Deliverable 7.5 - Market status report including benchmark with competing technologies

Task 7.3: Applications for IBC: market status, potential and economic benchmark of competing PV technologies

WP7: Communication, Dissemination & Exploitation

Lead participant: Becquerel Institute

Delivery date: 31/10/2023

Dissemination level: PU - Public

Type: R — Document, report

Document History

Date	Version	Prepared by	Organisation	Approved by	Notes
06/11/2023	v1	Gaëtan Masson, Philippe Macé, Elina Bosch, Adrien Van Rechem, Damien Gautier, Julien Van Overstraeten, Melodie de l'Epine	BI	Florian Buchholz	First version
07/11/2023	V1.1	Daiva Ulbikiene	PROTECH	Florian Buchholz	Minor editing

Acknowledgements

The work described in this publication has received funding from the European Union's Horizon Europe energy research and innovation programme under grant agreement № 101084259.

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Executive Summary

This deliverable aims to **identify suitable PV applications for IBC** cells and modules, assess their **market potential**, compare **competing PV technologies**, and explore **future possibilities**.

IBC technology is first presented, with its characteristics, strengths, weaknesses, what distinguishes it from other PV technologies, and its status within the current PV market. The different types of PV applications are then presented in details. The competitiveness of IBC technology is then studied for specific PV systems. An overview of the possible IBC evolution routes is finally provided.

The PV technological landscape has rapidly transformed, from small multi-Si cells to big mono-Si ones, and is now shifting from p-type to n-type, driven by cost decreases of wafers and an appetite for higher efficiencies

The PV industry is dominated by **c-Si monocrystalline** technologies and has seen significant changes, including a **shift from multi-crystalline to mono-crystalline** silicone wafers, a move from Al-Back Surface Field (Al-BSF) to Passivated Emitter Rear Contacted (PERC) cell technology, and a recent **take off of n-type technologies** such as TOPCon, IBC, and HJT.

The IBC technology is highlighted for its **unique rear-side design** and **increased energy conversion efficiency**. Despite past challenges, recent developments, including **polyZEBRA** and **POLO IBC** cells, have **improved cost-effectiveness**, **compatibility** with **manufacturing equipment**, and **efficiency**. These advancements position IBC technology as a promising solution for various PV applications.

Historically, IBC technologies represented a **small portion of the PV market**. However, recent developments in terms of cost have led to a **significant increase in annual installations**. Estimates show that almost 7 GW have been installed in 2022. Forecasts suggest that under a business-as-usual scenario, the annual market share of IBC technologies will **reach 12%** by the end of the decade, with annual installations **projected to reach around 134 GW by 2030**. These forecasts emphasize the expected growth and maturation of IBC technologies, aided by projects like IBC4EU.

IBC technology's potential is significant and largely varies from one PV segment to another, with most opportunities lying on the distributed PV segment and with integrated PV in the short term, while in the long term all applications are within reach, as cost decrease and efficiencies increase

- **Centralized**: This segment is characterized by large-scale plants, with capacities that are tending to grow larger and larger, up to several GW these days. This centralized market should account for just over half of the total market over the next decade.
  - **Conventionnal groud-mounted**: Currently account for the vast majority of centralized installations. The main focus for this segment is module affordability, as the primary objective is to enhance competitiveness and achieve the lowest possible LCOE.
  - **AgriPV**: This segment harmoniously combines agricultural activities with solar PV within the same land area. This sub-segment is set to grow significantly over the coming decade, thanks to all the co-benefits of such systems and to technical and economic progress.
  - **Floating**: These systems can be found on artificial/natural freshwater reservoirs or near/offshore sea water.
- **Distributed**: This segment encompasses diverse applications and integration methods within the distributed PV landscape all characterized by their decentralized nature. This distributed segment should account for just under half of all new installations in the coming decade.

- **BAPV**: These installations represent the vast majority of the distributed segment. It encompasses all so-called conventional installations where modules are positioned on buildings, most often on roofs, using mounting structures.
- **BIPV**: These systems seamlessly integrate into building structures, and are an integral part of their design and functionality. They emphasize aesthetics, customizability, and multifunctionality.
- **VIPV**: These specialized application of solar technology involve integrating photovoltaic panels or cells directly into vehicles. This type of system can extend the driving range of electric vehicles but also contribute to a reduced load on the electricity grid.
- **IIPV**: Finally, this segment includes all the systems seamlessly incorporating solar panels into infrastructure components, usually around or above roads.

From these descriptions, it appears that the end-use applications for which IBC technology should be the most attractive are the **distributed market**, especially **residential**, as well as **some integrated PV applications**. Their significant market potential in absolute terms, combined with a higher willingness to pay, makes these PV segments preferential targets that fit well with the attributes such as efficiency and aesthetics of IBC technology.

While IBC technologies remain more costly to produce than competing ones, they are already almost as competitive as them from an LCOE point of view. The IBC4EU innovations should help decrease the manufacturing cost to 0,12 €/Wp, thereby enabling competitiveness on all segments

The competitiveness of the IBC technology is assessed and compared in three case studies: (i) utility-scale PV: conventional ground-mounted PV (25 MW); (ii) BAPV: residential (5 kW) and (iii) BAPV: C&I (250 kW).

Manufacturing Cost & CAPEX comparison

All other things being equal, IBC technology has manufacturing costs roughly equivalent to those of competing technologies, but in practice economies of scale are such that, to date, PERC and TOPCon technologies have slightly lower costs. The IBC4EU project aims to accelerate the development of the technology so that manufacturing costs should be lower by the end of the project.

As a result of these differences in module manufacturing costs, the CAPEX of IBC installations is currently slightly higher than that of PERC and TOPCon installations, especially for large systems, where the CAPEX is more sensitive to module cost. Compared with mainstream PERC and TOPCon technologies, this results in a CAPEX for IBC installations that is currently around 20% higher for ground-mounted installations, around 10% for C&I installations, and only 3% for residential systems.

Levelized Cost of Electricity (LCOE) comparison

In centralized segments, IBC slightly less competitive than PERC (-12%) and TOPCon (-14%) due to higher module prices. Nevertheless, in distributed residential and C&I segments, where modules are a smaller CAPEX proportion, IBC can be considered nearly as competitive as PERC (-1% residential, -9% C&I) and TOPCon (-3% residential, -11% C&I), considering current technology and cost advancements.

The potential of IBC technology is huge and will shape the future of the PV sector with enhanced efficiency and affordability, with up to 60% market share by 2030, equivalent to 668 GW per year

Thanks to possible major technological developments, for example through projects such as IBC4EU, the IBC technology could achieve levels of performance in terms of **efficiency** and **manufacturing cost** that could enable it to **penetrate the market more significantly** than expected. Depending on the performance achieved by IBC, this technology could capture **from 12% of the annual market by 2030**, in the business-as-usual scenario, **up to 60%** in the best case. This would represent an **annual global IBC market** of **at least 134 GW** in **2030**, up to **potentially 668 GW** in the best case scenario.

1 Introduction

This document is a deliverable "D7.5 - Market status report including benchmark with competing technologies" of the project IBC4EU: Piloting novel cost-competitive bifacial Interdigitated Back Contact (IBC) technology for vertical integrated European GW scale PV production value chain.

This document is the result of Task "T7.3: Applications for IBC: market status, potential and economic benchmark of competing PV technologies" in Work Package "WP7: Communication, Dissemination & Exploitation". This task T7.3 and this deliverable D7.5 aim to identify suitable PV applications for IBC cells and modules, assess their market potential, compare competing PV technologies, and explore future possibilities, all with a focus on the high-efficiency IBC technology.

2 Method

To begin with, in Section 3, the PV technology landscape is briefly described, before showing how IBC technology currently fits into it. The operation and main characteristics of the IBC4EU technology are described, with a focus on the polyZEBRA and POLO IBC technologies that are being developed as part of the IBC4EU project. The performance and market figures for IBC technology are then compared in a summary table with the other dominant cell technologies. Finally, some historical figures for the IBC market over the last 10 years are given. Forecasts are also provided up to 2030, based on a business as usual scenario.

Secondly, PV applications are all reviewed, classified by segment (centralised/distributed) and sub-segments, with a description of the type of system, modules typically used, market strengths and weaknesses, and assessed in terms of the relevance of IBC technology to this type of application.

These sections will clearly identify where the characteristics of IBC technology meet the needs of specific types of PV applications. These targeted applications are then benchmarked from a Life Cycle Costing (LCC) and competitiveness point of view in Section 5 and an overview of the possible evolution routes of these variables is provided in Section 6.

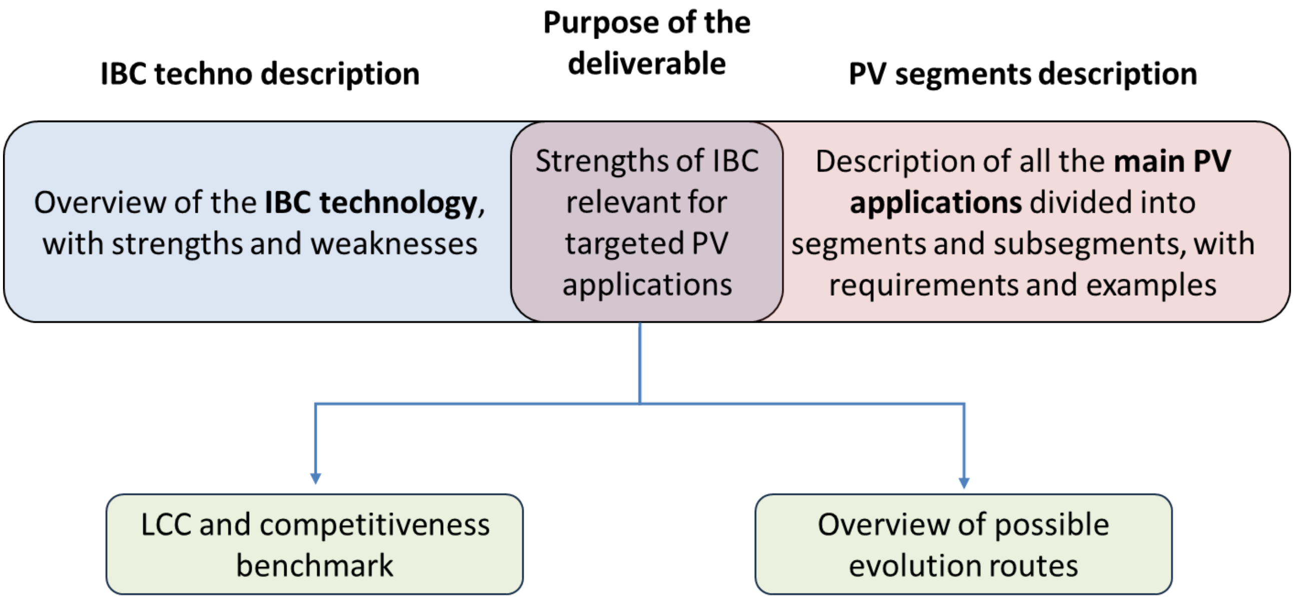


Figure 2-1: Quick summary of the deliverable goal

3 IBC in the PV technological landscape

3.1 PV technological landscape

The PV industry encompasses a **wide variety of different cell technologies**. In recent years, however, this technological landscape has undergone some major changes over the last few years with recent massive industrial and technological developments:

- **Transition from multi-crystalline to mono-crystalline wafers**, with multi-crystalline wafers accounting for 70% of the market in 2015 no more than 5% in 2022. These multicrystalline wafers should therefore be phased out of production in the years or months to come.

- **Shifting from Al-Back Surface Field (Al-BSF) to Passivated Emitter Rear Contacted (PERC)** cell technology. In 2015, Al-BSF technology held a dominant 90% market share, but it has significantly decreased and now represents only 5% of the market in 2022. This Al-BSF technology should also soon be phased out of production.

- **An emerging transition from the p-type PERC technology towards the n-type** including **Tunnel Oxide Passivated Contact (TOPCon)**, **Interdigitated Back Contact (IBC)** and **Heterojunction (HJT)** technologies. While PERC remains the mainstream choice, comprising almost 80% of the market in 2022, n-type technologies have been steadily growing from a mere 0,5% in 2015 and are projected to reach 17% market share in 2022. These n-type technologies are anticipated to become the market leaders by 2026.

Despite the significant technological diversity of the PV industrial landscape, the vast majority of the current market is dominated by c-Si monocrystalline technologies, with the PERC p-type, and the emerging n-type including TOPCon, IBC and HJT. These technologies will therefore be more specifically assessed alongside IBC in this report.

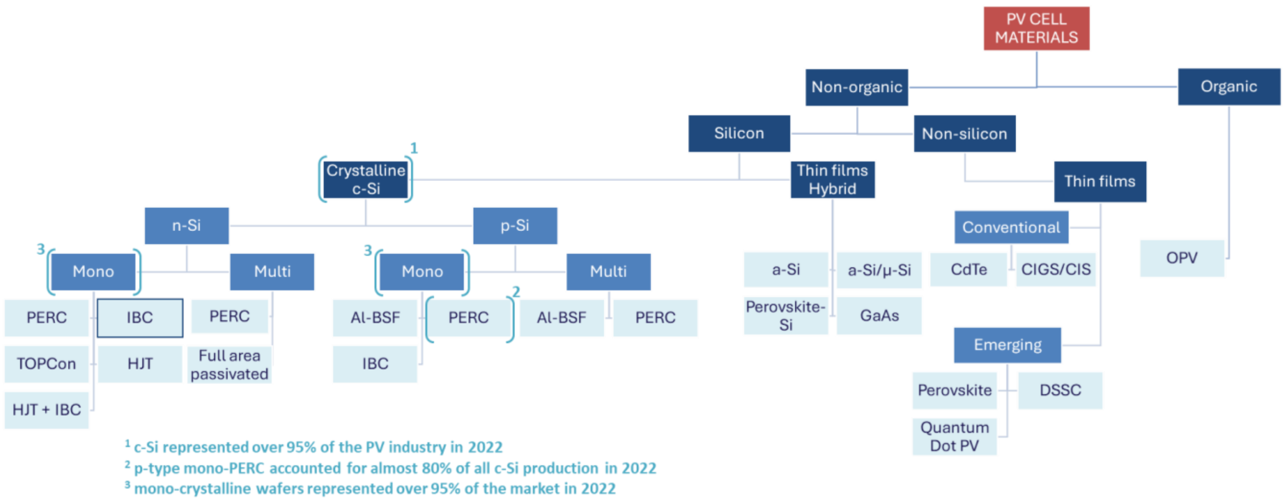


Figure 3-1: Overview of PV technologies

3.2 IBC solar cell technology

Interdigitated Back Contact (IBC) solar cell technology represents a significant advancement in PV architecture. IBC cells are distinguished by their unique **rear-side design**, featuring an interdigitated pattern of p and n-type contacts. One of the standout features of IBC cells is their **elimination of front-side metallization**, which leads to **increased energy conversion efficiencies**. Furthermore, these devices are ideally suited for implementing polysilicon-based passivating contacts for both polarities. These passivating layers, which are known for their high parasitic absorption, are applied to the rear side of the solar cell.

Despite their potential advantages, IBC solar cell technology historically faced certain challenges, limiting its adoption to high-price niche markets like residential rooftops and device-integrated applications. The complexities in manufacturing processes, primarily driven by the intricate interdigitated patterns, made IBC cells costly and less accessible.

