

DELIVERABLE REPORT



NEXUS

Market potential for PVKS/Si tandem modules and long-term impact assessment

**Deliverable D6.7
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NEXUS aims to accelerate Europe’s energy transition by developing perovskite-silicon tandem photovoltaic technology, via a new European paradigm: an eco-design approach, based on efficiency, cost, sustainability, circularity and social aspects and using abundant materials. NEXUS aims to develop stable, 2-terminal perovskite-silicon tandem solar cells and modules with high power conversion efficiencies, using sustainable, coherent and competitive European PV production, to create a viable economic pathway for the European commercialisation of this technology.

NEXUS is formed of a multi-disciplinary consortium: 13 partners from 10 countries; 6 industrial partners & 7 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
AgriPV	Agrivoltaics	LCC	Life Cycle Costing
AT	Ambitious Transition scenario, here DNV Energy Transition Outlook 2025	LCOE	Levelized Cost of Energy
BAPV	Building Attached Photovoltaics / Building Applied Photovoltaics	LUT	Lappeenranta-Lahti University of Technology
BNEF	Bloomberg New Energy Finance	MT	Minimal Transition scenario, here IEA Net Zero by 2050 (World Energy Outlook 2024 update)
BI	Becquerel Institute	PERC	Passivation Emitter Rear Contact
BIPV	Building Integrated Photovoltaics	PVKS	Perovskite technology
C&I	Commercial & Industrial	PVKS/Si	Perovskite/Silicon tandem technology
c-Si	Crystalline silicon	Si	Silicon
ETO	Energy Transition Outlook	TOPCon	Tunnel Oxide Passivated Contact
GM	Ground-mounted	TT	Total Transition scenario, here LUT 100% Renewable Energy Systems
IEA	International Energy Agency	VIPV	Vehicle Integrated Photovoltaics
IIPV	Infrastructure Integrated Photovoltaics		

1. Introduction

This deliverable assesses the **market potential of perovskite–silicon (PVKS/Si) tandem modules in Europe to 2050**. It provides a consistent view of how tandems could scale within the European PV market. The analysis combines **market trajectories, technology uptake paths and segment-level penetration** to produce prospective annual and cumulative market volumes, suitable for planning, investment and exploitation activities.

1.1. Description of the deliverable content and purpose

The document establishes European PV market trajectories to mid-century and allocates shares between incumbent single-junction silicon and PVKS/Si tandems. It draws on **three transition pathways** published by recognised **third-party organisations (IEA, DNV, LUT)** and applies a logistic diffusion model to describe **tandem uptake** within the accessible PV market. **Entry year is set around 2028**, in line with ITRPV roadmaps for first bankable perovskite–silicon tandem products [1]. The **lag time**, from entry to scale, is set at **six years**, based on what was observed when PERC entered the market and the time it took to capture around half of the total market. The split by application segment follows the end-user structure used in previous **D6.6 End-user applications** work and is extended to sub-segments such as building-applied, building-integrated, agriPV and floating PV [2]. The outputs include annual and cumulative volumes by technology and segment for 2030, 2035, 2040, 2045 and 2050, together with qualitative findings on timing, drivers of adoption and the increasing importance of **replacement cycles** in the 2040s. The concluding chapter distils the market implications and presents priorities for uptake that can feed exploitation planning.

1.2. Relation with other activities in the project

Assumptions on device efficiency, stability, module design and manufacturing readiness are aligned with the targets developed in the technical work packages, which provide the performance envelopes that condition tandem competitiveness at product level. The end-user applications assessment in D6.6 report supplies the segment definitions, drivers and constraints that underpin the split between centralised and distributed markets and the treatment of niche sub-segments. The approach adopted here aligns with the methodology used in Deliverable D5.4 “Social LCA including responsible raw material supply” for modelling future raw material demand. The findings also support exploitation and communication tasks by translating technical progress into time-bound market opportunities and by identifying the conditions that enable timely market entry during the current expansion phase.

2. Method

First, **long-term European trajectories** are defined, based on external scenarios setting the context. These figures are further refined into **PV market segment shares**, calibrated with historical data and short-term outlooks. Then, a **potential tandem penetration per segment is explored**. The method applied in the assessment is summarised in the scheme below.

