and innovation (Del Río & Kiefer, 2022). For instance, the innovation auctions designed by the German government was mainly dedicated to solar installations combined with storage facilities to encourage their adoption (Bundesnetzagentur, 2024). Implementing innovation and technology specific auctions aimed at perovskite technologies or emerging technologies might create a market demand that will increase firms and project developers' interest in this technology.

Another solution is to add non-price criteria to the auctions' pre-qualification and award conditions. Since the Net Zero Industry Act, the EU is encouraging countries to add non-price criteria such as resilience, environmental sustainability, innovation (new approaches or improvements), energy system integration, and supply chain growth, to boost the demand for European modules (IEA, 2024). However, the criteria must be tailored to the technology and allow for project differentiation to avoid other technologies or foreign companies benefitting from them (IEA, 2024) and to account for the competitive advantages of PSCs. Current EU procurement rules may unintentionally favor cheaper Chinese modules over sustainable, EU-made ones due to misaligned scoring systems (IEA, 2024). Large foreign firms might also expand production in the EU to meet local requirements while still outcompeting domestic producers thanks to economies of scale (IEA, 2024), threatening the success of the niche market created to protect PSCs. While non-price criteria can support the demand for locally made modules, attracting investments would require additional support (IEA, 2024). In addition, instruments like insurance schemes, price premiums and quality labels can be included in auctions policies to reduce perceived risks of investing in emerging technology (Georghiou et al., 2013). Lastly, if PSCs overcome toxicity issues, the modules will become more environmentally friendly due to reduced materials, easier and less energy intensive manufacturing processes. Therefore, governments should investigate how green public procurement[8] could be used for PSC integration in public buildings, helping to generate initial demand while signaling public commitment.

The evidence of procurement methods successfully encouraging innovation is scarce compared to the traditional FiTs and FiP schemes (Del Río & Kiefer, 2022). In fact, moving from FiTs to auctions may be detrimental to support innovation and emerging

[8] "Process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured." (Green Forum, n.d.)

technologies such as Perovskite (Blanco et al., 2022). The main advantages of FiT and FiP over auctions include the absence of capacity cap that increases the number of projects receiving support, they are less prone to project delays and cancellation, have reduced risks and transaction costs, and the level of support is higher due to less competition (Del Río & Kiefer, 2022). According to Del Río (2011), a higher technology specificity in the design of FITs is associated with more innovation and promotes the emergence of new technologies. Evidence from Spain and Germany shows that FITs create strong incentives to kick-start the RES market, increasing technology deployment and learning networks between producers, suppliers, local communities and policymakers to obtain feedback from early stages (Del Río & Gual, 2007). These advantages can be used to ensure broader support across the PSCs value chain, to facilitate market entry, and to trigger the deployment of many small-scale capacity additions which favor learning-by-doing effects. Nevertheless, the success of FiT in promoting innovation and competitiveness depends on the policy design (e.g., how they are fixed and when they are revised), the policy mixes, the technology targeted and their stage of development and the geographical context (Blanco et al., 2022; Del Río & Gual, 2007). In Spain, poor credit conditions, bureaucratic delays for the granting of investment subsidies, lack of coordination between PV manufacturers, the building sector and renewable producers have hampered the PV deployment and reduced the efficiency of FITs (Del Río & Gual, 2007). FiT does not always compensate for grid integration challenges and social benefits of renewable energy promotion do not outweigh the deployment cost under a FiT system (Del Río & Gual, 2007). While FiTs are an essential component for government strategy to promote solar PV deployment, they must be carefully designed and used in conjunction with policies that improve the overall innovation system, from manufacturers to administrative processes.