However, recent developments have led to a breakthrough in IBC technology, notably the introduction of **polyZEBRA** solar cells. These cells have gained recognition for their **compatibility with standard manufacturing equipment**, reducing production costs substantially. This compatibility streamlines the manufacturing process and makes it more cost-effective. Furthermore, polyZEBRA cells incorporate a unique rear-side design with busbars printed on fingers, resulting in savings in terms of materials used, energy required and therefore costs, as well as offering greater efficiency.

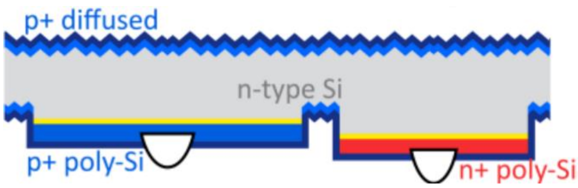


Figure 3-2: PolyZEBRA solar cell technology scheme

Another noteworthy development in IBC technology is the emergence of **POLO IBC** cells. These POLO cells take a distinct approach by utilizing **screen-printed organic conductive polymers** as both the passivation layer and rear electrode. This innovative design eliminates the need for conventional metal contacts, which further enhances cell efficiency and durability. Additionally, Polo IBC cells are known for their flexibility in accommodating various wafer sizes, making them suitable for a wide range of module designs and installations.

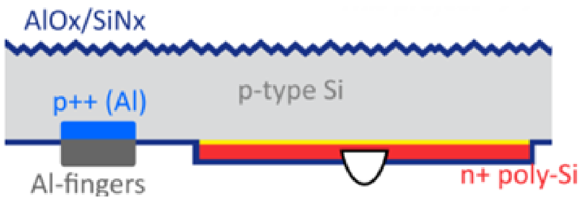


Figure 3-3: POLO IBC solar cell technology scheme

Advances in polyZEBRA and POLO IBC cell technologies are bringing significant improvements for IBC PV cells and modules. Their **cost-effectiveness**, **compatibility with existing equipment** and **low use of materials** make them compelling options for a variety of PV applications. These advances make a significant contribution to the solar industry's key objectives of **cost reduction**, **improved efficiency** and **module durability**. With continued research and development, IBC technology is set to play a key role in shaping the future of solar PV production, and the IBC4EU project is part of this process.

3.3 IBC comparison with other technologies

The Table 1 below compares the likely trends in the key characteristics of the four main cell technologies over the next few years.

Table 1: Comparison of cell technologies in mass production

	p-PERC	n-TOPCon	n-HJT	n-IBC
Efficiency forecast[1]	Cell Efficiency: 23.2% 23.6% 23.8% 24.0% 24.1% 24.1% 24.1% 24.2% 24.2% Module efficiency: 21.0% 21.4% 21.5% 21.7% 21.9% 22.1% 22.2% 22.4% 22.6% 2022 2023 2024 2025 2026 2027 2028 2029 2030	Cell Efficiency: 23.8% 24.3% 24.6% 25.0% 25.2% 25.4% 25.4% 25.5% 25.6% Module efficiency: 22.0% 22.2% 22.5% 22.8% 23.0% 23.2% 23.4% 23.7% 23.9% 2022 2023 2024 2025 2026 2027 2028 2029 2030	Cell Efficiency: 24.1% 24.5% 24.7% 25.0% 25.3% 25.7% 25.8% 25.9% 26.0% Module efficiency: 22.4% 22.5% 22.7% 22.9% 23.0% 23.2% 23.4% 23.7% 24.0% 2022 2023 2024 2025 2026 2027 2028 2029 2030	Cell Efficiency: 24.6% 24.9% 25.2% 25.4% 25.6% 25.8% 25.8% 25.9% 25.9% Module efficiency: 22.5% 22.7% 22.9% 23.0% 23.1% 23.2% 23.4% 23.7% 24.0% 2022 2023 2024 2025 2026 2027 2028 2029 2030
Most competitive module spot price (October 2023)[2]	0,16 €/Wp NB: these prices could be considered as unsustainable prices given the known information in terms of manufacturing costs[3]	0,17€/Wp NB: these prices could be considered as unsustainable prices given the known information in terms of manufacturing costs[1]	0,20€/Wp NB: these prices could be considered as unsustainable prices given the known information in terms of manufacturing costs[1]	0,28 €/Wp
Cell production capacities forecast[4]	2022e: 381 GW 2023f: 360 GW 2024f: 290 GW 2025f: 240 GW 2026f: 200 GW	2022e: 149 GW 2023f: 312 GW 2024f: 489 GW 2025f: 670 GW 2026f: 790 GW	2022e: 40 GW 2023f: 125 GW 2024f: 184 GW 2025f: 244 GW 2026f: 276 GW	2022e: 20 GW 2023f: 45 GW 2024f: 54 GW 2025f: 57 GW 2026f: 61 GW
Market share forecast[5]	78% 71% 55% 44% 34% 25% 18% 12% 9% 2022e 2023f 2024f 2025f 2026f 2027f 2028f 2029f 2030f	10% 16% 29% 36% 42% 47% 50% 51% 54% 2022e 2023f 2024f 2025f 2026f 2027f 2028f 2029f 2030f	3% 7% 9% 12% 14% 15% 17% 19% 20% 2022e 2023f 2024f 2025f 2026f 2027f 2028f 2029f 2030f	3% 3% 5% 6% 7% 8% 10% 12% 12% 2022e 2023f 2024f 2025f 2026f 2027f 2028f 2029f 2030f
Main threats / opportunities	+ High availability of equipment & consumables — Limited prospects for improvements Pronounced LID rates	+ Lower CAPEX than competing n-types + Low temperature coefficient and no LID + Mature manufacturing process Expensive poly-Si deposition	+ Low temperature coefficient + High low-light performance — Not compatible with existing production lines High silver paste consumption	+ Low degradation + Improved high-temperature performance — High cost due to silver consumption

[1]From ITRPV 2023 [5]

[2]Including FOB (Free On Board) and transport fees. FOB from ITRPV [6], FIB (Freight, Insurance and Freight) from pvXchange [7], consulted on 18/10/2023

[3]Based on a position paper from ESMC [8]. See also Section 5.1

[4]Projections from ITRPV 2023 [5], Infolink [6] and manufacturers insights including LONGI, AIKO, SPIC, VALOE & FuturaSun

[5] Becquerel Institute analysis, adapted from ITRPV 2023 [5]

3.4 IBC market status

Until now, IBC technologies have been in its infancy, suffering from a number of constraints that have caused them to **stagnate at around 3% of the annual market**. Over the period 2013-2020, the overall development of PV was such that IBC annual market tripled over this period despite the fact that this technology was still very much in the minority. Since 2021, IBC technologies have benefited from the beginning of the **market transition towards n-type technologies** to start increasing annual installations significantly (+99% between 2021 and 2022), reaching 6,9 GW installed in 2022.

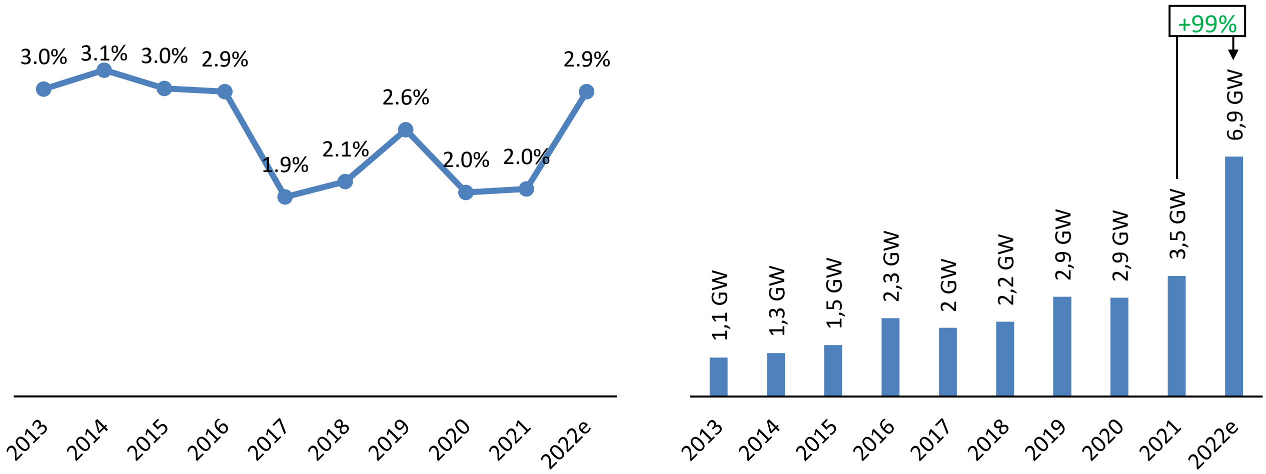


Figure 3-4: Global IBC annual installed capacity share & market
(Becquerel Institute analysis, based on ITRPV 2023)

Assuming a "business as usual" development, the annual market share of IBC technologies should **reach 12% by the end of the decade**, according to Becquerel Institute analysis, based on ITRPV forecasts. According to these projections, annual IBC installations are forecast to increase by **around 40% year on year**, reaching around **134 GW by 2030**. It is important to note that these are **forecasts based on a business-as-usual** scenario, but IBC technologies are expected to continue to mature, through projects such as IBC4EU, and could capture a larger share of the market.

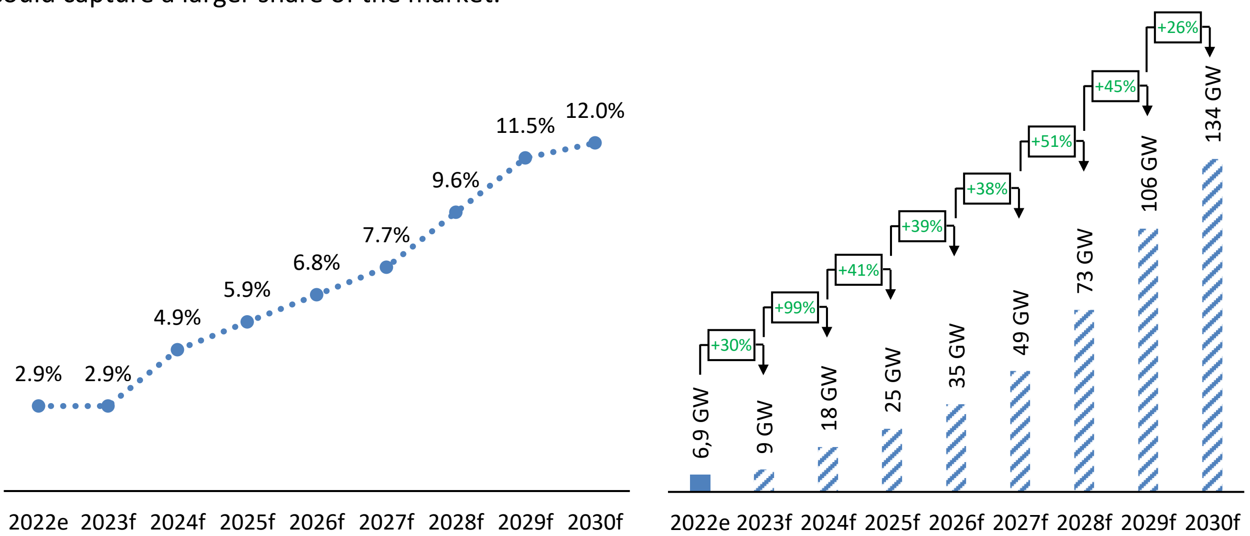


Figure 3-5: Forecasted global IBC annual installed capacity share & market
(Becquerel Institute analysis, based on ITRPV 2023)

4 Overview of PV applications

4.1 Method

This section presents the various possible applications for PV systems, categorised by sub-segment as shown in Figure 4-1 below.

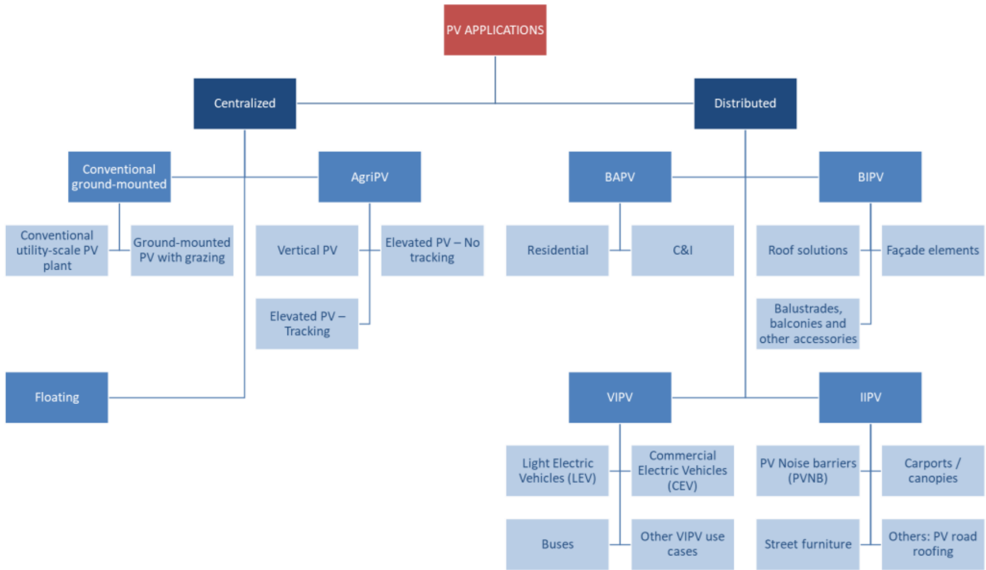


Figure 4-1: Overview of PV application landscape

For the major sub-segments, a forecast is given in terms of **annual installed capacity**, and **annual revenue from module sales**, at **global level up to 2030**. This forecast has been established through a comparative analysis from Becquerel Institute. Revenues from module sales are estimated on the basis of the likely trend in the **spot price** according to a **learning curve**[1], to which are added surpluses relating to transport, insurance, customs charges and intermediaries, the amount of which depends on the sub-segment.

A **SWOT matrix** then summarises the strengths, weaknesses, opportunities and barriers for the specific development of this type of application. Finally, their **interest in IBC and IBC4EU technology** is assessed using the following criteria, on a scale of 0 to 3:

- **Market potential**: A general estimation of the market potential, taking into account technology maturity, feasibility and available areas of exploitation.
- **Willingness to pay**: Module price is not equally important for all PV applications. For example, for large installations, a small variation in price will significantly affect the total cost, while for smaller systems, the price of the modules may be a lesser factor than the cost of the installation and other components.
- **Module aesthetic**: An aesthetic module with rather dark or black colors sometimes facilitates its adoption, in particular for systems with visual exposure. The aesthetic aspect of the systems is therefore more valuable for certain applications, increasing the willingness to pay for them.
- **Module and cell efficiency**: For some sub-segments the surface area available for the PV system is limited and it is therefore important that the cells and/or modules have high efficiency for the installation to be relevant.

[1] Starting from an average spot price of 0,240€/Wp in 2022, with a learning rate of 20% [6] [4]

4.2 Centralized

The **stationary centralized PV segment** gathers three main families: **conventionnal ground-mounted PV**, **agriPV** and **floating PV**. This segment is characterized by large-scale plants, with capacities that are tending to grow larger and larger, up to several GW these days. Although self-consumption is possible for some smaller installations, the most common model is typically total grid injection.