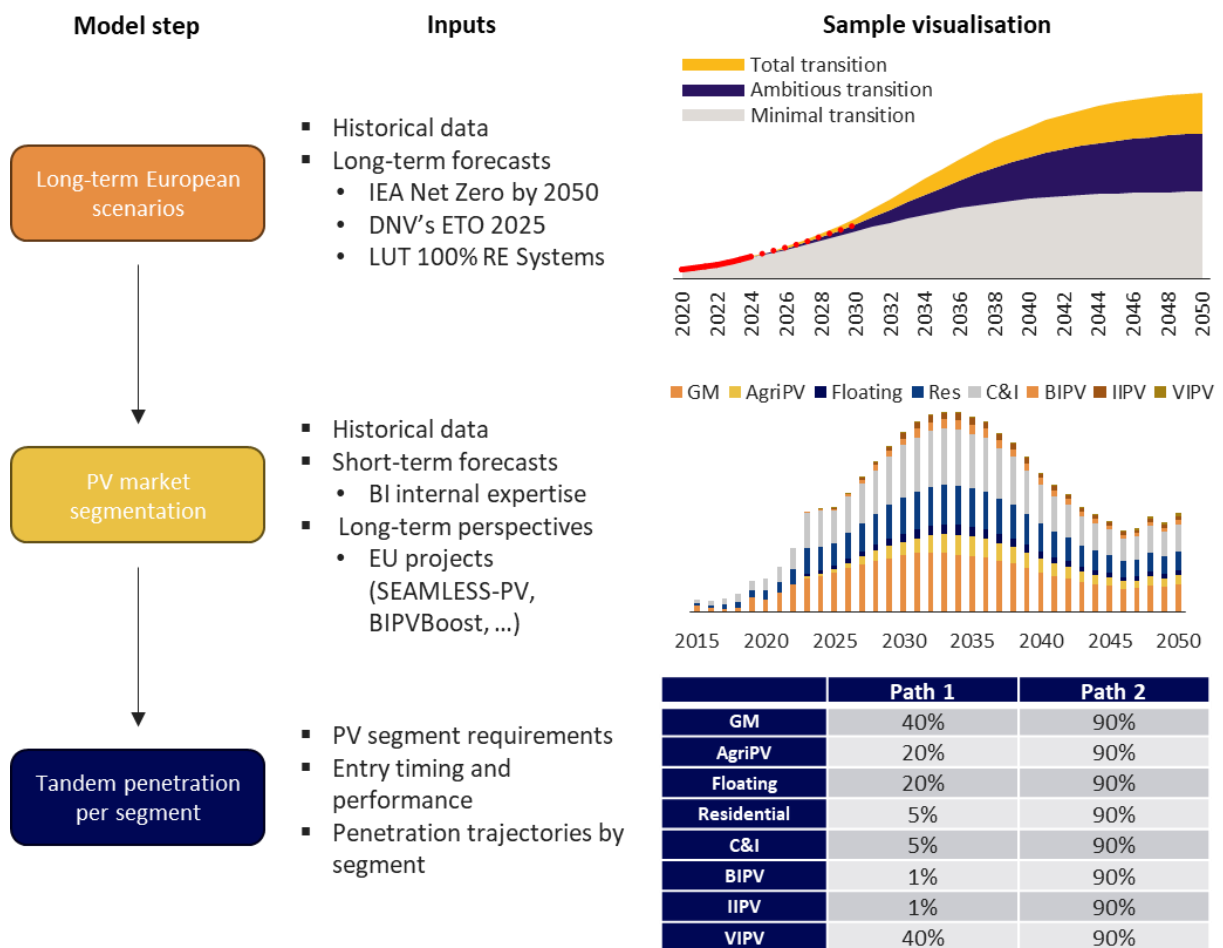


Figure 2.1: Method summary for tandem penetration by segment in Europe

3. Long-term impact scenarios

3.1. European scenarios

This section defines the European market figures used in the assessment. They describe the total addressable market within which PVKS/Si tandem modules may deploy, providing the basis for the segment and technology splits.

Three transition scenarios are drawn from established literature and recognised institutions. The European pathways are derived from the following anchors:

1. Minimal transition: **IEA Net Zero by 2050** (WEO 2024 update) [3]
2. Ambitious transition: **DNV Energy Transition Outlook 2025** [4]
3. Total transition: **LUT 100% Renewable Energy Systems** [5]

Table 3.1 Selected scenarios with cumulative solar PV capacities installed by 2050 in GW

Scenario's name	Organisation	Scenario's official name	Publication	2050
Minimal transition (MT)	IEA	Net Zero 2050 (WEO 2024 update)	2024	1 558 GW*
Ambitious transition (AT)	DNV	Energy Transition Outlook 2025	2025	2 673 GW
Total transition (TT)	LUT	LUT Energy System Transition Model	2022	3 314 GW

Notes. Values are rounded to the nearest gigawatt.

**Where the source provides a range or partial data, the consolidated value is reported in the Annex.*

These scenarios were selected to cover three complementary perspectives: an **intergovernmental organisation** (IEA), a **private risk management company** (DNV) and **leading university research in energy system models** (LUT). This combination offers both methodological diversity and reliance on widely recognized sources.

The large differences in PV deployment reflect contrasting assumptions on **final energy demand** and electrification, the contribution of nuclear and carbon capture, the pace of cost and learning effects, and the strength and timing of policy implementation. Grid and land constraints, as well as treatment of storage and sector coupling, also vary across the sources, which leads to different cumulative PV outcomes by 2050.