Once a protective space has been created to facilitate the development of PSCs, it creates an opportunity to transform the technology into an innovation (Smith & Raven, 2012). The nurturing phase can be approached with a strategic niche management perspective, which emphasizes the need for experimental projects, or a TIS perspective, focusing on knowledge creation, market experimentation and formation, entry of firms and legitimation of technology (Smith & Raven, 2012). Direct public investments in collaboration with industries to support demonstration efforts and R&D activities have shown positive results for the scale up of energy technology, to stimulate R&D investment and to drive innovation (Blanco et al., 2022; Böhringer et al., 2017). For instance, investment subsidies and soft loans can support the development of pilot manufacturing lines, helping firms scale production and demonstrate reliability. However, policymakers must ensure that appropriate support is provided across the full development cycle, including TRLs above 5, which is currently lacking. Including a cost and R&D difficulty assessment in the TRLs framework, might provide clearer guidance on the amount of public funding required at higher readiness levels (Mankins, 2002; Mankins, 2009). Moreover, BIPV incentives should be expanded and harmonized across countries, as PSCs' properties are especially suited for architectural integration. The co-development and nurturing of PSCs TIS and the BIPV industry, which are both in the niche market phase, should be further studied by policymakers.

Lastly, to embed PSCs in the broader energy system and industrial policy framework (empowerment), a European roadmap for advanced PV niche development could be developed as part of the Net-Zero Industry Act and the European Green Deal objectives. Indeed, the PSC TIS in Europe is spread across all Member States, with strong collaborations between different research institutes and companies. This roadmap would align MS' efforts and provide long-term strategic direction to help firms plan technology and innovation development strategies. For instance, the EU solar energy strategy published in May 2022 as part of the REpowerEU plan includes a section on the need to support perovskite cells, although the description is quite superficial (The Commission of the European Parliament et al., 2021). Several international organizations such as ETIP-PV (2024), have published a roadmap regarding the development of emerging PV technologies, which could be used by the EU to design adapted policies.

IV.2.2 – Legitimation: Reducing perceived risks and uncertainties and building institutional credibility

Gaining legitimacy is essential for PSCs to attract investment. However, unstable policy signals and high upfront investment costs remain key obstacles to the legitimation of PSCs among users, investors, and public authorities. Targeted measures are needed to reduce perceived risks and strengthen the institutional credibility of PSCs.

The usual strategy for an industry to improve its legitimacy is to conform to established institutions (Bergek et al., 2008a; Bergek et al., 2008b). This means for PSCs to comply with existing sustainability, performance, or safety standards as well as broader European and national requirements that shape the industrial and commercialization process of technologies. Otherwise, an industry can try to influence institutional frameworks by manipulating existing institutions or by creating new ones to achieve institutional alignment (Bergek et al., 2008a; Bergek et al., 2008b). These three strategies for building legitimacy are aligned with niche empowerment strategies as identified by Smith and Raven (2012): fit-and-conform, which aligns innovations with existing regimes, and stretch-and-transform, which seeks favorable systemic change. Therefore, the legitimation process is a crucial function for establishing the niche market required for the development of PSCs. The PSC TIS is in the formative phase of development which means that legitimacy is primarily acquired through a technology assessment based on the knowledge, performance and potential of the technology and how it aligns with problems at the societal level. Bergek et al. (2008b) underline the difficulty and uncertainty surrounding assessment design because various stakeholders try to serve their own goals when setting criteria. Consequently, what is legitimate depends on the actor group concerned and might evolve in response to changing problem agendas at the societal or landscape level (Bergek et al., 2008a; Bergek et al., 2008b). For instance, government interest in PSCs relies on its benefits to achieve strategic, economic, social and sustainability goals, manufacturers prioritize easy and low-cost manufacturing techniques and project developers pay more attention to the LCOE[9] and the payback period of their investment. Moreover, emerging technologies are generally supported by smaller players who do not have access to the media and political connections and resources of large established incumbents (Bergek et al., 2008b). Listening to a variety of stakeholders, collecting various arguments and developing internal competencies and independence are crucial for policymakers to design policies grounded on critically assessed expectations and normative legitimacy (Bergek et al., 2008b). In addition, the formation of a protected market fosters the appearance of new entrants and smaller companies, who can in return form coalitions to advocate for the development of PSCs and the creation of suitable institutions (Bergek et al., 2008b). In conclusion, policymakers can enhance the legitimation of PSCs by including a variety of visions in their institutional framework (top-down approach) but also by implementing policies leading to the formation of early and protected market spaces enabling learning, new entrants' development and the creation of advocacy coalitions (bottom-up approach). Building institutional legitimation can reassure investors and firms regarding the long-term potential of PSCs and therefore reducing "unjustified" high up-front costs currently limiting the technology deployment. In addition to being useful for market formation, well designed FiTs and FiP provide long-term revenue predictability and reduce exposure to market volatility, which can reassure investors and project developers regarding the profitability of their investments. If project developers know that a demand for this technology is certain on the long term, they will increase the demand for PSCs and therefore manufacturers across the value chain will be guaranteed to sell their innovation output (Del Río & Kiefer, 2022). Consequently, the desirability of PSCs will increase across