In the case of **agriPV**, adaptations in terms of row spacing or height above ground for mounting structures may be necessary. This agriPV segment is still in its early development, and brings together very different sub-categories of PV systems, depending on the type of agricultural activity concerned.

Floating PV can be found on artificial/ natural freshwater reservoirs or near/offshore sea water, although the latter has only been tested as part of pilot projects.
The centralized market should account for just **over half of the total market** in the years to come. The annual market should increase 5-fold over the decade. The **agriPV** and **floating** sub-segments, which are in their infancy today, should account for a significant share of the market by 2030.

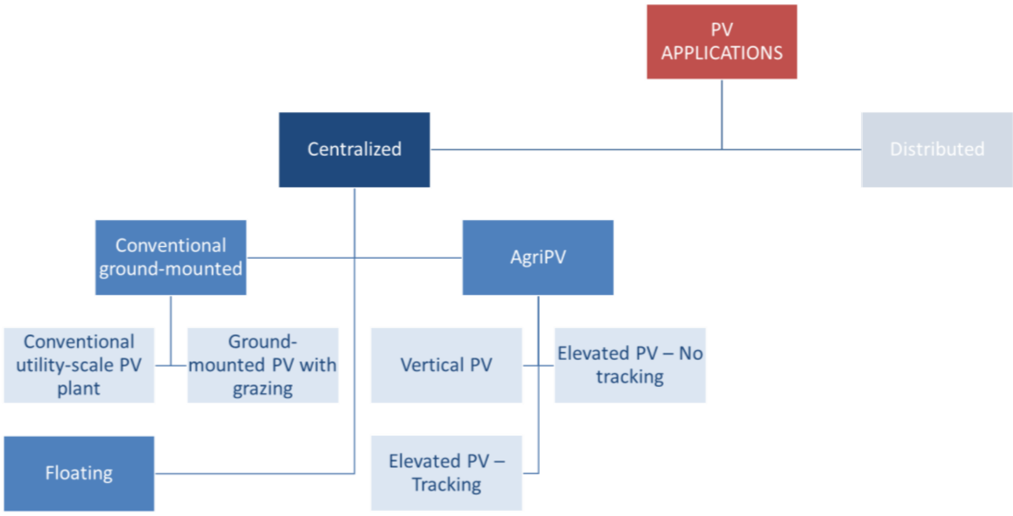


Figure 4-2: Overview of centralized PV application landscape

As this **centralized** market is already **mature** and involves large volumes of modules, module prices should continue to fall over the coming years. Nevertheless, the total value of the module market in this segment should continue to rise thanks to steady market development, and potentially triple by 2030. However, the distribution of these market shares is likely to suffer from fierce competition, driven by the quest for the lowest cost to maximize the profitability of these large installations.

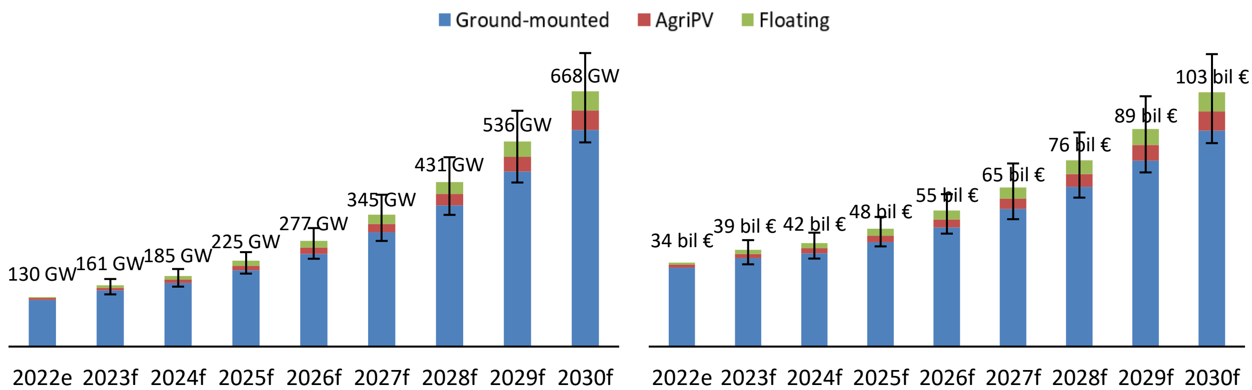


Figure 4-3: Global centralized annual module market & business opportunity

4.2.1 Conventional ground-mounted

Conventional ground-mounted systems currently account for the vast majority of centralized installations, with ranges from a few hundreds of kW to several GW. As far as ground-mounted PV applications are concerned, land can either be solely used to welcome the PV system or land use can be shared between the PV system and an agricultural activity. In this later case, adaptations to the PV system in terms of space between rows or height above the ground for the mounting structures may be required.

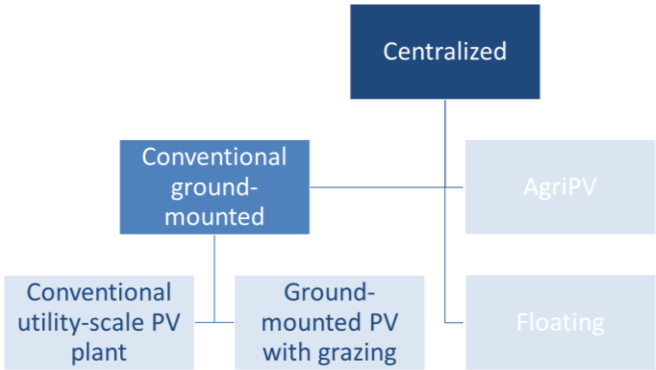


Figure 4-4: Overview of conventional ground-mounted application landscape

This centralized segment is the most developed, but is expected to maintain strong growth and could increase 5-fold by 2030, representing a threefold increase in module revenues.

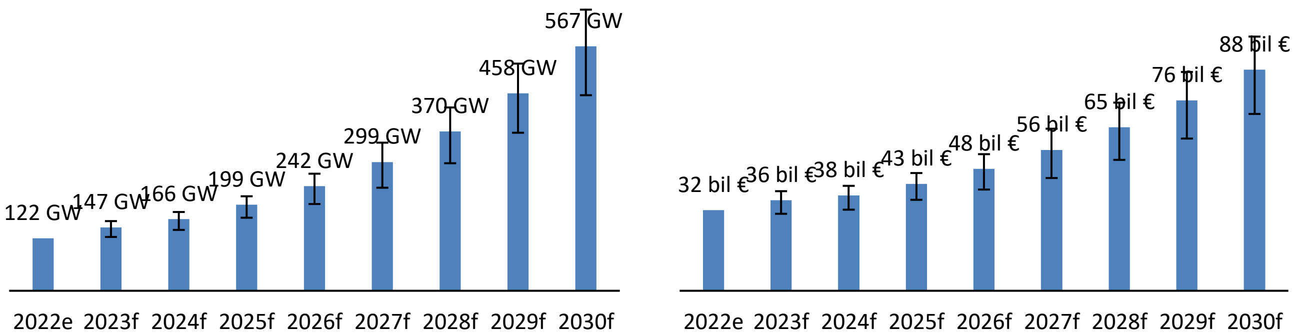
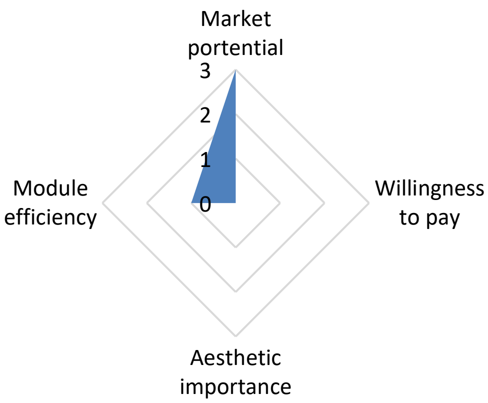


Figure 4-5: Global annual conventional ground-mounted module market & business opportunity

4.2.1.1 Conventional utility-scale PV plant

These **conventional utility-scale PV plant** account for almost all of this sub-segment. For such systems, there is a distinction between **bifacial** and **monofacial** modules. While bifacial modules currently hold a minority share of the market, their rapid growth is anticipated. Additionally, at the system level, there is a choice between **fixed tilt mounting structures** and **tracker systems**. Presently, fixed tilt structures dominate the market, although their market share is expected to decrease as tracker costs decrease and their benefits in terms of lowering LCOE become evident.

Notably, the primary focus for conventional ground-mounted PV plants is **module affordability**, with **efficiency** considerations ranking second in importance. Other factors are of minor significance, as the primary objective is to **enhance competitiveness** and **achieve the lowest possible LCOE**. PERC is currently the leading cell technology for this type of application, but n-type technologies, and in particular TOPCon, which are still in the minority, should rapidly develop significantly.



Strengths: Most mature PV use, benefiting from efficient land use, economies of scale, high capacities and optimal orientations.

Weaknesses: Suitable land for large-scale PV installations may be limited in certain regions, potentially leading to land use conflicts or potential aesthetic concerns and opposition from local communities.

Opportunities: Ongoing technological developments, such as more efficient solar modules and advanced tracking systems, can improve system performance and reduce costs.

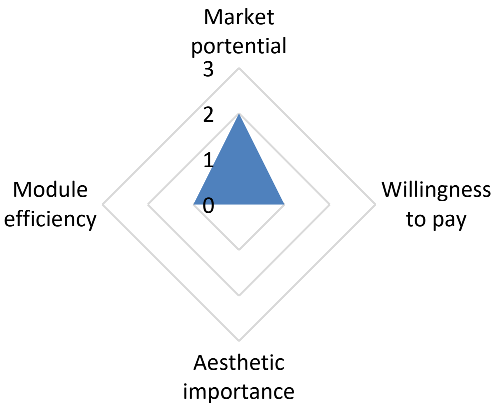
Threats: Changes in government policies, tariffs, or regulations can impact the economic viability of utility-scale ground-mounted PV projects more significantly due to their larger scale.

Figure 4-6: IBC cells used in conventional ground-mounted utility-scale PV plant (source: ISC Konstanz)

4.2.1.2 Ground-mounted PV with grazing

Ground-mounted power plants on agricultural land are technically classic ground-mounted power plants: structures, and PV modules, with a height of between 1m and 3m at the highest point, facing south. Particular attention can be paid to the foundations to minimize the impact on the soil, and on the cabling and structure in order not to harm the animals. The PV technology used is mature and cost-optimized. The PV yield and PV density (about 1MWp per ha) are at their optimum. The distance between the rows can be optimized for agricultural use with an impact on the density.

This agriPV use sparks some controversy around the definition of agriPV, in some countries the agriPV definition and its corresponding legal framework apply to solutions integrated into the existing agricultural activity, or where the agricultural activity is the main activity. The ground-mounted PV with grazing frequently does not satisfy these requirements, mostly because PV electricity production is the main activity (no grazing before PV installation) or the area in the field dedicated to agricultural production is separated from the one dedicated to PV. Additionally, ground-mounted PV with grazing barely presents any difference to conventional ground-mounted PV power plants.



Strengths: Technologically mature, equivalent to ground-mounted PV.

Weaknesses: Restricted construction permits in some countries, susceptibility to animal damage, lower financial support.

Opportunities: Vast global suitability on grazing land (25% of total land).

Threats: Stringent agricultural construction rules, potential food security challenges.

4.2.2 AgriPV

Agrivoltaics, often referred to as **agriPV**, is an innovative land-use practice that harmoniously combines **agricultural activities** with photovoltaic solar power generation **within the same land area**. It involves the co-location of solar panels or PV systems alongside agricultural cultivation, organic farming, or even livestock grazing. Essentially, **agrivoltaics optimizes land resource utilization** by simultaneously harnessing renewable solar energy and fostering agricultural productivity. Key principles include **efficient land use sharing**, **resource optimization**, and **microclimate control** through **shading effects**. This approach offers various benefits, including **increased land use efficiency**, **diversified income streams** for landowners and **reduced environmental impact**. However, challenges such as system design, crop selection, and regulatory considerations must be carefully addressed to ensure the successful integration of agrivoltaic systems into sustainable land-use practices.

This definition of agriPV encompasses a wide variety of different systems, the main sub-segments of which will be detailed in the following sub-sections.

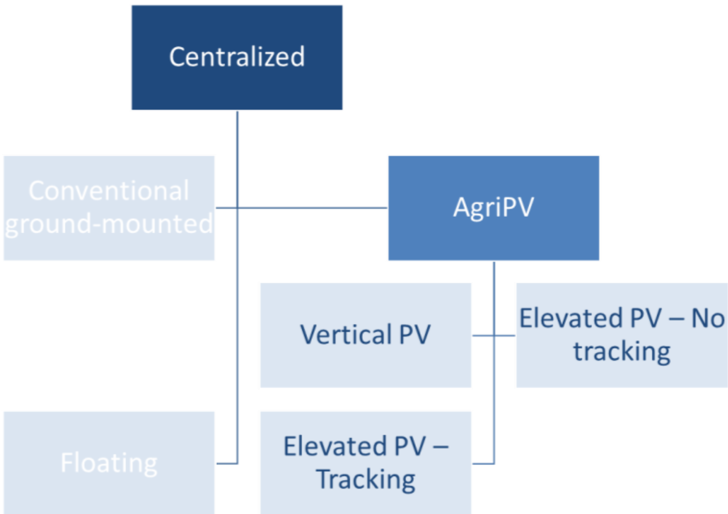


Figure 4-7: Overview of agriPV application landscape

This sub-segment is set to grow significantly over the coming decade, thanks to all the co-benefits of such systems and to technical and economic progress. The annual market for these systems could increase by a factor of 6 by 2030, which represents an almost 4-fold increase in module revenues.