The **International Energy Agency's Net Zero by 2050** scenario is a normative, Paris-aligned pathway. The 2024 update in the **World Energy Outlook** refines the trajectory to 2030, with figures reported at the global level [3]. European values in this assessment are derived from those global series using the conversion assumptions set out in the Annex. Compared with DNV ETO 2025 and LUT 100% RES, NZE places greater weight on energy efficiency and demand reduction and retains material roles for nuclear and carbon capture, utilisation and storage. As a result, the PV capacity required is lower than in the other pathways, and NZE is treated here as the **Minimal transition (MT)** pathway.

DNV's Energy Transition Outlook 2025 provides a quantified pathway of the global energy system to 2060 with a regional split that includes Europe. It is a single forecast grounded in proven technologies and cost trends, rather than a set of scenarios. Policy announcements without clear implementation are not fully credited. It projects solar to supply about 47% of global electricity by 2060 [4]. This assessment uses the Europe regional series from this ETO 2025 dataset, and milestone years are completed with an S-curve interpolation to produce a coherent annual series to 2050. This pathway is referred to as the **Ambitious transition (AT)**.

LUT University's 100% Renewable Energy Systems work is based on the LUT Energy System Transition Model, an hourly, 27-node optimisation framework that couples power, heat, transport and industry and balances supply and demand at least cost with storage, hydrogen and interconnection represented [5]. The European pathway in this assessment uses the Europe-level outputs from the model and is expressed as a coherent annual trajectory to 2050. This pathway is referred to as the **Total transition (TT)**.

In several cases the sources provide headline milestones or partial time series rather than full year-on-year annual data. To ensure a complete and internally consistent set of European trajectories, Becquerel Institute modelled cumulative market volumes using an S-curve formulation. The S-curve produces a plausible year-by-year evolution that converges to the published 2050 levels and remains consistent with historical European deployment.

The three pathways provide total European market volumes to 2050. These volumes act as boundary conditions for the penetration of PVKS/Si tandem modules in later sections, where deployment shares are assigned by application segment and time horizon.

The PV market and its growth are expected to contract in the medium term. Residential additions slow as suitable roof area saturates and incentives are reduced or refocused. Utility and C&I growth is tempered by grid connection queues, land and acceptance constraints, and price cannibalisation that lowers revenue certainty. Financing conditions and tighter permitting add friction to new build. A larger share of yearly activity shifts to the replacement of ageing systems as they reach the end of their service life, and to targeted expansion in constrained sites, so net growth moderates even as cumulative capacity keeps rising.

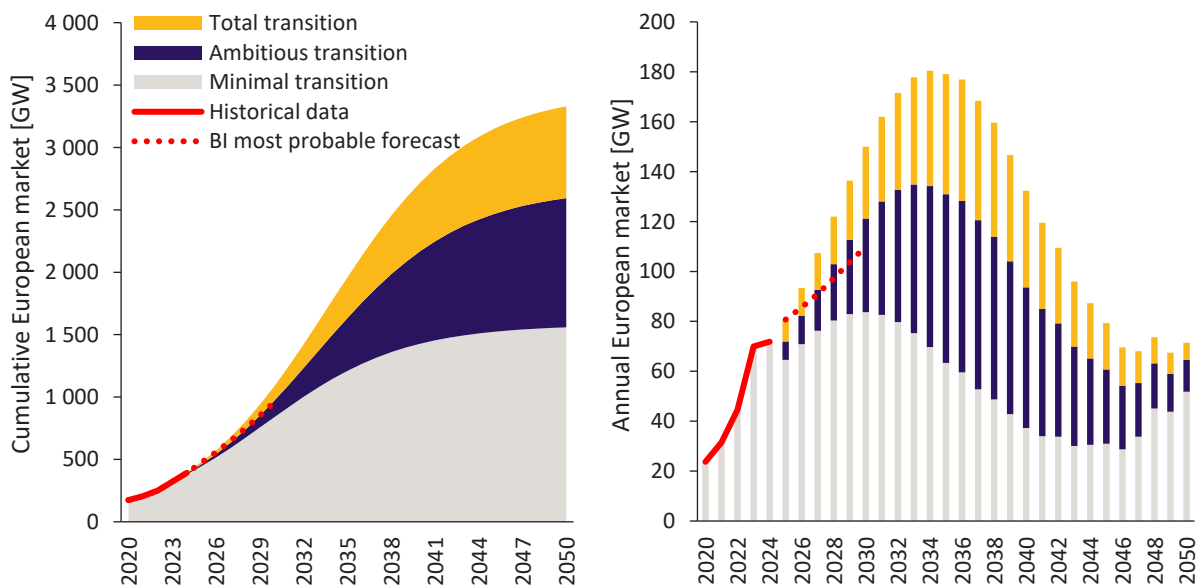


Figure 3.1: Cumulative (left) and annual (right) European PV volumes under MT, AT and TT, 2020 to 2050 (GW)

3.2. Split per segment

Based on the total European market volumes defined in Section 3.1, the distribution by application segment is estimated to 2050 for each scenario. The approach combines historical evidence with short-term market forecasts in order to produce a consistent trajectory over the full horizon.