[9] The Levelized Cost of Energy is a metric for gauging the average cost of electricity generation over the lifetime of an energy asset. LCOE can be determined by dividing an energy asset's total lifetime costs by the asset's total energy generation over its life cycle (Gomstyn & Jonker, 2024).

the entire value chain, legitimizing the potential higher upfront costs associated with scaling up manufacturing capacities.

IV.2.3 – Resource mobilization: Strengthening access to funding and key complementary assets

Implementing policies to foster market formation and legitimation will not have intended impacts if firms don't have access to the resources they need. Resource mobilization in the PSC innovation system is undermined by gaps in private and public financing, limited production infrastructure, and critical grid infrastructure bottlenecks such as permitting delays, congestion, and curtailment risks.

Public financial support in PV technology and R&D has been declining since 2011 (Figure 17), but the activities beyond R&D that are impacted by national funding are not detailed (Chatzipanagi et al., 2023). However, the TIS analysis and the findings on the VoD concept indicate that funding usually lacks between demonstration and large-scale commercialization (Tassey, 2014). Technology-push policies such as direct investment in R&D and demand-pull policies like procurements increase the level of financial resources available for firms but are generally not sufficient to bridge the gap (Tassey, 2014). An effective strategy for policymakers is to align investment with the different roles and needs of basic research, proof-of-concept and technology platforms, and applied development (Tassey, 2014). They should also optimize who participates (universities, industry, governments, etc.), how they collaborate and the supporting infrastructures and resources (skills and knowledge) (Tassey, 2014). Additionally, when public institutions and governments use TRLs to evaluate project proposals, they overlook the evolving needs for funding which reduces their investment for intermediate to high TRLs (Héder, 2017). This issue can be partly fixed by policymakers in designing project proposal assessments that account for the reality of PSCs development and the financial needs of the TIS. Beyond public funding, firms also face a decline in private investment directed toward PV technologies. Lüthi & Wüstenhagen (2011) argue that non-economic barriers can significantly raise the perceived risk of PV investment, thereby reducing the amount of investment realized in PV technologies. In Europe, the duration of the administrative process is the most important barrier to investments, followed by the level of feed-in tariffs, the political instability and the uncertainty regarding capacity cap on the grid (Lüthi & Wüstenhagen, 2011). These risks increase the premium investors require to invest capital in PV projects. For instance, or each six months of project delays, an added feed-in tariff of 3.68 ct/kWh may be required (Lüthi & Wüstenhagen, 2011). In low-risk conditions of policy instability[10], the feed-in tariff needs to be 4.10 ct/kWh higher, whereas in high-risk conditions[11] a price premium of 10.28 ct/kWh will be required to maintain the same level of attractiveness (Lüthi & Wüstenhagen, 2011). Administrative simplification, policy stability, long-term visibility and support from government are key to attract investment and sustain innovation. Lastly, corporate PPA are not policies, since they are a long-term contract between energy suppliers and energy consumers, usually large firms, but they will represent the second driver of capacity installation between 2024 and 2030 (IEA, 2024). According to Daszkiewicz (2020), policymakers can facilitate the adoption of corporate PPA in organizing a liberalized electricity market where developers are independent and have the right to build, own, operate and sell electricity to the grid or another party. Corporate PPA are usually more attractive when there is limited policy support (Daszkiewicz, 2020), which can be used in the later PSCs development stage when there will be a need to move from a protected niche market to large scale deployment in real economic conditions.