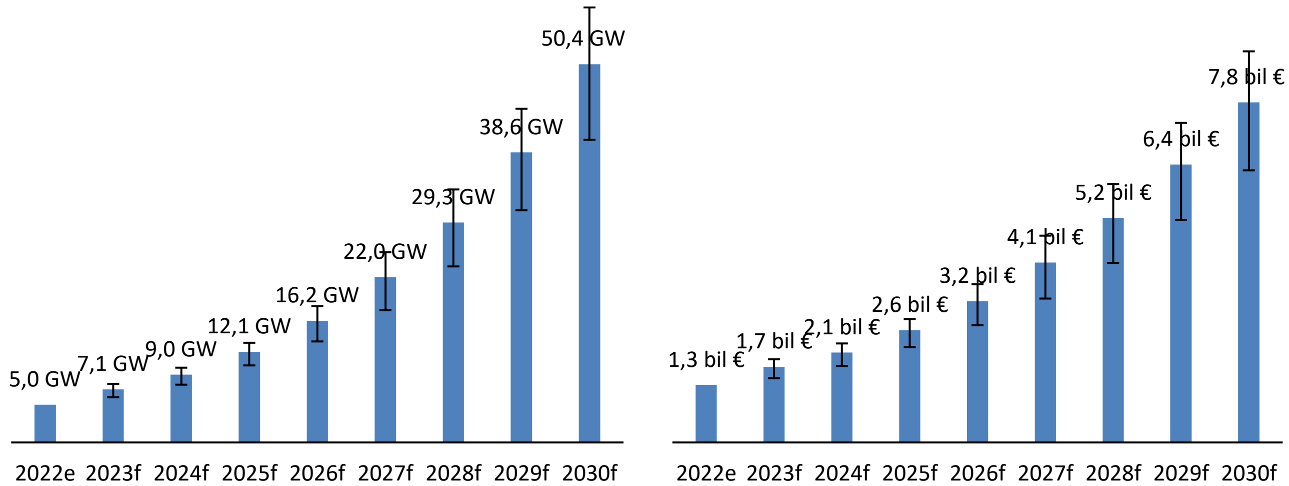
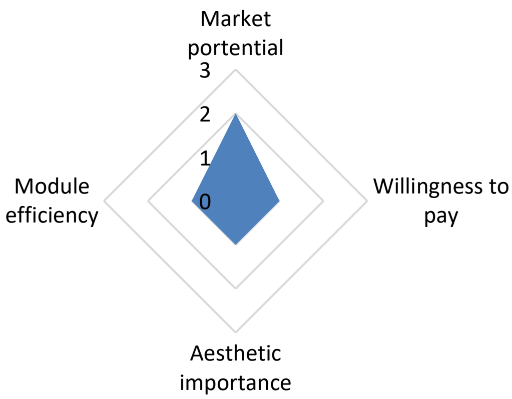


Figure 4-8: Global annual AgriPV module market & business opportunity

4.2.2.1 Vertical PV

This subsegment of agriPV covers systems whose PV modules are **vertically oriented** to **capture solar radiation from both sides**. To accommodate conventional agricultural machinery and minimize shading of crops, there is usually a minimum **spacing of 8 meters between rows**. This arrangement results in a **smaller land footprint**, and the density of PV modules is influenced by the row spacing. Based on initial field feedback in North Europe, there is an estimated 10% deviation from the optimal yield. In cases where an East-West orientation is chosen, shifting energy production towards the morning and evening can be advantageous, particularly in scenarios involving economic models like self-consumption or temporal price valorization.



Strengths: Extensive potential land area, no soiling due to snow.

Weaknesses: Wind vulnerability, reduced production during peak sun hours, low adoption.

Opportunities: Vast cropland potential, particularly in higher latitudes.

Threats: Stringent agricultural construction rules, potential food security challenges.

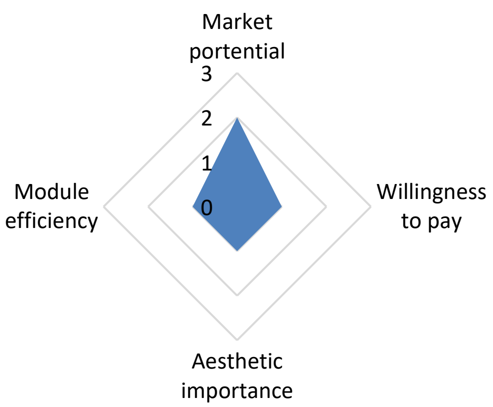
Figure 4-9: Vertical AgriPV plant (source: ISC Konstanz)

4.2.2.2 Elevated PV – No tracking

Elevated PV systems without tracking mechanism are systems where the PV modules are raised above a ground-mounted plant using different types of structures, typically around 4m to 5m above crops or to accommodate agricultural activities like machinery and shrub planting.

There is a great **diversity** in the design of such systems: **height**, the **distance between rows**, etc. The installations can be adapted to the farmer's needs. The **PV density** can be high (almost that of a conventional ground-mounted plant) or lower with semi-transparent modules for example, however, the understanding f crop compatibility in various geographical regions remains somewhat limited.

Elevated systems without tracking must have a design adapted to the agricultural project, with no tracking the use of semi-transparent modules is more desirable. This choice not only aligns with the agricultural context but also yields cost savings by eliminating the need for tracking infrastructure, extra associated investment and O&M costs related to it.



Strengths: Diverse design options, cost-effective (lower CAPEX and OPEX in comparison with same systems with tracking), offers crop protection from extreme weather.

Weaknesses: Lack of sunlight control for crops, limited crop suitability knowledge.

Opportunities: Theoretically adaptable to all cropland, although precise figures are unavailable.

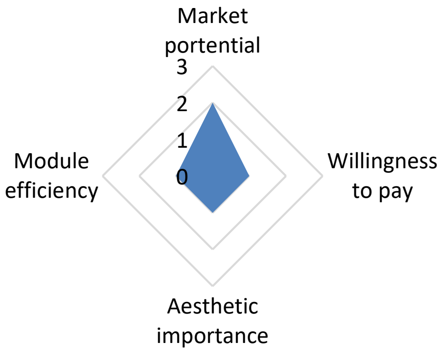
Threats: Increased PV density may harm crops, stringent construction rules on agricultural land, food security concerns, potential for farmers to shift to PV due to higher profitability.

4.2.2.3 Elevated PV – Tracking

Elevated PV systems with tracking mechanism are also elevated above the crops, 3 or 5m above the ground, to facilitate the passage of machinery and mitigate shading effects on the ground. These systems are equipped with **trackers on 1 or 2 axes**, driven by the needs of the agricultural activity while optimising electrical production. This sub-segment is sometimes referred to as dynamic agrivoltaics or advanced agrivoltaics.

While the **initial investment** for this agriPV approach tends to be higher in comparison to other agriPV systems, it holds the unique advantage of **controllability**, ensuring a harmonious **balance between agricultural and PV outputs**. This balance optimization relies on the implementation of **crop-specific algorithms** to govern the tracking system. However, it's worth noting that managing the tracking system and developing these algorithms can impact the overall operational costs of the system.

Most of the elevated PV with tracking solutions available in the market are 1-axial. A few manufacturers offer already a 2-axial tracking system, however, the cost and operating complexity of these 2-axial systems are higher. The tracking system potentially helps to protect the crops from environmental hazards whenever necessary.



Strengths: Adaptable to various crops, flexible for PV or agriculture prioritization, offers weather protection, reduces evapotranspiration and associated costs.

Weaknesses: Highly costly and cost-sensitive. Still in its early steps, resulting in limited knowledge regarding the actual impact of PV production on crops. Potential conflicts may arise between farmers and electricity producers over sunlight allocation.

Opportunities: Theoretically adaptable to all cropland, although precise figures are unavailable.

Threats: Stricter regulations for PV on farmland, food security concerns, farmers shifting to more profitable PV.

4.2.3 Floating

Floating PV can be found on artificial/natural **freshwater reservoirs** or near/offshore **sea water**, although the latter has only been tested as part of pilot projects. These systems offer a number of advantages, including a **reduced water evaporation**, making them useful in water-scarce regions, improvements in **water quality** with decreased algae growth, improved efficiency of modules through **water-cooling effect** as well as **elimination of shading effects**, and provide **opportunities for integration** with hydroelectric or water treatment plants. The main cell technology in this segment is PERC, but TOPCon could develop significantly, and thin-film technologies could also be relevant for their lightweight and flexibility potential.

This sub-segment is still in its infancy, but is growing rapidly thanks to the many co-benefits it offers and the significant development potential offered by the available space. Growth in this sub-segment is thus set to be exponential over the next decade, with the annual market expected to increase 10-20-fold by 2030.

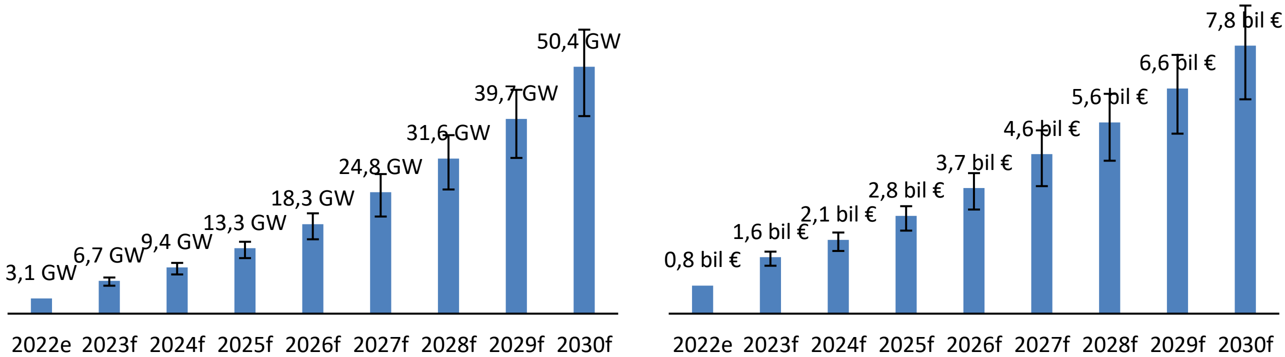
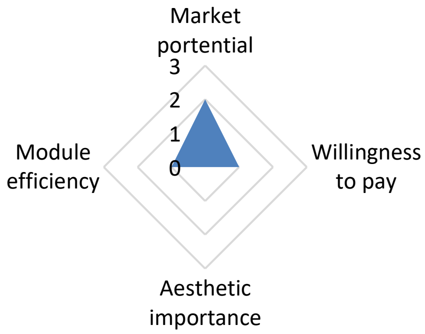


Figure 4-10: Global floating PV market & business opportunity



Strengths: Cooling effect enhances PV efficiency. Reduces water evaporation. Dual-purpose integration with existing infrastructure.

Weaknesses: Complex installation and maintenance. Energy production variability.

Opportunities: Global potential for deployment on water bodies.

Threats: Environmental and regulatory challenges. Competition for water resources.

Figure 4-11: Floating PV installation (source: TNO)

4.3 Distributed

The **distributed PV segment** encompasses diverse applications and integration methods within the distributed PV landscape all characterized by their decentralized nature, and which are usually divided into 4 main categories:

- **Building Applied PV (BAPV)**: This subsegment involves PV systems added onto existing structures, such as solar panels on rooftops or facades. BAPV systems offer the most efficient way to harness solar energy within urban and suburban environments.
- **Building Integrated PV (BIPV)**: BIPV takes integration a step further by incorporating solar modules as integral building elements, including solar windows, solar roof tiles, or solar cladding. These installations seamlessly blend with architectural designs.
- **Vehicle Integrated PV (VIPV)**: VIPV involves the incorporation of PV technology into vehicles, including cars, buses, and even boats. Solar panels on vehicle surfaces can provide auxiliary power and extend the range of electric vehicles.
- **Installation Integrated PV (IIPV)**: IIPV encompasses various integration methods for PV systems into installations or infrastructure, such as solar canopies at parking lots, solar-covered walkways, or solar panels integrated into outdoor furniture.

Each of these subsegments offers distinct opportunities and challenges within the distributed PV domain. Further exploration into these subcategories will provide a comprehensive understanding of their market in the distributed PV landscape.

This distributed segment should account for **just under half of all new installations in the coming decade**. This should translate into a 4-fold increase in module volume in the global annual market, and a more than 2-fold increase in associated revenues.

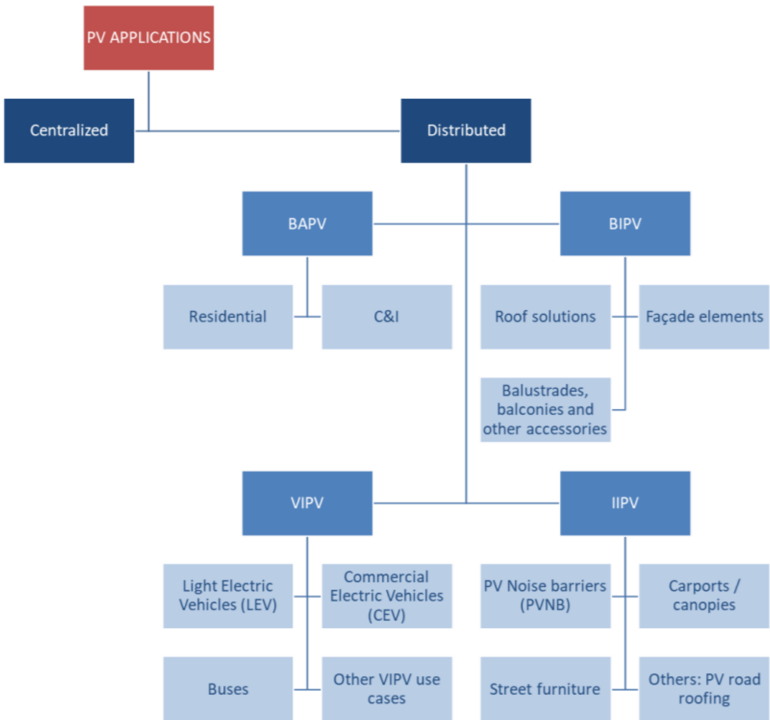


Figure 4-12: Overview of distributed PV apllication landscape

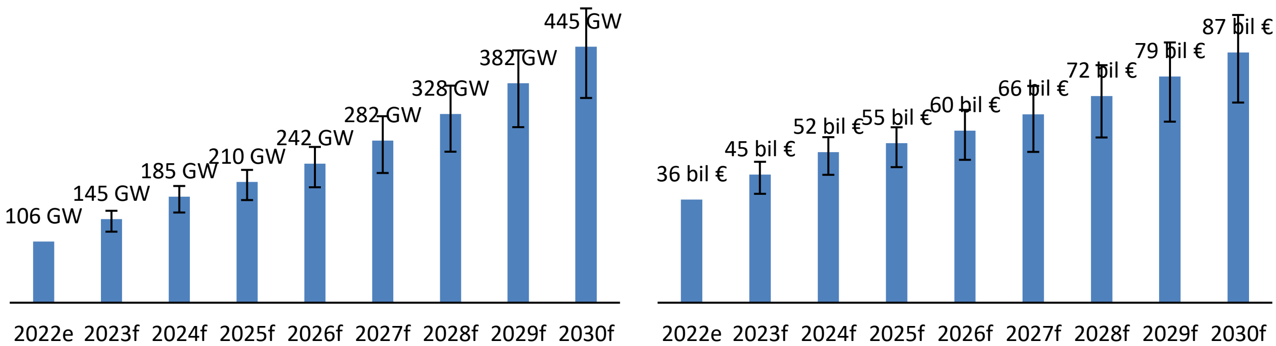


Figure 4-13: Global annual distributed module market & business opportunity

4.3.1 BAPV

Building Applied Photovoltaics (BAPV) represents the vast majority of the distributed segment. It encompasses all so-called conventional installations where modules are positioned on buildings, most often on roofs, using mounting structures. BAPV systems are often divided into sub-categories according to two different characteristics of the concerned building:

(i) directly, the range of annual electricity consumption
(ii) indirectly, the typical PV installed capacity ranges

These subsegments are often divided as follow:

- **Residential**: [0;10] MWh & [0;10] kWp
- **Commercial & Industrial (C&I)** [10;+] MWh & [10;1000] kWp

This BAPV subsegment also includes the so-called simplified BIPV installations. They correspond to BIPV (Building-Integrated PV) systems but using conventional modules mounted on specific mounting structures. This method cuts costs compared with a more expensive BIPV structure. Since the modules and systems are similar to those of BAPV, this type of applications is included here as such.