The segment definitions and terminology follow the end-user application map established in *D6.6 End-user applications assessment* [2]:

- **Centralised vs distributed.** Shares are derived from Becquerel Institute assessments based on historical installations and short-term forecasts, with the split assumed to stabilise between 2035 and 2050.
- **Specific subsegments** are assessed across these centralised and distributed markets. Long-term penetration were based on multiple sources, including ITRPV, but also BI expertise and previous work conducted in initiatives such as SEAMLESS-PV or BIPVBoost [1] [6] [7]. Centralised segment referenced in the analysis include **utility-scale ground-mounted** plants, **agriPV** and **floating** installations. Distributed market covers rooftops in the **residential** and **commercial and industrial** sectors, as well as **BIPV** applications. Other specific segments include **IIPV** and **VIPV**.

Shares are calibrated to 2015 to 2024 history. The years 2025 to 2050 follow forecasts and move within bounded paths set by a qualitative assessment of various structural drivers, including regulatory conditions, technology maturity, competitiveness at system level, grid availability and congestion, and socio-demographic factors. Where relevant, practical ceilings are applied based on stock or land-use constraints [6] [7]. For each scenario and each year, the sum of all segments aligns with the total European market figures extracted from the identified scenarios. Replacement volumes from end-of-life are included in annual additions using the lifetime assumptions documented in the Annex.

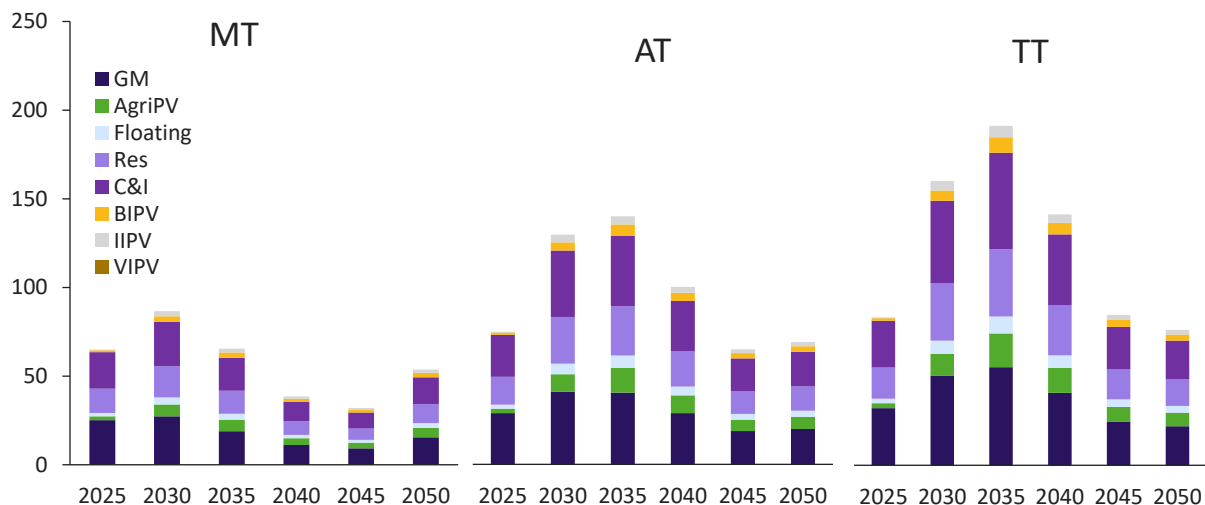


Figure 3.2: Annual European PV additions by subsegment under MT, AT and TT, 2020 to 2050 (GW)

4. PVKS/Si tandem potential penetration

This section translates the European PV market trajectories described in Section 3 into a potential market for PVKS/Si tandem modules by 2050. For each combination of transition scenario (MT, AT, TT) and application segment, the share of annual installations that could be met by tandems is estimated, based on expected efficiency, service life and manufacturability relative to incumbent n-type c-Si.

Section 4.1 introduces two stylised technology uptake paths for PVKS/Si tandem PV that are used in the quantitative assessment.

Tandem uptake within each segment is represented with a logistic diffusion model (Section 4.2). On this basis, peak penetration levels by sub-segment are derived (Section 4.3), together with the resulting annual market volumes under the different European PV scenarios (Section 4.4).