Regarding manufacturing capabilities and PV glass supply, policymakers can provide grants to boost domestic manufacturers like Spain (IEA, n.d.), add on-price criteria in their procurement designs to the conditions that they are tailored to local firms and PSCs' characteristics (IEA, 2024), implement fiscal and financial policies such as capital grants and rebates, soft loans, tax discounts, tax waivers or other tax benefits, that reduce upfront costs and provide more affordable investment conditions (Daszkiewicz, 2020). Fiscal and financial policies present also the advantage of being easy to manage and can be adjusted within the budgetary work of the government (Daszkiewicz, 2020), thereby following the evolution of the TIS needs as the technology is being developed. Industrial policies are also a central part of building manufacturing capabilities and must be further studied.

Lastly, critical grid infrastructure bottlenecks such as permitting delays, congestion, and curtailment risks can be managed with policies tailored to these specific challenges. Typical measures include introducing stricter criteria for grid queue entry to reduce speculative applications, shifting from "first come, first served" to "first ready, first served" connection models, authorizing multi-project connections request and current projects to leave the queue, and incentivizing the development of grid-friendly projects through location-based tariffs or interconnection planning (IEA, 2024). Additionally, new policies supporting storage and hybrid systems (storage + modules) deployment can

[10] One significant unexpected policy change in the last 5 years (Lüthi & Wüstenhagen, 2011)
[11] Three significant unexpected policy changes in the last 5 years (Lüthi & Wüstenhagen, 2011)

balance the system, provide ancillary services and reduce economic and technical curtailment. However, they are subject to grid connection queues as well, reducing the scope of their positive impacts (IEA, 2024). China has also invested in grid infrastructure and has adjusted the FiT schemes to provide stronger incentives for new project development in areas where system integration is less challenging (IEA, 2024). The European Union has also highlighted the necessity to add a location component in policies to reflect the grid conditions and encourage production in areas less likely to exacerbate congestion. They further state that "collaboration and coordination among various stakeholders, including policymakers, grid operators, energy producers, and consumers, will be essential in building a resilient and efficient power system for the future" (Joint Research Center, 2024). Policies encouraging self-consumption are implemented in many countries (Table 1), which results in less grid congestion (Bertsch et al., 2017; Ciocia et al., 2021; Escobar et al., 2020; Mateo et al., 2018), increased legitimacy and can help create a market for PSCs. However, since 2022, the market share of rooftop installations in decreasing, from 31% in 2022 to 20% in 2024 (SolarPower Europe, 2024). Policymakers should investigate the potential issues in current policy design to foster the adoption of PV modules for self-consumption. Depending on the issues identified, PSCs might even be an attractive alternative to c-Si modules.

IV.3 – Summary

The comparative analysis of national policy instruments across eight European countries highlights the diversity of public policies supporting PV innovation and deployment since 2015. It further reveals an approach based on a mix of technology-push and technology-pull instruments aimed at fostering the adoption of PV technologies. However, to address the systemic barriers that prevent the innovation and commercialization of PSC technologies in Europe, policymakers must design and implement coordinated policies that strengthen weak TIS functions. In particular, market formation, legitimation and resource mobilization are interconnected and central to the transition of PSCs from the demonstration stage to early commercial deployment.

First, building initial market demand and creating protecting niche markets is essential to shield PSCs from market competition and against incumbent c-Si technologies. Public procurement, technology-specific FiTs and auctions tailored to emerging technologies can provide the demand and revenue stability needed to support experimentation, industrial scale-up, and the entry of new firms. Nevertheless, the design of these instruments is crucial to capturing the expected benefits. Policymakers should particularly pay attention to the level of FiT, how they are determined and when, as well as the inclusion of non-price criteria in competitive auctions. Additionally, targeted support mechanisms, such as green public procurement, pilot project subsidies, and technology-specific innovation auctions, can reinforce early demand while mitigating risks for investors and developers.