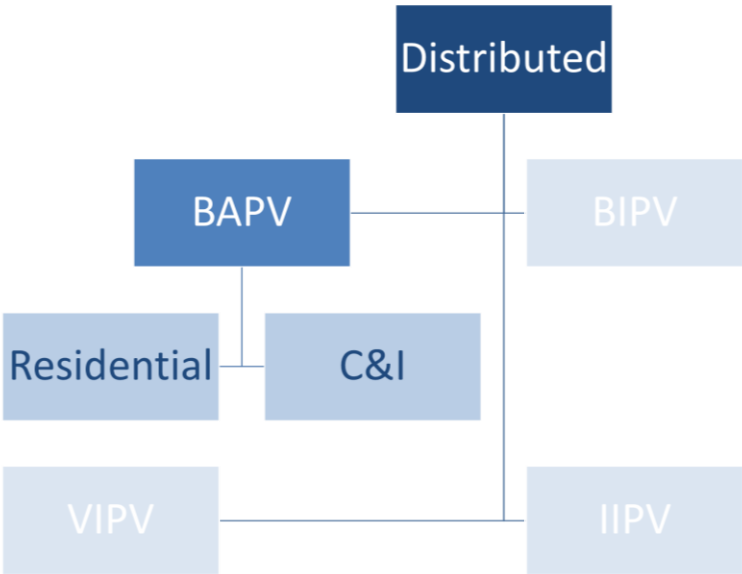
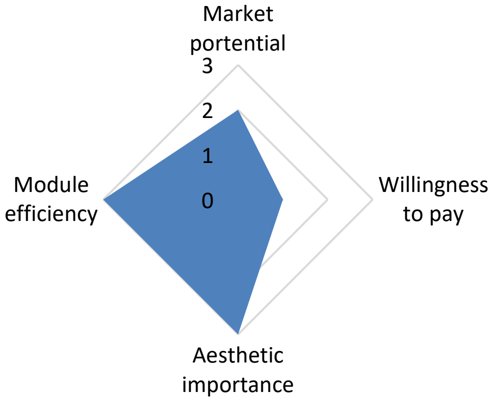


Figure 4-14: Overview of BAPV application landscape

4.3.1.1 Residential

The **residential** sub-segment groups together installations **from 0 to 10 kWp** usually intended for private individuals. Due to the relatively small size of the systems, the cost of the modules represents a smaller part of the overall cost structure of the installation, enabling the positioning of more expensive modules than in other market segments. Beyond cost, the important parameters for modules are therefore **aesthetics** and **efficiency**, to maximize production on a limited area, while blending in harmoniously with its surroundings.

This residential market represents a majority of the number of BAPV installations but should account for less than half of installed BAPV capacity over the next decade due to the small size of the installations.



Strengths: Technologically mature, high demand, variety of designs

Weaknesses: Expensive systems

Opportunities: Incentives, possibilities with battery storage

Threats: Volatility of support measures

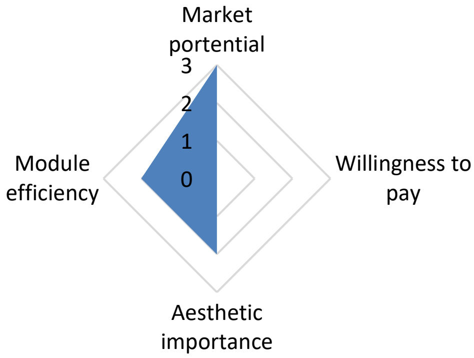
Figure 4-15: ZEBRA modules on residential roofs (source: FuturaSun)

4.3.1.2 C&I

The **commercial & industrial (C&I)** sub-segment includes installations ranging **from 10 kWp to 1 GWp**. These installations are generally installed on the roofs of businesses, factories or warehouses, optimising large unused areas and making it possible to supply electricity to buildings that are generally high consumers, enabling them to achieve high levels of self-consumption.

Module affordability is of higher importance for C&I compared to residential applications as module price represents a higher share in the total end-user price, and economic attractiveness is often among the main drivers. For commercial and industrial customers, module aesthetics are a less important decision criteria. In addition, depending on the building configuration and the electricity consumption, the importance given to module efficiency might differ. In the case of BAPV, module weight can also be an important decision criteria, due to roof bearing capabilities, which are often limited on this segment but also the necessity to keep it easily manageable by a single installer.

Although this sub-segment concerns a smaller number of installations than the residential sector, the installed capacities are such that these installations should represent a majority of the systems installed between now and 2030.



Strengths: Technologically mature, installations can be scaled to optimise utilisation and self-consumption

Weaknesses: Space requirements, complex decision-making

Opportunities: Incentives, possibilities with battery storage

Threats: Volatility of support measures

Figure 4-16: PV modules on industrial roofs (source: FuturaSun)

4.3.2 BIPV

Building Integrated Photovoltaics (BIPV) stands out in the solar PV landscape due to its seamless integration into building structures. Unlike traditional PV installations, BIPV becomes an integral part of the building's design and functionality. It emphasizes aesthetics, customizability, and multifunctionality, often serving as cladding, shading, or even windows. BIPV installations can therefore be divided into 3 main categories:

- Roof solutions
- Façade elements
- Balustrades, balconies and other accessories

Such installations nonetheless face a number of barriers, including the significantly higher cost of the systems, building regulations, safety standards and the necessary collaboration between architects, engineers and solar experts. These barriers are such that this sub-segment is still very much in the minority, although it should continue to grow.

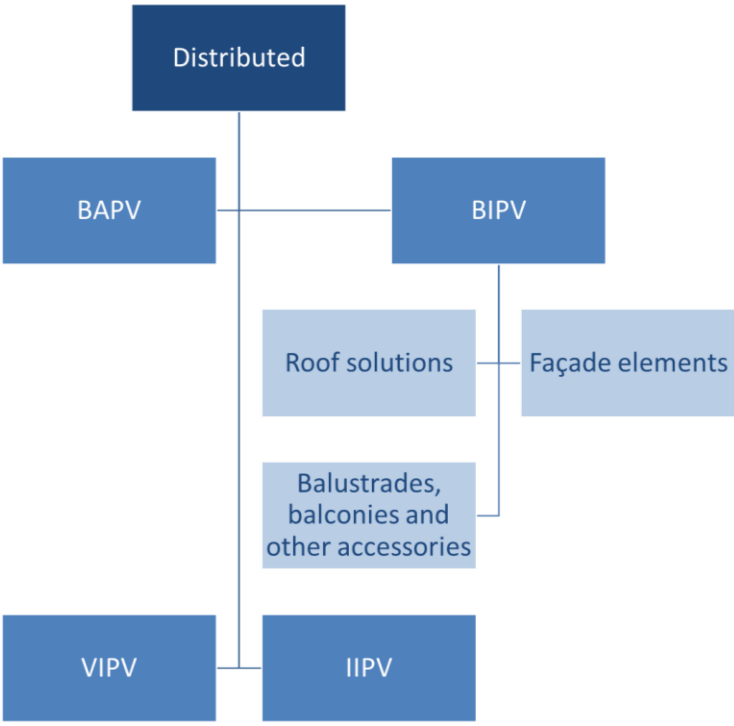


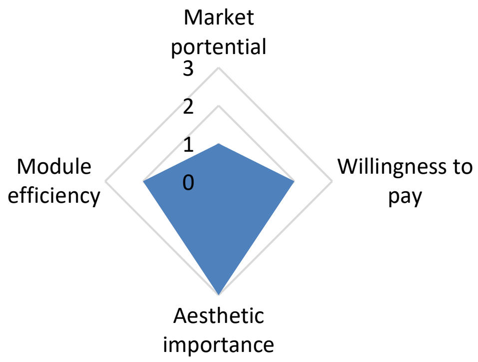
Figure 4-17: Overview of BIPV application landscape

4.3.2.1 Roof solutions

This category includes **all roofing solutions**, which can be seen as an evolution of in-roof mounting systems. In those solutions, the roofing is made of specifically designed roof components which include PV characteristics.

Those components are designed to be integrated both **aesthetically** and in terms of **functionality**, including **thermal insulation** for example. They can resemble traditional modules but with better functional and aesthetic integration through colors notably, or mimic usual building elements such as tiles, shingles, seamed metal sheets or skylights, but integrating PV capabilities.

Roof solutions are usually aimed at the residential market.



Strengths: Full integration leading to lower cost sensitivity and higher acceptance of the technology. Drives the demand for customized manufacturing.

Weaknesses: Relatively costly technology.

Opportunities: Near zero energy building policies and other policies encourage development of all BIPV products. These technologies are expected to gain maturity over the coming years.

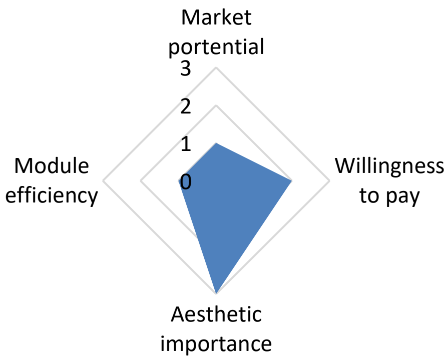
Threats: Very large and diversified products exist, with no real benchmark.

4.3.2.2 Façade elements

Façade elements can be divided into two main categories: **rainscreen** and **curtain walls**.

- **Rainscreen** are also called "cold" or ventilated façade elements as there is a ventilation space between the façade cladding and the second layer of façade elements, creating a capillary break to allow drainage and evaporation, making the water/air barrier more effective. BIPV rainscreen elements can replace traditional rainscreen elements, fulfilling its base functions as well as electricity generation. As there is a second layer assuming thermal insulation duties, the rainscreen itself is not meant to provide thermal insulation (although it can in some cases), therefore having less requirements and a lower cost sensitivity compared to curtain wall BIPV elements.
- Also called non-ventilated or "warm" façade elements, **curtain wall façade elements** are expected to boast thermal insulation capacities, and are often (semi-)transparent, acting as cladding, outside layer of the building, and light source simultaneously. Compared to rainscreen façade elements, curtain wall façade elements combine more functionalities, but have a higher cost sensitivity due to these additional requirements.

Both elements are usually aimed at the non-residential market.



Strengths: Full PV integration is necessary for this configuration. Transparency and coloring needs drive the demand for specific modules.

Weaknesses: Current elevated costs can prove prohibitive.

Opportunities: Near zero energy building policies and other policies encourage development of all BIPV products. Customization possibilities enable the acceptance of this type of product.

Threats: Acceptance and inclusion into conventional architecture and construction processes are progressing slowly.

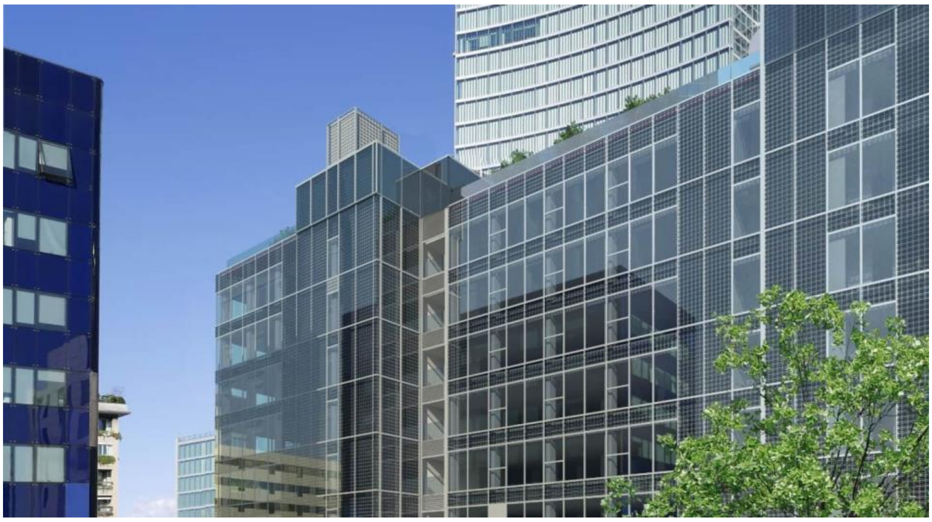
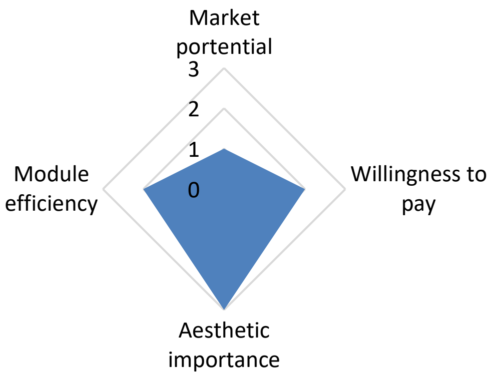


Figure 4-18: PV cells integrated in building façades (source: ISC Konstanz)

4.3.2.3 Balustrades, balconies and other accessories

This category includes all building elements that can be considered non-essential to the building, but which allow for BIPV products that combine electricity generation with another function useful to the building such as shading or fall protection.

While balustrades and balconies are the most common, shading elements and louvers are other examples of such “accessories” to the building.



Strengths: Those products are easier to place than roof or façade elements. Transparency and colouring needs drive the demand for specific modules.

Weaknesses: As they are of secondary importance, the market and acceptance for such products is limited.

Opportunities: Near zero energy building policies and other policies encourage development of all BIPV products.

Threats: A variety of products exist, with no real benchmark or definition, preventing swift market uptake.

Figure 4-19: PV balustrade on ISC building (source: ISC Konstanz)

4.3.3 VIPV

Vehicle Integrated Photovoltaics (VIPV) is a specialized application of solar technology that involves integrating photovoltaic panels or cells directly into vehicles. This type of system can extend the driving range of electric vehicles but also contribute to a reduced load on the electricity grid and charging infrastructure due to electricity generation near the consumers. These VIPV systems can be categorised into sub-systems:

- Light Electric Vehicles (LEV)
- Commercial Electric Vehicles (CEV)
- Buses
- Other VIPV use cases

This sub-segment currently constitutes a **niche**, and its development **is linked to the development of electric vehicles**.

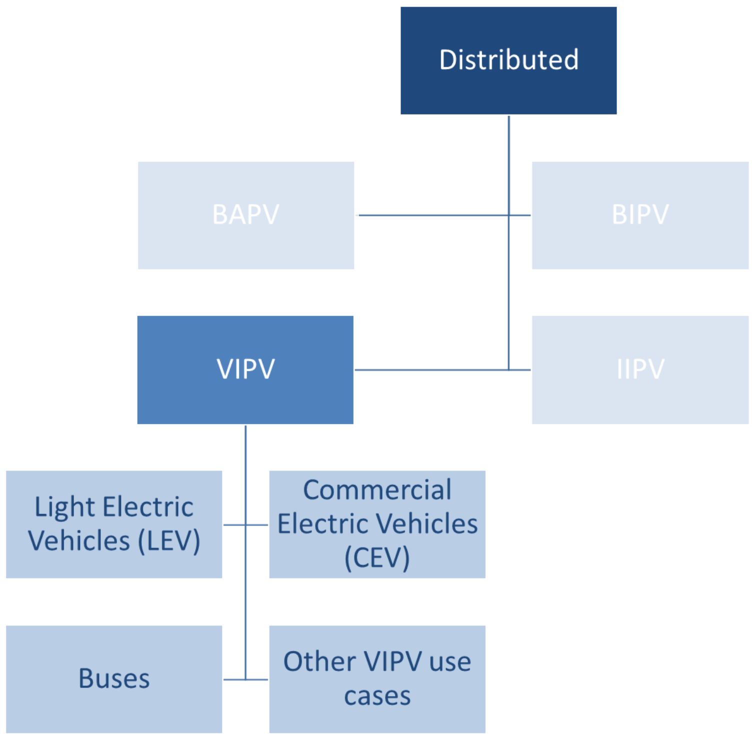
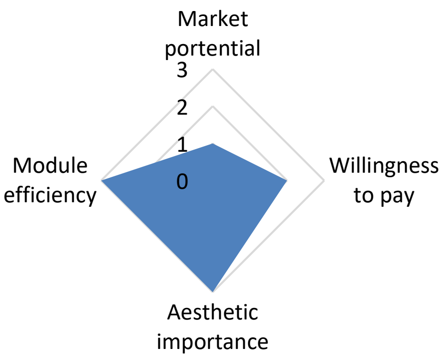


Figure 4-20: Overview of VIPV application landscape

4.3.3.1 Light Electric Vehicles (LEV)

PV integration in **light electric vehicles (LEV)**, initially aimed at supporting lighting and air-conditioning, has evolved with advancements in PV technology and cost reductions. VIPV is primarily implemented for hybrid and electric vehicles, as more relevant electricity consumers, but not exclusively to it.