4.1. Definition of the tandem uptake paths

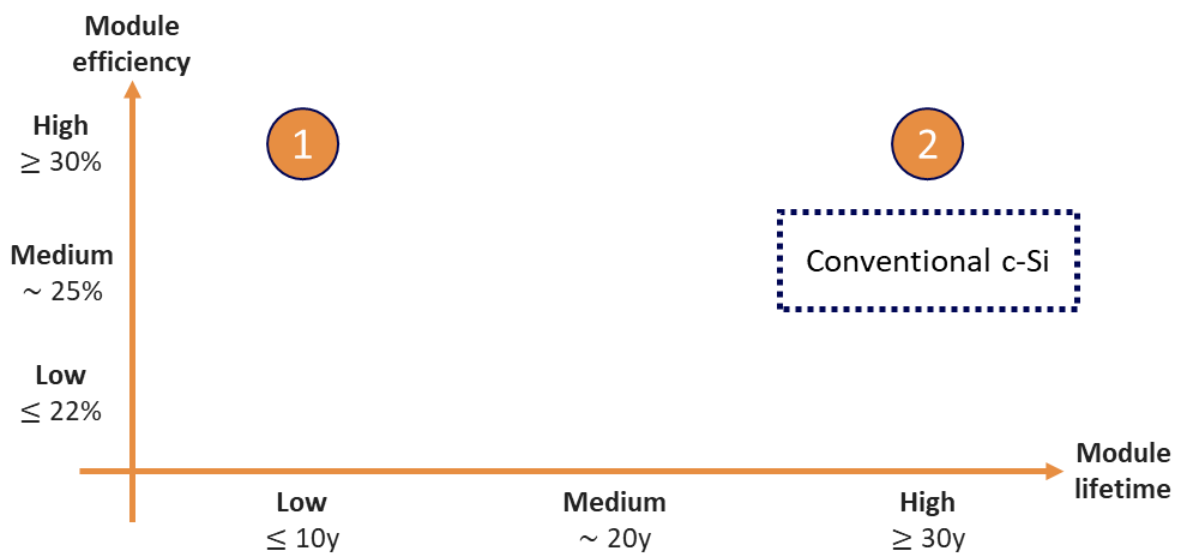


Figure 4.1: Summary of possible performance paths for perovskite-based PV products

Path 1. Short lifetime with high efficiency

Tandem modules deliver high specific yield but carry shorter warranted life. This profile suits space-constrained sites and early adopters willing to trade lifetime for efficiency. Bankability in large ground-mounted and building-integrated projects remains modest until stability improves.

Path 2. Long lifetime with high efficiency

The perovskite layer combines robust stability with high efficiency through improved compositions, defect passivation, thermo-mechanical control and tandem-grade encapsulation. Modules deliver a clear efficiency lead together with long warranties and predictable field performance. Balance-of-system gains from higher energy density are realised across segments, enabling broad deployment in rooftops and in utility-scale plants. By the 2040s this profile supports default selection for most new additions, with further gains as ageing PV installations are renewed when modules reach the end of their service life.

4.2. Market penetration model

Tandem perovskite–silicon uptake is modelled with a **logistic S-curve** applied within each subsegment. The curve is defined by three parameters. **Entry year** marks the start of meaningful commercial availability. **Lag time** governs the speed from entry to the inflection point. **Peak share** sets the asymptote within the accessible market.

The **entry year** is set to **2028** in line with public manufacturing roadmaps and ITRPV timelines for first commercial tandem products. Entry timing is critical because it shifts the entire curve along the time axis and therefore changes cumulative deployment. An earlier entry increases the area under the curve even if the subsequent growth rate is unchanged. A later entry compresses the window for scale-up and lowers cumulative market capture by 2050.

The **lag time** is set to **six years**, reflecting diffusion observed in recent cell technology transitions such as PERC and the early TOPCon rollout. Lag time is measured from entry to the inflection point, where the annual growth of market share is at its maximum. It captures qualification and warranty cycles, production learning and yield ramp, equipment retooling, supply chain adaptation, and the accumulation of field data that underpins bankability. A shorter lag implies faster displacement of incumbent n-type offerings. A longer lag implies extended coexistence and slower share gains.

The **peak share** is scenario-dependent within the technology uptake framework defined in Section 4.1. Saturation remains below 100 percent to account for other technologies, should it be thin film (CdTe, CIGS, ...) or c-Si p-type based, single junction or tandem. Within the n-type market, the maximum attainable share depends on the efficiency need for the end-use application, the cost competitiveness at system level, and the lifetime requirement. Given the penetration timeline, this maximum share should mainly target the replacement of modules in ageing PV installations as they reach the end of their expected service life.