Second, increasing the legitimacy of PSCs should be done through both top-down and bottom-up approaches. On one hand, policymakers must develop inclusive, credible technology assessments that reflect the vision of different stakeholders, including manufacturers, developers, researchers, and end-users. On the other hand, policies that foster early market adoption create spaces for new actors to emerge, form coalitions and advocate for institutional changes favorable to PSCs, thus reinforcing legitimacy through strong engagement and feedback.

Third, resource mobilization must be reinforced to ensure that firms are able to respond to market formation and legitimation actions. This includes not only direct financial support for R&D and demonstration projects but also sustained public investment specifically designed for each development stage to bridge the gap between research and large-scale commercialization, while fostering collaboration across academia, industry, and government. Reducing non-economic barriers like administrative delays and policy instability is crucial in attracting private investments and lowering perceived risks. Furthermore, creating a suitable environment for the development of corporate PPAs, boosting manufacturing through targeted incentives, and addressing grid infrastructure challenges with tailored policies will enable the successful innovation and deployment of PSCs while aligning with broader national and European strategic, political, economic and sustainability objectives.

V – Discussion and future research

This thesis explores how public policy can better support firms in managing technological innovation and commercializing emerging solar cell technologies, in particular perovskite-based solar cells, in Europe. Using the Technological Innovation System framework with some insights from the Technology Readiness Levels and Valley of Death framework, key systemic challenges impeding PSCs commercialization and the policy implications have been identified.

The results confirm previous literature on innovative systems which highlight the importance of aligning policies with the development of a technology and the changing dynamics of its environment (Bergek et al., 2008a; Blanco et al., 2022; Hekkert et al., 2007; Reichardt et al., 2016; Tassey, 2014). In particular, the PSC TIS in Europe is in the formative phase, between demonstration and niche market, where functions such as market formation legitimation and resource mobilization show some weaknesses. This is consistent with prior empirical studies on renewable energies technologies which suggest that systemic failures on these functions hinder the development of the TIS (Bergek, 2013; Eleftheriadis & Anagnostopoulou, 2015; Johnson & Jacobsson, 2001). This study also reaffirms the importance of the VoD concept, not only from a financial perspective but also regarding policies and complementary assets, by demonstrating a lack of coordinated support mechanisms in intermediate TRLs (5 to 7) that makes it difficult for firms to demonstrate, scale, and industrialize PSCs technologies (Muscio et al., 2023; Tassey, 2014: Teece, 1986). The impact of VoD on renewable technology development is further emphasized by Muscio et al. (2023), who also suggested a mix of policies to foster innovation, technological development and EU competitiveness.

In line with the recommendations made in this study, the literature emphasizes that demand-side policies such as FiTs and public procurement as well as niche market protections are essential to market formation but need to be carefully designed to account for the specificities of the targeted technology (Blanco et al., 2022; Del Río & Kiefer, 2022; Gephart et al., 2017; Muscio et al., 2023; Reichardt et al., 2016). Yet, this study finds that current governments do not offer much technology-specific incentives and overlook the specific risks and needs of emerging PV technologies, which tend to reinforce the dominance of mature technologies. Concerning legitimacy, existing scholarship highlights the role of societal acceptance and regulatory alignment in legitimizing new technologies (Bergek et al., 2008a; Bergek et al., 2008b; Del Río & Kiefer, 2022; Markard et al., 2015). The case of photovoltaic technologies confirms this, as the toxicity and stability issues, the uncertainty of long-term support and demand affect the amount of investment directed towards PSCs and the creation of a niche market. Resource mobilization remains a widely acknowledged challenge for technology development and adoption despite a strong focus on financial resources rather than on complementary assets (Bergek, 2019). This study reinforces this point, showing that both the lack of consistent financial resources and complementary assets, such as manufacturing and grid infrastructures, are major blocking mechanisms in PSCs development. Several studies highlight the impact of policy on the mobilization of resources for renewable energy (Blanco et al., 2022; Böhringer et al., 2017; IEA, 2024; Lüthi & Wüstenhagen, 2011). This study builds on that to recommend a coherent EU-level strategy aligned with PSC deployment needs.