Typically, PV integration occurs on the car's flat rooftop, with some installations on its sides and front. Integrating PV on curved surfaces and windows remains challenging, but advancements in flexible and window-based PV technologies hold promise. Additionally, the development of colored PV aims to make PV integration in cars more appealing to the general public.



Strengths: Passenger cars are ubiquitous; PV integration alleviates the battery and contributes to mitigating electricity grid consumption. EV car range is significantly increased.

Weaknesses: Higher costs added to EVs; Low area available for integration.

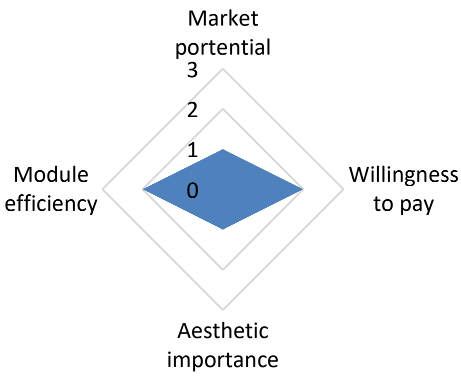
Opportunities: Ultimately all passenger car vehicles could have some degree of PV integration.

Threats: The benefits of VIPV are highly dependent on the driver profile.

Figure 4-21: PV cells integrated in LEV (source: TNO)

4.3.3.2 Commercial Electric Vehicles (CEV)

PV integration in **Commercial Electric Vehicles (CEV)** offers fewer challenges compared to Light Electric Vehicles (LEV) due to larger horizontal surfaces. Some CEVs also have additional electricity needs, such as refrigeration, creating an opportunity for PV integration to reduce strain on the battery. Given the larger flat surfaces of CEVs, higher PV capacities are expected on the rooftop and sides. Aesthetics are likely to be of lower importance in this VIPV use case compared to LEVs. Although many companies have introduced CEVs commercially, VIPV options for CEVs are yet to be developed on a wider scale.



Strengths: LCEV demand is set to explode in the next decades; PV integration alleviates the battery and contributes to mitigating electricity grid consumption. LCEV range is significantly increased, so less frequent battery charging stops. More flat surfaces than LEVs. Support to auxiliary utility services in LCEVs (e.g. cooling).

Weaknesses: Higher costs added to EVs; Low area available for integration.

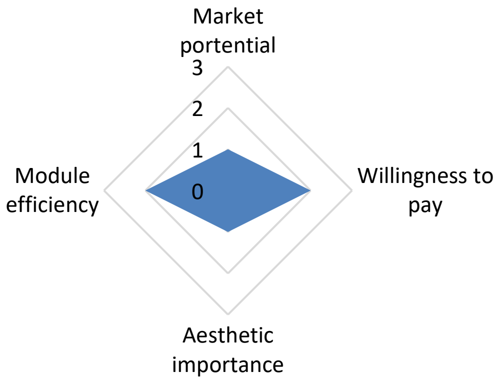
Opportunities: Ultimately all LCEVs could have some degree of PV integration.

Threats: The benefits of VIPV are dependent on the driving profile.

Figure 4-22: PV integrated in CEV (source: TNO)

4.3.3.3 Buses

Integrating PV into **buses** is feasible for both existing electric and non-electric buses. Conventional diesel buses, in particular, benefit from PV integration as they have additional electricity needs for air conditioning and appliances. This integration not only enhances capacity but also promotes the adoption of integrated PV mobility, even before transitioning to an all-electric fleet.



Strengths: Easily integrated on existing buses (both EV and Diesel) to supply auxiliary electricity needs. Buses have mostly flat surfaces, PV integrations will not face many challenges, except for windows.

Weaknesses: The PV element is a cost adder with benefits only observable in the medium-term.

Opportunities: Ultimately all buses could have some degree of PV integration.

Threats: The benefits of VIPV are dependent on the driving profile.

Figure 4-23: PV integrated into a camper van (source: FuturaSun)

4.3.3.4 Other VIPV use cases

The integration of photovoltaics is possible for virtually every existing means of transport. The most popular PV integration for vehicles, excluding land-road vehicles, is for boats. Boats constitute a great opportunity for solar PV given that they are disconnected from the grid once they leave the dock or port. The vast majority of PV existing currently in boats is not integrated PV but BAPV. Some pilot projects have been developed for aircraft but the use for commercial PV integration is far, the same thing goes for trains (often BAPV).

Figure 4-24: PV cells used in boats (source: ISC Konstanz)

4.3.4 IIPV

Finally, the **Infrastructure Integrated PV (IIPV)** sub-segment brings together most of the remaining non-conventional PV systems, seamlessly integrating PV into infrastructure that are usually located around or above roads. There is a wide variety of possible such systems, which can be grouped into the following categories:

- PV Noise barriers
- Carports / canopies
- Street furniture
- Others: PV road roofing

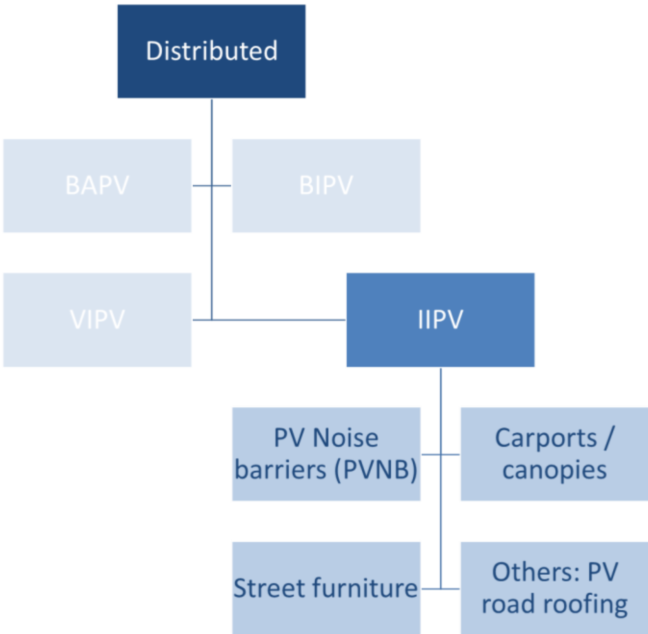


Figure 4-25: Overview of IIPV application landscape

These installations, like the other integrated PV segments, require special modules that integrate the IBC cells directly into the infrastructure concerned, making this segment a very small niche to date. However, with the rapid development of PV, and in particular IBC technology, which is perfectly suited to its needs, this segment could develop rapidly, particularly in Europe.

4.3.4.1 PV Noise barriers (PVNB)

Various configurations exist for **PV Noise barriers (PVNB)**, including top-mounted, berm-mounted, or fully integrated options. The latter approach aims to blend acoustic and energy performance, necessitating specialized integrated PV modules.

The market potential for PVNB is substantial, given the available areas near highways and railways, with current installations reaching MW-scale capacity. Additionally, vertical bifacial setups enable energy capture from North-South oriented roads, complementing East-West roads utilizing South-oriented modules.

Beyond meeting noise reduction requirements, customizing modules is crucial to seamless integration into various designs and ensuring resilience against external factors such as dust and weather. This customization maximizes power output potential.

Figure 4-26: PV noise barrier (source: TNO)

4.3.4.2 Carports / canopies

Large **non-building roof areas**, such as **parking lots**, **bus or train stations**, and **carports**, are increasingly seen as prime candidates for integrated PV solutions. By incorporating PV, these roofs can offer both shading or protection from rain and snow while simultaneously generating energy.

The requirement for specialized module manufacturing is relatively low, although diverse aesthetic factors may necessitate some degree of customization. While traditional PV can be installed on these roofs, integration holds the promise of enhancing performance, aesthetics, and cost-effectiveness. The added value of integrated PV modules has spurred demand for such solutions, with a growing emphasis on their compatibility with EV charging infrastructure.

Numerous projects that resemble commercial PV-integrated carports are already operational, although the integrated aspect is not always explicitly emphasized. This technology is mature and possesses substantial growth potential, particularly in the realm of commercial carports due to their larger surface areas.

Residential carports, although smaller in scale compared to their commercial counterparts, still hold significant promise. Depending on local legislation and incentives, they can prove financially viable for both prosumers and the grid. The term "canopies" encompasses various outdoor roofing structures designed to provide shade or protection from rain and snow for purposes beyond just parking (e.g., patios, pergolas, gazebos, etc.). Canopies present a valuable opportunity for prosumers, offering additional space for PV installations, especially when rooftops are unsuitable. In some instances, they may benefit from less stringent regulations compared to traditional buildings.

The increasing focus on aesthetics and cost-effectiveness is driving the trend toward PV module integration rather than simple mounting. This heightened demand has the potential to stimulate the growth of integrated module manufacturing, while the synergy with EV charging continues to be a significant motivator for residential carport adoption.

4.3.4.3 Street furniture

The utilization of PV technology on **street furniture** like **bus shelters** has been tested in various cities worldwide, showcasing a range of grid-connected or standalone systems. These installations often feature modules that can be mounted, integrated, transparent, or even colored, offering benefits such as electricity generation, illumination, and the power supply for visual displays and audio equipment.

However, the widespread experimentation with bus shelter PV applications raises questions about their economic viability, suggesting a degree of uncertainty regarding their market potential. While the cumulative area of bus shelters appears promising for PV deployment, individual bus stops typically offer limited space, which may not justify grid-connected PV systems. Consequently, standalone alternatives with integrated storage are under consideration. Yet, the practical benefits beyond lighting, such as display screens primarily used for advertising, may hold limited appeal to the public.

In contrast, grid-connected PV systems for larger shelter areas, akin to bus "stations," with optimal sun exposure, could form a niche market for customized integrated PV solutions, especially when aesthetics play a crucial role in public infrastructure.

Similar to bus shelters, public lighting infrastructure presents substantial aggregate areas but limited exploitable space per unit, making profitability less straightforward. While the concept is not new, recent advancements in LED technology and batteries enhance the feasibility of such installations. In the case of small bus stops, grid connection provides minimal advantages, whereas standalone PV lighting systems can operate autonomously, potentially alleviating the evening grid load on a large scale.

From a technological standpoint, these applications demand minimal specific or customized manufacturing, with many current examples utilizing traditional modules, albeit occasionally in smaller sizes, alongside specialized mounting structures.

Figure 4-27: PV integrated in street furniture (source: FuturaSun)

4.3.4.4 Others: PV road roofing

Road roofing technology represents an emerging approach aimed at harnessing the untapped potential of roads and railways. The main currently active development is a German-Austrian-Swiss research project called PV-SÜD, led by a consortium including Fraunhofer ISE, Forster FF and the Austrian Institute of Technology.

As for PVNB, the potential is large considering the available roadway and railway areas. However, whether this potential will turn into a market remains to be seen, as PV on rooftops, grounds, and other areas around road and rail remains much more competitive at present.

Many challenges remain, especially around the mounting structure, which must withstand strong mechanical constraints to comply with safety regulations. Above a certain length, such structures could be considered as tunnels, which would add further constraints. Regulatory and technical requirements are the biggest obstacles to wide road roofing development.

As the objective is to create an elevated ground for PV deployment, there are not many specific requirements in terms of module manufacturing, except if transparency needs are considered. Indeed, one could see such projects developed using traditional modules, without actual integration.

4.4 Summary table

In summary, the matches between the characteristics of IBC products and the specific needs of the diverse PV applications are summarised in the table below.

Table 2: Summary of PV applications where IBC technology is most valuable (rating out of 3)

	Market potential	Cost sensitivity	Aesthetic	Module efficiency	Final appreciation for IBC4EU
IBC as conventional modules					
Conventional ground-mounted					
Conventional utility-scale PV plant	3	3	0	1	1
Ground-mounted PV with grazing	2	2	2	2	1
AgriPV					
Vertical PV	2	2	1	2	1,25
Elevated PV – No tracking	2	2	2	2	1,25
Elevated PV – Tracking	2	2	2	2	1,25
Floating	2	2	0	2	1
BAPV					
Residential	3	2	3	3	2,25
C&I	3	3	2	2	1,75
IBC as special modules					
BIPV					
Roof solutions	1	2	3	2	2
Façade elements	1	2	3	1	1,75
Balustrades, balconies and other accessories	1	2	3	1	2
VIPV					
Light Electric Vehicles (LEV)	1	3	3	2	2,25
Commercial Electric Vehicles (CEV)	1	2	2	1	1,5
Buses	1	2	2	1	1,5
Other VIPV use cases	1	2	2	1	1,5
IIPV					
PV Noise barriers	1	2	2	2	1,75
Carports / canopies	2	2	2	2	1,75
Street furniture	1	2	2	2	1,75
Others: PV Road roofing	1	2	2	2	1,75

The applications identified – at the moment, considering technology and cost advancements – as being the most relevant for IBC technology, and in particular for the products developed as part of the IBC4EU project, are therefore those for which module cost is not the most decisive factor, but rather the efficiency and aesthetics of the modules i.e. primarily **residential BAPV**.

To a lesser extent, IBC technology is also particularly valuable in integrated sub-segments such as **BIPV** or **light electric vehicles**. However, the IBC4EU project is expected to focus primarily on the production of **conventional modules**, which cannot be used as such in these integrated applications. It is therefore interesting to note that the cells produced as part of the project could also be used for purposes other than the production of conventional modules, although this is likely to be their main use.

5 LCC comparison

The competitiveness of the IBC technology compared to three other technologies is assessed in three case studies. These are:

- Utility-scale PV: **conventional ground-mounted PV** (25 MW considered in the next sections)
- BAPV: **C&I** (250 kW considered in the next sections)
- BAPV: **residential** (5 kW considered in the next sections)

Residential BAPV and C&I installations have been chosen as case study because, as demonstrated in the previous section, they are the preferred target for the conventional modules developed as part of the IBC4EU project, considering technology and cost advancements at the moment. A utility-scale conventional ground-mounted installation is also being studied, as this market segment is one of the largest and will continue to develop very rapidly, representing very large volumes to be captured in the coming years.

5.1 Manufacturing cost & CAPEX Comparison

5.1.1 Manufacturing cost comparison

The differences in CAPEX between the different systems studied depend largely on the differences in manufacturing costs for the different technologies. Below, in Figure 5-1, are listed the average manufacturing costs identified by Becquerel Institute on the basis of manufacturer insights.