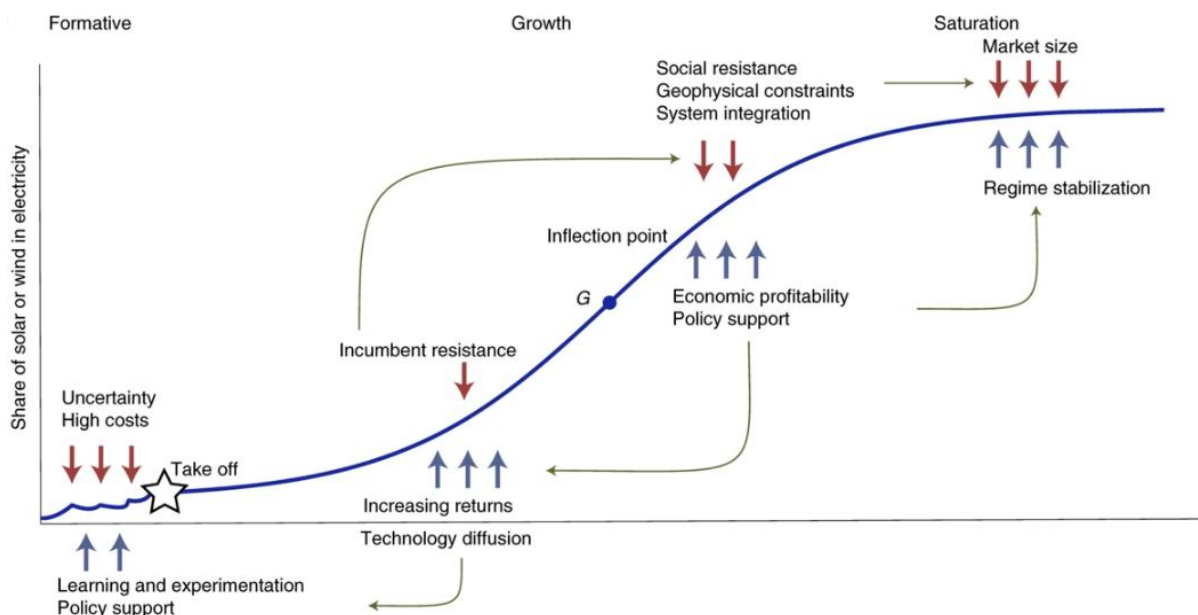


Figure 4.2: Illustrative S-curve of technology diffusion showing formative, growth, and saturation phases [8]

4.3. Penetration across sub-segments

Penetration by sub-segment is estimated with the diffusion framework detailed in Section 4.2 and uses the segment definitions and drivers documented in the end-user assessment. Shares are expressed as the portion of annual European installations in each sub-segment that can be captured by perovskite–silicon tandems. Values represent attainable peaks by 2050, with the year-by-year profile given by the S-curve.

Table 4.1: Tandem perovskite penetration of each segment hypothesis depending on their lifetime & efficiency performances

	Path 1 Short lifetime High efficiency	Path 2 Long lifetime High efficiency
Ground-mounted	40%	90%
AgriPV	20%	90%
Floating	20%	90%
Residential	5%	90%
C&I	5%	90%
BIPV	1%	90%
IIPV	1%	90%
VIPV	40%	90%

Ground-mounted plants target the lowest levelised cost of electricity. Procurement is driven by bankability, supply at scale, and designs that cut balance-of-system and operating costs. Tandem adoption is therefore conditioned by clear LCOE gains at system level. Under **Path 1** (short lifetime, high efficiency) the efficiency lead can yield competitive LCOE in selected sites, so a peak near **40%** is attainable, though shorter warranties limit volumes. Under **Path 2** (long lifetime, high efficiency) long service life and strong yields support wide adoption and make the replacement of existing modules at the end of their service life attractive, with capture approaching **90%** of annual additions.

AgriPV and **floating PV** face similar constraints, including product standardisation and operation in harsher environments. In these segments, lead may also be perceived as a concern given the proximity to crops and water, but this has not been explicitly modelled in the shares. **Path 1** reaches about **20%** in each case as high efficiency delivers value despite shorter life. **Path 2** reaches about **90%** once stable long-life products and compatible mounting systems are standard.

BAPV on conventional rooftops in **residential** and **C&I** segments depends on efficiency and weight on constrained surfaces. **Path 1** stays near **5%** because shorter lifetime limits rooftop economics. **Path 2** rises toward **90%** with both high efficiency and long lifetime.

BIPV requires certified products that meet building codes, suit architectural needs, and match the service life of the building envelope. **Path 1** remains near **1%** since shorter lifetime is incompatible with façade replacement cycles. **Path 2** approaches **90%** once integrated products combine high efficiency with durable service life. **IIPV** follows the same logic and uses the same assumptions.

VIPV values high efficiency on limited surface area and operates on shorter system lifetimes. **Path 1** attains about 40%. **Path 2** can reach about **90%** when high efficiency is paired with sufficient durability.

4.4. Results

Across the two tandem technology uptake paths, the annual European PV market rises toward a plateau between 2030 and 2040, then eases into a lower but persistent run-rate as market saturation sets in. Under all three PV development scenarios, the S-curve model assumes that the most easily capturable PV volumes will gradually be exhausted, leaving progressively less space for new installations. As the installed PV stock ages, the replacement of modules and systems that reach the end of their service life takes a larger share of yearly additions, so post-peak activity is driven more by stock turnover than by net expansion. This pattern is visible under all of the three PV development scenarios described in Section 3.

Path 1: Short lifetime & High efficiency

Tandems deliver a clear efficiency lead, but warranted life remains shorter than mainstream products. Utility procurement is driven by lowest LCOE, so higher specific yield makes tandems competitive in many sites and concentrates volumes in ground-mounted projects through the 2030s. Bankability constraints from shorter warranties and limited long-duration data keep uptake in rooftops and building-integrated applications secondary. AgriPV and floating add smaller but visible shares. Annual additions peak between 2030 and 2040, then activity shifts toward replacing modules in early utility-scale assets as they reach the end of their service life, alongside targeted deployments where higher energy density eases grid or land constraints.