While the TIS framework has proven valuable for analyzing the performance of technology-specific innovation systems and policies, especially in renewable energy (Bergek et al., 2008a; Darmani et al., 2014; Hekkert et al., 2007; Reichardt et al., 2016), its limitations must be acknowledged. Key methodological challenges impacting the analysis outcome include defining the system boundaries, selecting relevant actors and relationships, and choosing performance measurement methods (Carlson et al., 2002; Markard et al., 2015). Moreover, the development of emerging energy technologies implies socio-technical transitions, such as strategic actions by incumbent actors or policy evolution, which is a subject that cannot be fully captured in a TIS analysis (Markard et al., 2015). In addition to the limitations inherent to the TIS framework, the way it was applied in this thesis raises additional constraints. First, due to the immaturity of the PSC market and the exclusive reliance on secondary data, the analysis could not carry out the six-step scheme by Bergek et al. (2008). In particular, the functions of knowledge development and diffusion, influence on the direction of search, entrepreneurial experimentation and development of positive externalities were not assessed, which may have overlooked relevant dynamics shaping the innovation process. Additionally, boundary setting and the definition of relevant structural components (i.e., defining which actors, institutions, and interactions to include in the focal TIS) was particularly challenging. The scope was constrained to the European level and focused on a limited selection of actors (e.g., firms, research bodies, policymakers), potentially overlooking international knowledge flows, global value chain integration, or local niche developments occurring elsewhere. Ultimately, the absence of primary data limits the exploration of actor expectations, network structures, or any informal knowledge and challenges specific to PSCs, which are crucial for assessing system functionality.

These limitations point to several implications. First, future research should complete the TIS analysis by including the other functions as well as new perspectives on innovation and technology development, such as the multi-level perspective and the strategic niche management and transition management approaches (Caniëls & Romijn, 2008; Weber & Rohracher, 2012). Second, empirical research incorporating interviews with firms, regulators and researchers could offer a more detailed understanding of institutional dynamics and actor strategies within the PSC innovation system. It could lead to a discussion on the impact of blocking mechanisms and policy issues on the design of technology and innovation management strategies within firms. For instance, Hall et al. (2014) have explored the relation between legitimization processes and organization's strategy to design a framework enabling more efficient technology development and diffusion. Lastly, the discussion on policies to overcome functional weaknesses focused on energy policy but future study could include innovation and industrial policies to expand the analysis to broader political levels that influence technology development, manufacturing capacities, and long-term competitiveness.

Conclusion

This thesis examined how public policy can better support firms in developing technological innovations and commercializing emerging solar cell technologies, in particular perovskite-based solar cells, in Europe. The analysis combined the Technological Innovation System framework with complementary concepts such as Technology Readiness Levels and the Valley of Death to identify the systemic challenges currently limiting PSC commercialization.

The analysis revealed that although Europe has a strong presence in early-stage research in PSCs, the transition from laboratory research to market-ready products remains hindered by weaknesses in three TIS functions: market formation, legitimation, and resource mobilization. More specifically, these weaknesses include difficulty attracting investment and creating an early demand for PSCs, insufficient institutional legitimacy and stability, and inadequate access to industrial, and grid-related resources. To address these barriers, the thesis explored policy options based on current energy policy instruments implemented in eight European countries. Findings show that policy instruments such as technology-specific feed-in tariffs, targeted public procurement, investment subsidies for pilot manufacturing, and tailored auction designs can foster innovation development and investments, creating more favorable conditions for PSC scale-up. Moreover, coordinated policy frameworks that link energy, innovation, manufacturing and grid development will be essential for supporting firms throughout the entire innovation cycle, from R&D to commercialization.