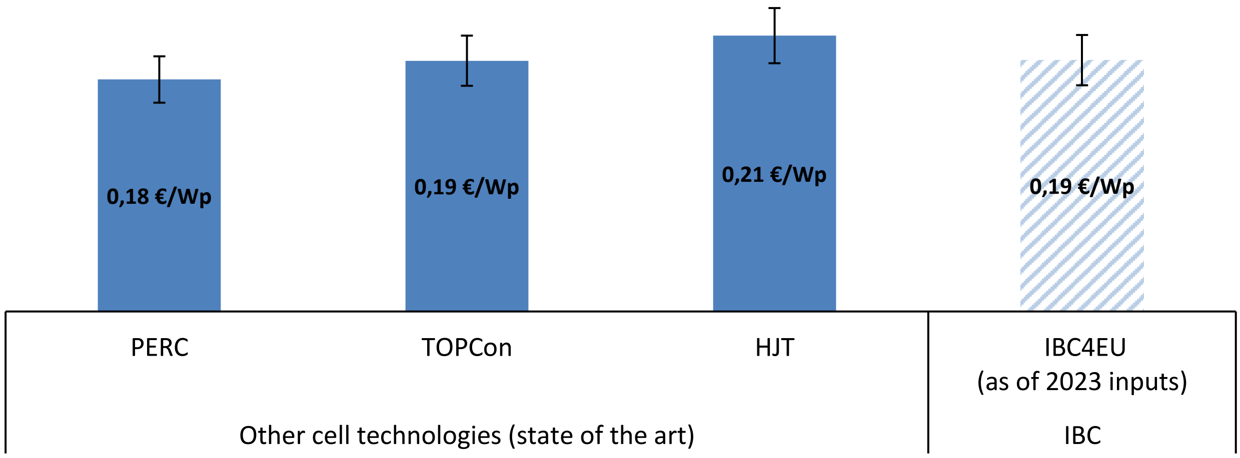


Figure 5-1: Manufacturing cost by cell technology for a similar plant size (>5GW vertically integrated) [1] [2] [3]

These manufacturing costs are given all other things being equal, i.e. for the same manufacturing capacity (>5GW vertically integrated), from literature and manufacturers' insights [1] [2] [3]. In practice, however, the scales involved are currently larger for PERC and TOPCon than for HJT and IBC. These differences in production capacity therefore accentuate the differences between these technologies in terms of module spot prices, as shown in Summary Table 1 in Section 3.3. For this reason, in the rest of the calculations in this section, the values used will be these spot prices shown in Table 1.

It should be noted that expected technological advances should reduce these manufacturing costs in the years to come. In a 2021 report, the National Renewable Energy Laboratory (NREL) estimated these cost reductions for c-Si modules, in a graph shown here in **Error! Reference source not found.**.

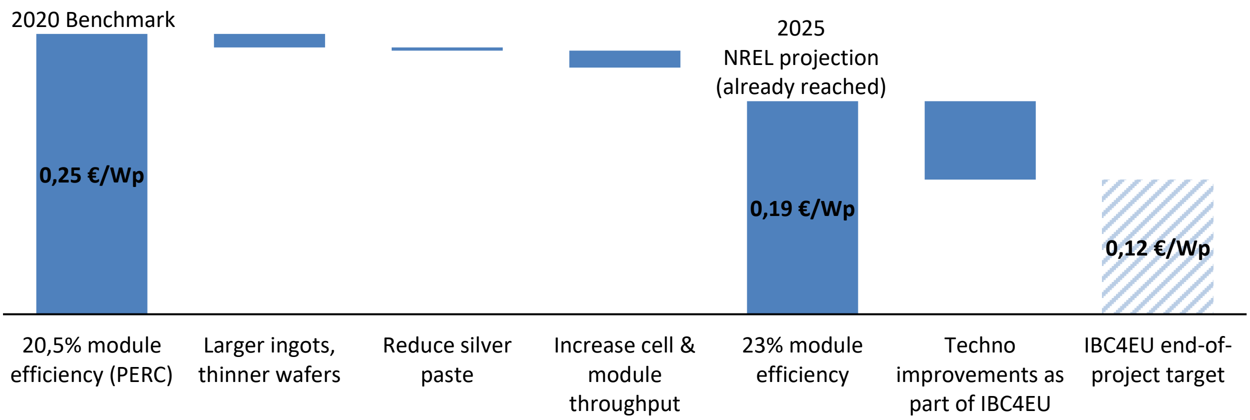


Figure 5-2: Technology roadmap with projected minimum sustainable prices for mono-Si modules, assuming 15% gross margin (adapted by the Becquerel Institute from NREL [9])

The manufacturing cost reductions planned by NREL between 2020 and 2025 have already been achieved in 2023. As part of the IBC4EU project, further technological improvements are planned, such as a reduction in wafer thickness, replacement of silver paste by copper paste and improved efficiency, which should make it possible to get closer to a manufacturing cost of 0,12€/Wp by the end of the project.

5.1.2 CAPEX comparison

For a given application and installed capacity, the CAPEX may vary from one cell technology to another for two main reasons. First, as presented in Section 5.1.1 the different technologies are associated with **different module manufacturing costs** and consequently **module prices**. Second, as presented in Section 3.3, the different technologies are associated with **different module efficiencies**. Better performing technologies typically allow for a lower number of modules to be installed to reach the same total PV plant installed capacity. This enables a **lower price in €/Wp** for other CAPEX items, mainly cabling, structure or mechanical installation. With regards to this aspect, the IBC technology benefiting from the highest module efficiency allows the highest savings on the balance of system. The methodology suggested by Fraunhofer ISE has been used. In Error! Reference source not found., the CAPEX ranges for different PV applications and different technologies are presented. This range only reflects the uncertainty on module prices due to recent important price fluctuations as well as the prices differences that can exist from one manufacturer to another. Other factors influence prices, such as local conditions and product or project, which may result in variations

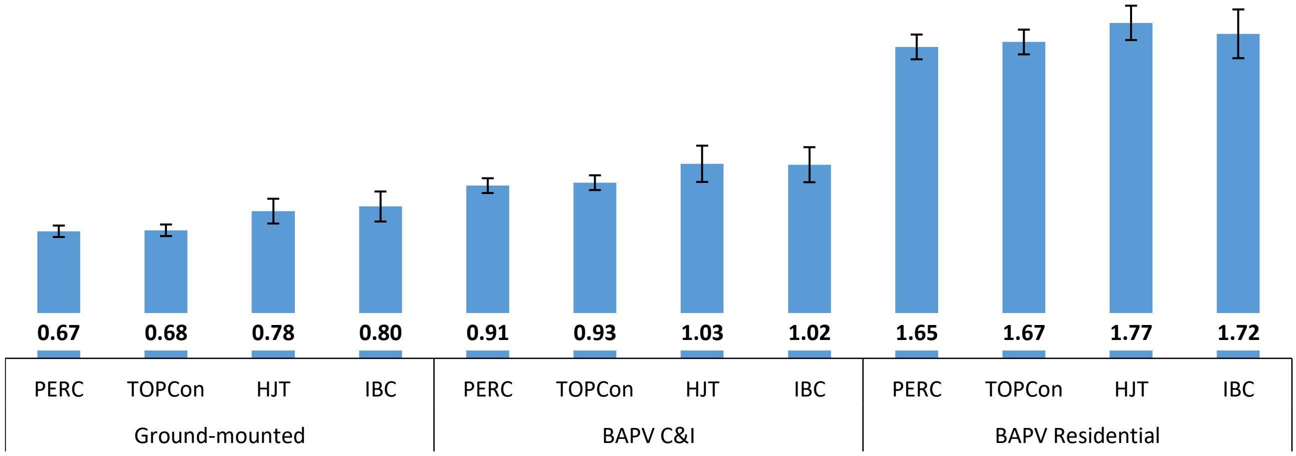


Figure 5-3: CAPEX range (in €/Wp) for different PV applications and different technologies

from 4% to 10% [4].

In **Figure 5-4**, the average CAPEX breakdowns for different PV applications and different technologies are presented. The benefit of higher efficiencies and thus higher module power (for an equivalent module area) on some cost items of the balance of system can be observed.

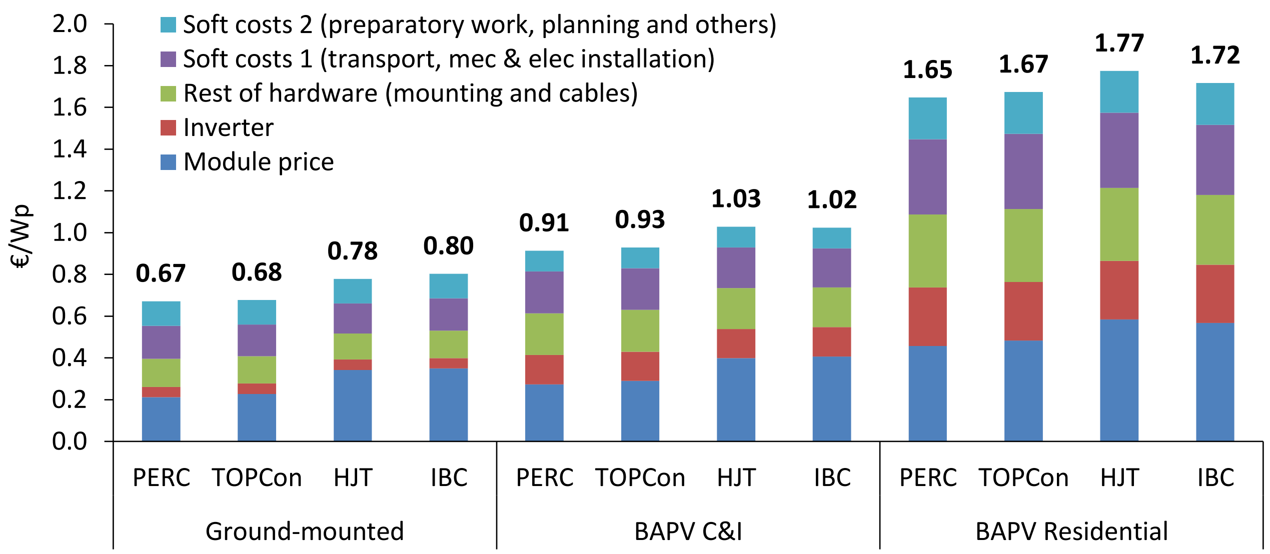


Figure 5-3: Average CAPEX breakdown for different PV applications and different technologies (module prices refer to end-user prices including shipping costs as well as distributors' and installers' margins)

5.2 LCOE Comparison

In the subsequent LCOE calculations, a further distinction is made between the different technologies in addition to cost-related differences. From existing products' datasheets, the typical degradation rates for each technology have been retrieved. PERC technology demonstrates the lowest guaranteed performance after one year with a 2% performance loss rate. For competing technologies, the guaranteed performance after one year is globally better with a 1% performance loss rate in the first year for most products. Same trends can be observed for performance losses in the subsequent year with 0,6%/yr for PERC modules and between 0,25% and 0,43% for the competing n-type technologies. In addition, for n-type technologies the performance gain from the lower temperature coefficient is factored in. For that it is estimated that the performances of n-type technologies are on average higher by 0,5%. These techno-economic assumptions are summarized i n Table 3 for the systems, and Table 4 for the modules.

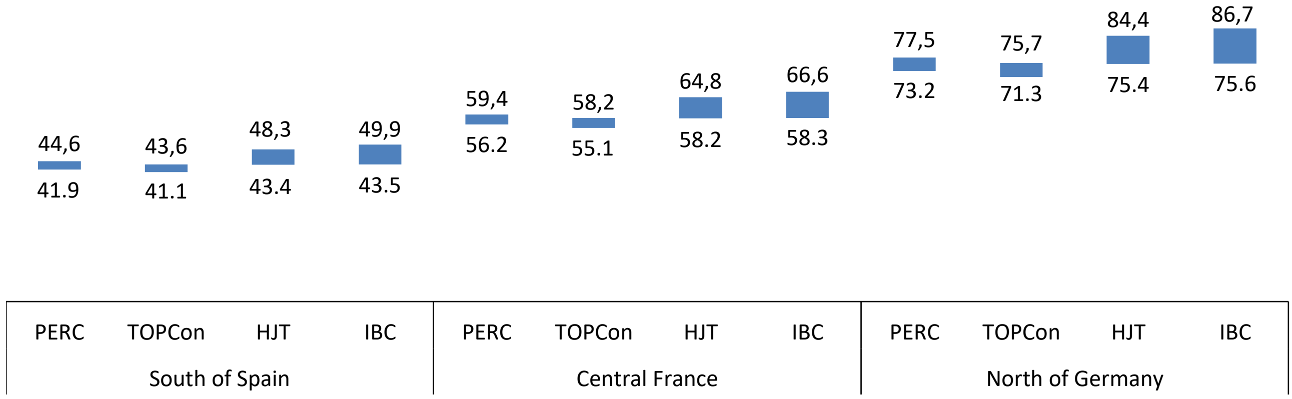


Figure 5-5: Equity LCOE range (in €/MWh) for different technologies for the first study case: a 25 MW ground-mounted PV

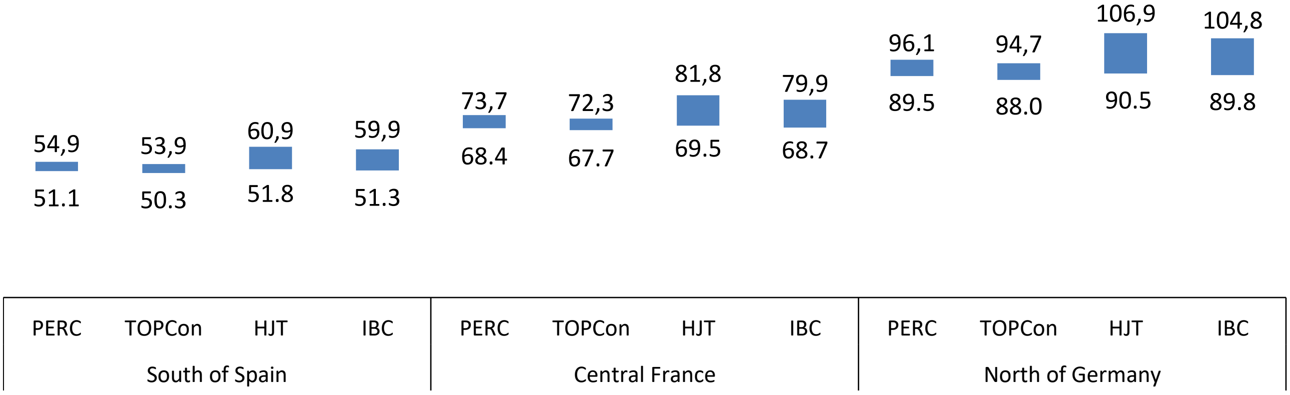


Figure 5-6: Project LCOE range (in €/MWh) for different technologies for the second study case: a 250 kW C&I rooftop PV