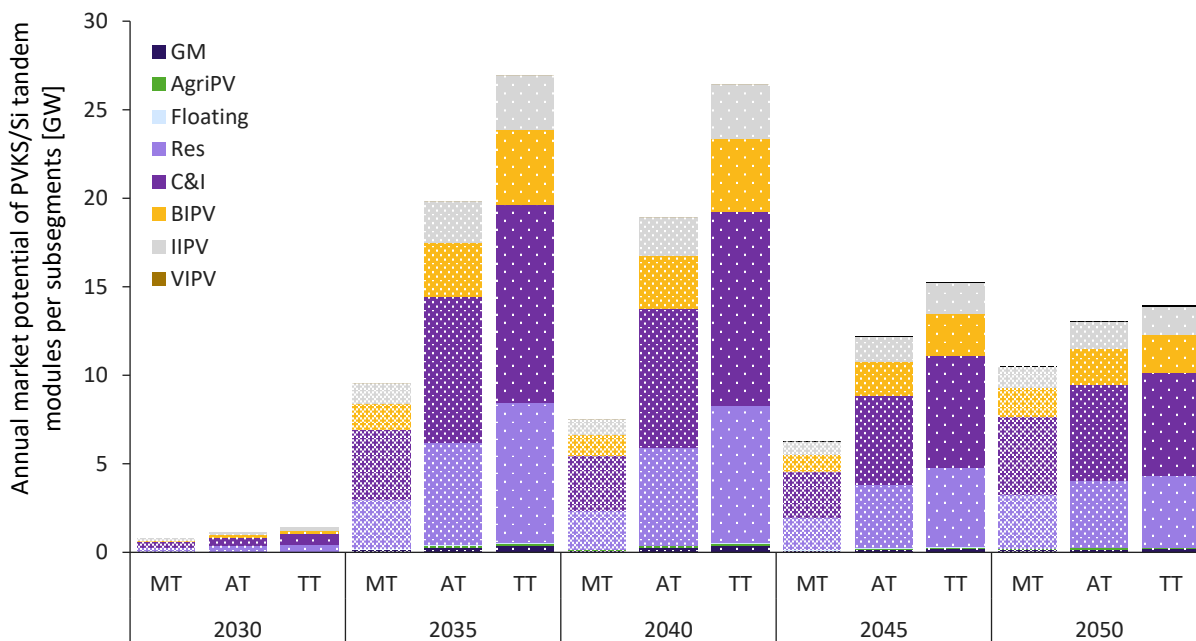


Figure 4.3 Annual market potential (in GW) of PVKS/Si tandem modules per subsegments under PVKS/Si tandem penetration path 1 (short lifetime & high efficiency)

Path 2: Long lifetime & High efficiency

Under the second uptake path, adoption is broad across segments. Robust field performance, predictable yields, and strong balance-of-system effects make tandems a default choice for new capacity by the mid-2030s. Ground-mounted installations dominate absolute volumes due to the scale of centralised procurement, while distributed applications contribute earlier and then continue to grow within their physical and regulatory ceilings. In MT the peak is lower and occurs earlier, while AT and TT produce a higher crest in the mid-to-late 2030s before easing to a sustained replacement cycle. By the 2040s, annual additions are increasingly a mix of replacing modules and systems that have reached the end of their service life and targeted expansion where networks and land availability favour higher energy density.