In summary, if the EU aims to strengthen energy sovereignty and industrial competitiveness in the PV sector, it must ensure that public policy not only funds research but also builds the systemic conditions that allow promising technologies like PSCs to succeed on the European and global market.

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Appendix 1

Abbreviations

c-Si: crystalline silicon-based solar cells

BIPV: Building-integrated photovoltaics

EU: European Union

FiP: Feed-in Premium

FiT: Feed-in Tarriff

IS: Innovation System

LCOE: Levelized Cost Of Energy

MS: Member States (of the European Union)

PSC(s): Periovskite-based solar cell(s). Include both single-junction and tandem architecture

PV: Photovoltaic. Refers to the technologies and industry

R&D: Research and Development

RES: Renewable energy sources, including photovoltaic

RPS: Renewable Portfolio Standards

TIS: Technological Innovation System

TRL(s): Technology Readiness Level(s)

VC: Value Chain

vc: venture capital

VoD: Valley of Death

VRE: Variable Renewable Energy

Appendix 2

Major European companies across the upstream and midstream PSC VC (based on Chatzipanagi et al. (2023), Feng et al. (2023), Perovskite-info (2024), and the companies' website)

Perovskite materials producers		
Country	Company name	Activities
Switzerland	Avantama	Successfully developed an engineering process to synthetize stable perovskite
	SolarOnix	R&D on new materials and components for perovskite to supply researchers
Sweden	Dyenamo	Perovskite passivation materials to improve PSC performance and durability
Perovskite equipment makers		
Country	Company name	Activities and status
Germany	Aixtron	Develop industrial fabrication processes in collaboration with universities and research institutes. Originally a provider of deposition equipment to the semiconductor industry
	Bergfeld Lasertech	Specialized in the development of laser processes for thin layers and surfaces with electrical functionality.
	MBRAUN	Manufacturing equipment specifically designed for perovskite production
	Coatema Coating Machinery	Development of coating for cells and batteries
Netherlands	Eternal Sun Spire	Design perovskite and tandem testing tools to evaluate cell performance and stability
	SparkNano	Provide advanced Spatial Atomic Layer Deposition (ALD) technology for the fabrication of cells
Denmark	FOM Technologies	Develop manufacturing processes to help perovskite large scale production, particularly slot-die coaters for solution-processes perovskite
	InfinityPV	Create compact lab equipment for slot-die coating and roll-to-roll processing to bridge research and industrial production.
France	JACOMEX	Develop glovebox and workstation to produce perovskite cells

Sweden	FlexLink	Conveyor systems and robots to increase production efficiency and sustainable manufacturing
Perovskite cell and module producers		
Country	Company name	Activities and status
England	Oxford photovoltaic	Spin out from Oxford University – Perovskite/Si tandem solar cells. Full size wafers developed in 2017; world's first volume production line established in Germany; commercial-sized perovskite-on-silicon tandem solar cell achieving efficiency of 26.8%
	Aerosolar	Spin out from Queen Mary University of London. Is developing a method to improve the formation and stability of low-temperature-annealed perovskite solar cell
	GCell by G24 Power	Has laboratories to improve the stability of PSCs and improve roll-to-roll coating
Italy	Enel Green Power	Has developed a perovskite/Si tandem cell achieving efficiency of 25,8%
Sweden	Evolar	Acquired by the American company First Solar
	EXEGER	Specialized in flexible and customable cells
Poland	Saule Technology	Specialized in producing perovskite solar cells printed on thin, flexible substrates at low temperatures.
Switzerland (Operate mainly in Germany, but tried, and failed, to delocalize to the USA)	Meyer Burger	Develop high efficiency PSC and large-scale manufacturing capacities in collaboration with universities, laboratories and institutions. It is a well-established firm in the c-Si industry with a vertically integrated value chain

Appendix 3

Key Non-Firm Actors Across the Value Chain

The following list encompasses the key universities, research institutes, EU projects, collaborative platforms, innovation centers, and intergovernmental institutions that participate in the focal TIS. Information comes from each actor's website.