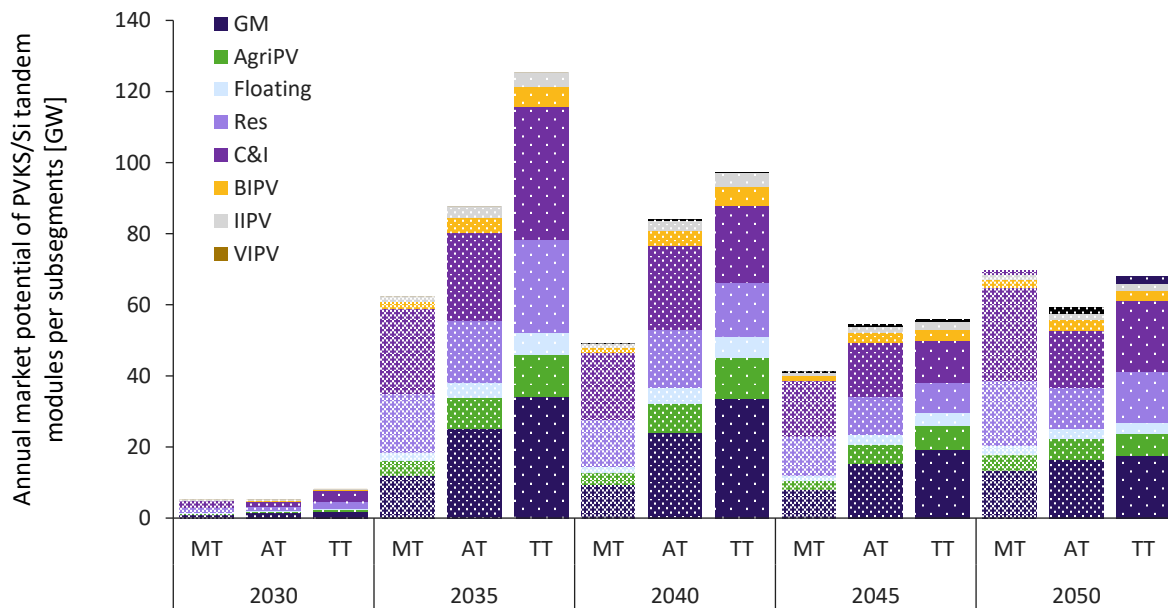


Figure 4.4 Annual market potential (in GW) of PVKS/Si tandem modules per subsegments under PVKS/Si tandem penetration path 2 (long lifetime & high efficiency)

5. Conclusions and key findings

Enter during the current boom, not after it

The PV market in Europe is currently expanding rapidly, with high year-on-year growth. By the time tandems reach volume, annual additions could already be slowing. Early availability of tandem products is key because each year of delay leaves more of the present demand to other installed technologies and reduces the window to build market share before growth slows.

Start where efficiency per area (power density) matters most

Initial uptake will concentrate on surface-constrained applications, notably residential and C&I rooftops, with BIPV contributing if perovskite products manage matching building-envelope lifetimes. These segments value specific yield and the module accounts for a smaller share of total system cost than in centralised plants, which reduces the penalty of any module price premium.

Scale into utility projects with cost and capacity proof

The step-up in absolute volumes could come from ground-mounted plants once tandems combine their clear efficiency lead with long, warranty-level lifetime, bankable warranties, predictable degradation, and multi-GW manufacturing. Compatibility with existing n-type lines and future cost savings could enable tandems to integrate into this highly competitive segment. A similar, though smaller, opportunity could also emerge in AgriPV and floating PV segments.

Plan for the replacement phase

As already installed systems age and modules reach the end of their service life, a wave of replacement of existing PV infrastructure is expected over the coming decades. This will create opportunities even in case of late market entry, through reinstalling or replacing ageing modules in already installed systems. In parallel, emerging segments such as BIPV, IIPV or VIPV should scale later than the mainstream markets and thus offer additional room for PVKS/Si tandem modules.

6. Annexes

6.1. Annex 1: Note on European figures derived from IEA NZE (WEO 2024)

The latest IEA Net Zero by 2050 update in World Energy Outlook 2024 reports PV totals at the global scale only. To obtain European values, a time-varying European share of global annual additions was applied, calibrated to recent deployment and structural drivers. The resulting annual series was converted into a cumulative European path using an S-curve to ensure a smooth, historically consistent trajectory to 2035 and beyond. The table below reports the assumed shares and the deduced European market volumes used in the assessment.

Table 6.1: Assumed European shares and deduced PV volumes from IEA NZE (WEO 2024)

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Global Cumulative market [GW]	2 747	3 389	4 094	5 018	5 833	6 694	7 836	8 901	9 996	11 029	12 078
Global Annual market [GW]	643	642	705	924	815	861	1 142	1 065	1 095	1 033	1 049
Assumed share of Europe in Global market	9,2%	10,1%	9,8%	8,1%	9,9%	10,0%	6,8%	7,0%	6,5%	6,4%	5,8%
Deduced European market in IEA scenario [GW]	59	65	69	75	80	86	77	75	71	66	60

6.2. Annex 2: Service life assumptions

The scenario framework uses a simplified representation of PV system service life that takes the expected lifetime of PV modules as its starting point. Assumed lifetimes are consistent with current industry practice for product and performance warranties and with the trends reported in the International Technology Roadmap for Photovoltaics (ITRPV), which indicate a gradual extension of typical module service life beyond today’s 25-year benchmark as reliability improves [1].

Average lifetimes for new installations are assumed to increase over time, reflecting improvements in product reliability, warranties and operational practices. Table 6.2 summarises the values used in the analysis. These lifetimes apply to all systems commissioned in the indicated periods, irrespective of the application segment (ground-mounted, rooftops, BIPV, AgriPV, floating, IIPV, VIPV).

Table 6.2: Expected average service life for systems installed (adapted from ITRPV [1])

Before 2020	Between 2021 and 2025	In 2030	In 2040	In 2050
20 yrs	25 yrs	30 yrs	35 yrs	40 yrs

These lifetimes are used to determine when installed capacity reaches the end of its expected service life within the long-term scenarios and, therefore, how much of future annual PV additions comes from replacement of ageing systems. Early replacements or repowering driven by non-technical factors (such as site redevelopment, building renovation cycles or vehicle scrappage) are not modelled separately and are assumed to remain limited compared with the volumes driven by the normal service-life profile.

7. References

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