Research institutes and innovation centers are conducting cutting-edge research on materials, device architectures, upscaling, and stability of perovskite solar cells.

- Imec (Belgium): Research on perovskite modules and tandem integration; active in the Solliance consortium.
- Fraunhofer ISE (Germany): Europe's largest solar research institute; work on stability, tandem cells, reliability testing.
- CEA-Liten (France): Involved in R&D on next-generation PV technologies including perovskites and hybrid tandem cells.
- Helmholtz-Zentrum Berlin (HZB) (Germany): Leading work on tandem perovskite-silicon cells and fundamental perovskite research.
- TNO – Energy Transition (Netherlands): Participates in Solliance; works on upscaling and tandem integration.
- ZSW – Centre for Solar Energy and Hydrogen Research (Germany): Focus on thin-film solar cells including perovskite variants.
- Empa – Swiss Federal Laboratories for Materials Science and Technology (Switzerland): Research on flexible and low-cost perovskite PV.

Universities are critical in advancing fundamental understanding, training talent, and participating in EU consortia. Sometimes, then even create spin-out that actively participate in the commercial development of cells (see table 1).

- École Polytechnique Fédérale de Lausanne (EPFL) (Switzerland): EPFL has a laboratory dedicated to perovskite cell research and responsible for many publications and advancement in the field.
- University of Oxford (UK): Extensive perovskite research; spinout Oxford PV is commercializing tandem cells.
- University of Cambridge (UK): Research on perovskite materials, stability, and device physics.
- University of Valencia (Spain): Participates in EU perovskite R&D projects.

- University of Rome "Tor Vergata" (Italy): Known for work on printable perovskite PV technologies.
- Eindhoven University of Technology (Netherland): Investigate perovskite solar cells from various perspectives such as band gap tuning or multi-junction cells.

EU-Funded Projects & Collaborative Platforms enable transnational R&D and the sharing of infrastructure and knowledge.

- Viperlab: Provides open access to European infrastructure for perovskite and tandem PV testing and development and foster collaboration between European academic and industrial researchers.
- Pepperoni: Composed of expert covering the full VC, it focuses on scalable production and integration of tandem perovskite/Si cells to bring them from TRL 4-5 to TRL 7; part of the Horizon Europe program.
- TESTARE: Develops reliability and testing frameworks for perovskite PV technologies. It is a Horizon Europe project initiated in the University of Cyprus in cooperation with top research institutions.
- Nexus, Luminosity, Diamond, Pearl and Pilatus, etc. There are many other European projects, either industry-led or part of Horizon Europe aimed at improving efficiency, reliability and sustainability and at scaling-up manufacturing processes for the commercialization of perovskite solar cells (PEPPERONI, n.d.-b).

Consortia and Innovation Networks unite academia, research, and industry to facilitate innovation and knowledge exchange.

- Solliance Solar Research: A cross-border Dutch-Belgian-German consortium focused on thin-film solar technology, especially perovskite and tandem cells. Includes Imec, TNO, Holst Centre, and universities.
- EERA PV (European Energy Research Alliance – Photovoltaic): Collaborative platform that coordinates R&D in PV across Europe.
- ETIP PV (European Technology and Innovation Platform for Photovoltaics): Industry and research body that shapes European PV policy and priorities, including support for emerging technologies like PSCs.

Intergovernmental Organizations provide analysis, benchmarking, and policy recommendations relevant to emerging PV technologies.

- IEA PVPS – International Energy Agency – Photovoltaic Power Systems Programme: Task 17 focuses on advanced PV materials and tandem technologies.

- Mission Innovation – Green Powered Future Mission: Supports next-gen PV (including perovskites) through coordinated global public R&D investment