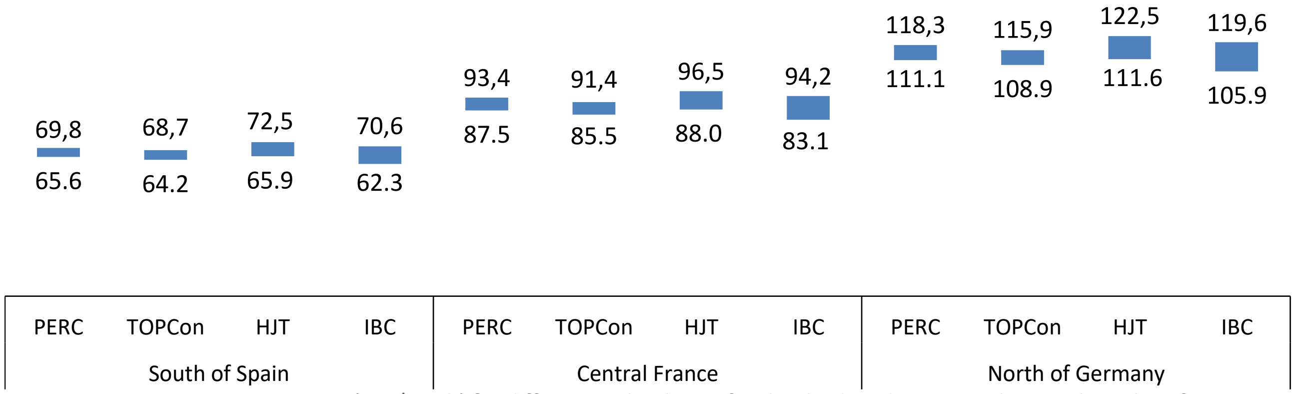


Figure 5-4: Project LCOE range (in €/MWh) for different technologies for the third study case: a 5 kW residential rooftop PV

Table 3: Summary of techno economic assumptions for the LCOE calculations related to the PV system

Parameter	Unit	Utility-scale PV: conventional ground-mounted PV	BAPV: C&I	BAPV: residential
Size	***[kWp]***	**25 000**	**250**	**5**
OPEX	*[€/kWp.yr]*	15,5	8	10
Cost of equity	*[%]*	8%	N/A	N/A
Share of debt	*[%]*	80%	N/A	N/A
Cost of debt	*[%]*	3%	N/A	N/A
WACC (nominal)	*[%]*	3,4%	5%	2%
Yield	*[kWh/kWp]*	Southern Spain: 1706 Central France: 1275 Northern Germany: 981	Southern Spain: 1650 Central France: 1231 Northern Germany: 942	Southern Spain: 1650 Central France: 1238 Northern Germany: 975

Assumptions common to the 3 systems: *Lifetime = 30 years; Depreciation = 20 years; Average annual inflation = 2,5%; Corporate tax rate = 25%*

Table 4: Summary of techno assumptions for the LCOE calculations related to the modules

Parameter	Unit	PERC		TOPCon		HJT		IBC	
		Utility scale[1]	**BAPV[2]**	**Utility scale[3]**	**BAPV[4]**	**Utility scale[5]**	**BAPV[6]**	**Utility scale[7]**	**BAPV[8]**
Module power	*[Wp]*	540	400	570	400	612,5	415	440	435
Module efficiency	*[%]*	20,91%	20,96%	22,1%	21,1%	22,5%	21,85%	22,3%	22,4%
Module size	*[m²]*	2,58	1,91	2,58	1,90	2,72	1,895	2,235	1,94
Degradation rate (year 1)	*[%]*	2,0%	2,0%	1,0%	1,0%	1,0%	1,0%	1,0%	1,0%
Degradation rate (year >1)	*[%/y]*	0,60%	0,60%	0,40%	0,40%	0,29%	0,29%	0,25%	0,25%

[1] From Jinko Tiger Pro: JKM545-565M-72HL4-(V)-F3-EN.ai (shwebspace.com)
[2] From Jinko Tiger: JKM385-405M-60RL3-(V)-F1-EN.ai (shwebspace.com)
[3] From Jinko Tiger Neo: JKM570-590N-72HL4-(V)-D2-EN (shwebspace.com)
[4] From Jinko Tiger: JKM355-375N-6TL3-(V)-D1-EN.ai (shwebspace.com)
[5] Average between RISEN Hyper-ion and 3SUN B60: RSM110-8-565-585BHDG IEC1500V-30mm 2023H2-2-EN.cdr (risenenergy.com) & 3SUN_B60.pdf
[6] Average between Huasun Himalaya and Meyer Burger White: G10-182-108-DS_EN (huasunsolar.com) & DS_Meyer_Burger_White_fr.pdf (meyerburger.com)
[7] Adapted from IBC Solar MonoSol
[8] From IBC Solar MonoSol: IBC MonoSol 425 MS10-HC-N - IBC Solar Artikelkatalog NL (ibc-solar.nl)

6 Overview of possible IBC evolution routes

As indicated in Section 3.4, in a business-as-usual scenario developed by Becquerel Institute based on ITRPV [5], IBC technology should at least double its share of the global market, rising from 2,9% in 2022 to 12,0% in 2030, with an annual market that would increase tenfold from 6,9 GW to 134 GW in 2030. These assumptions are framed within a more global forecast of annual PV market growth reaching 1113 GW in 2030 according to Becquerel Institute forecast.

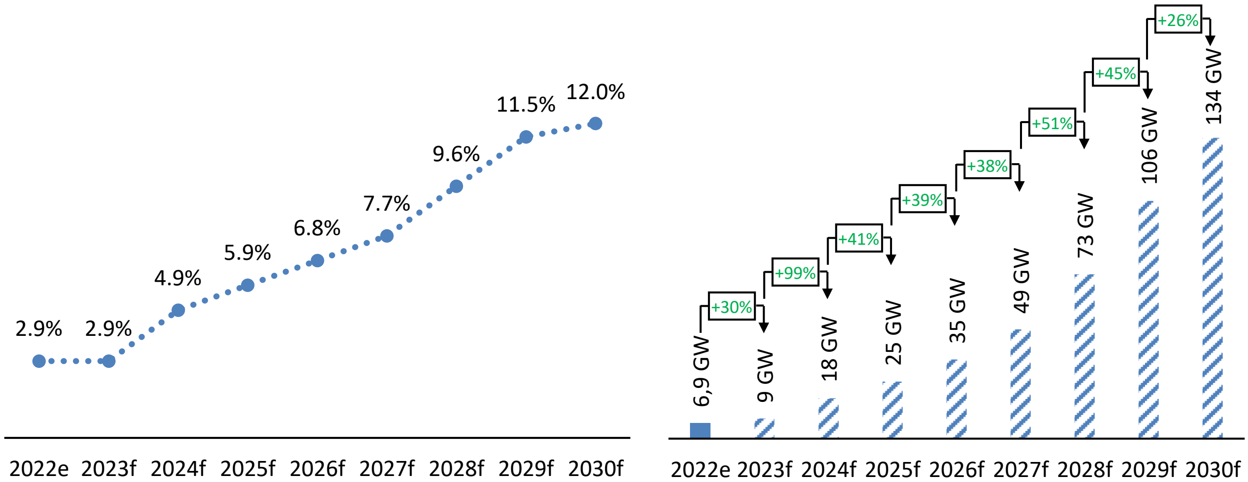


Figure 6-1: Forecast global IBC annual installed capacity share & market (Becquerel Institute analysis based on ITRPV 2023 [5])

Nevertheless, if IBC technology delivers on all its promises in terms of efficiency and cost, IBC could capture a larger share of the market than in this conventional scenario. Three scenarios have been defined according to the performance achieved by the IBC technology in the next years:

Table 5: Basic assumptions of the three scenarios

	BAU scenario	Intermediate scenario	Best case scenario
IBC efficiency	Higher than other technologies	Higher than other technologies	Higher than other technologies
IBC manufacturing cost	Significantly higher (>15%) than other technologies	Slightly higher (10-15%) than other technologies	On par or lower than other technologies
Share of the n-type annual market that will be captured by IBC by 2035	15%	30%	100%

Based on these basic parameters, possible changes in IBC market share are estimated using an S-curve, also known as a logistic curve, that is commonly used to illustrate the progress of the diffusion of an innovation through its life cycle. In recent years, the penetration of PERC technology on the PV market has thus followed a logistic curve between 2013 and 2021, and on the basis of this observation the parameters of such a curve will be adapted to create the estimate of the IBC market for each scenario.

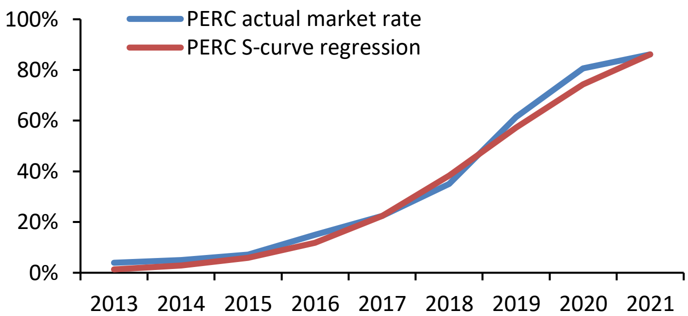


Figure 6-2: Approximation of PERC's past penetration on the annual market with an S-shaped curve

Business as usual scenario

This scenario, in which the performance of the IBC is higher than that of other technologies but its price is also significantly higher (>15% higher) than that of other technologies, should restrict the IBC to a part of the distributed market, and particularly the residential market. The market share thus captured should increase from around 3% today to around 12% in 2030, which corresponds to the business as usual scenario. This would represent 134 GW of the annual CBI market, as indicated above.

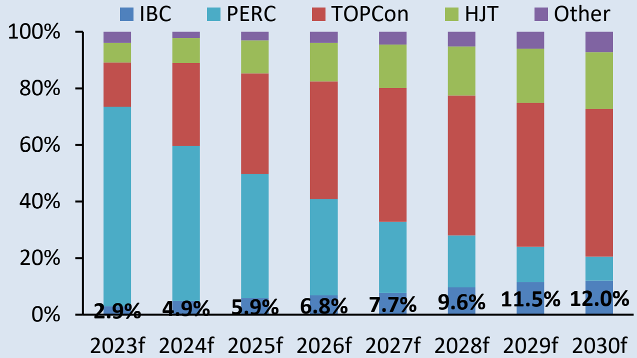


Figure 6-3: Forecasted future market share by technology in a business as usual scenario (Becquerel Institute analysis)

Intermediate scenario

Assuming that the cost of IBC is only slightly higher than other technologies (10 to 15%), and that its efficiency is better, IBC could then capture most of the segments identified above, i.e. distributed and residential in particular. Overall, IBC would be expected to account for up to 30% of installations using n-type, which would represent almost a quarter of the total market, and more than 250GW of annual installations by 2030.

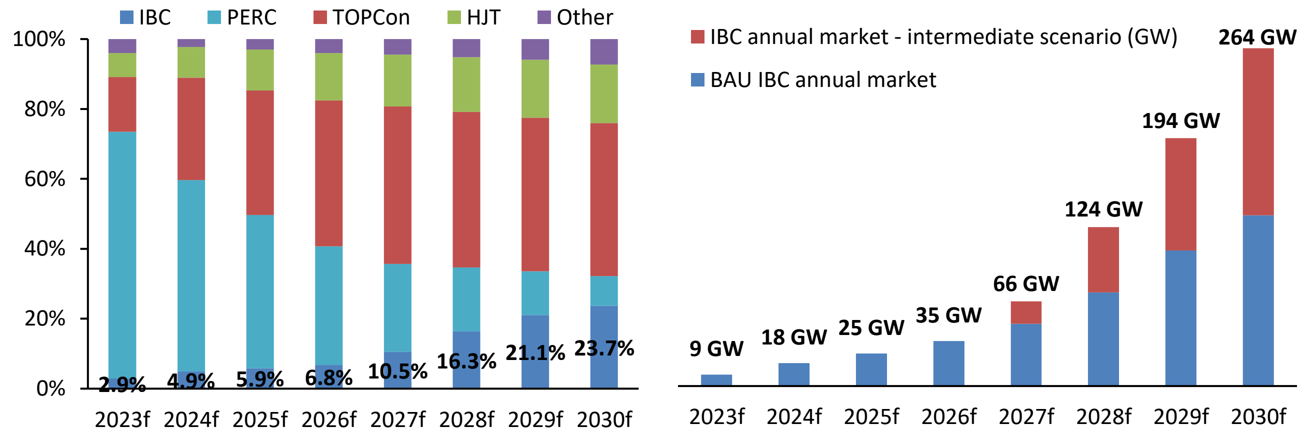


Figure 6-4: New possible market share captureable by IBC in an intermediate scenario (Becquerel Institue analysis)

Best case scenario

Finally, if, in addition to its greater efficiency, the IBC manages to achieve costs similar to or even lower than those of other technologies, the IBC could gradually become the dominant n-type technology, thereby stealing the market share expected from TOPCon and HJT. This would represent 60% of the global annual market by 2030, and around 668GW in 2030 in this best case scenario.

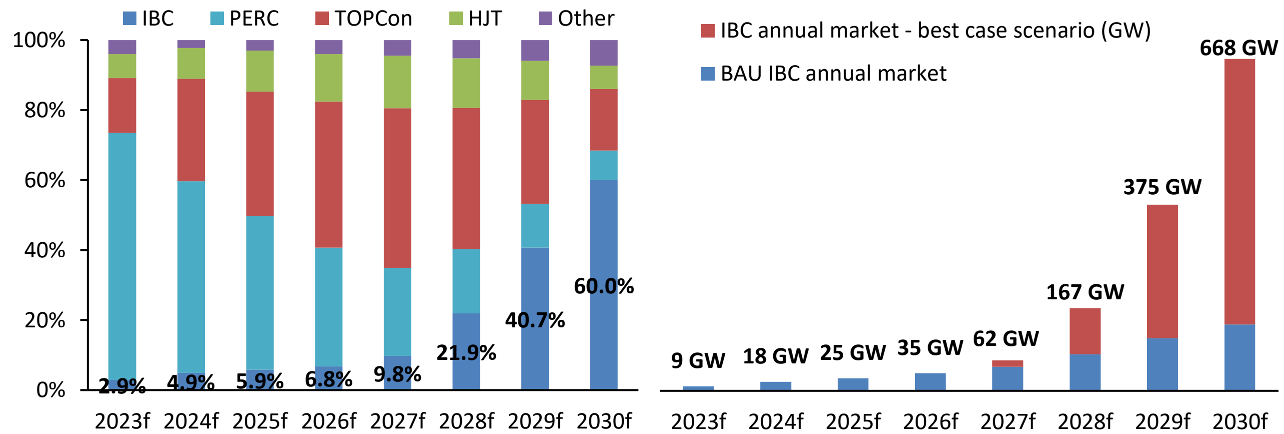


Figure 6-5: New possible market share captureable by IBC in a best-case scenario (Becquerel Institue analysis)

IBC cell possibilities

In this project, the target end-use applications mainly concern systems using **conventional modules** for **traditional PV applications**, which in any case account for the vast majority of the market. In addition to these conventional modules, the products developed as part of the IBC4EU project, such as the **polyZEBRA or POLO IBC cells**, could be used in their own proper right in other more marginal markets like **integrated PV**, particularly thanks to their **aesthetic** appeal and **high efficiency**, which make them an ideal fit , as described in Section 4.

Figure 6-6: Example of IBC cells integrated in LEV (source: Sono Motors car, from ISC Konstanz website)

Over and above possible evolution routes in conventional markets, IBC could become the predominant technology for systems like PV integrated to **Light Electric Vehicules**, and BIPV systems such as **roof solutions**, **balustrades, balconies and other accessories**. For the time being, however, such markets are **niche** and their development, although expected, is difficult to predict at this stage.

7 Conclusion

- The **distinctive features** of the IBC technologies developed as part of this project, such as a reduction in wafer thickness, replacement of silver paste by copper paste and improved efficiency will enable **manufacturing costs** – currently slightly higher than those of competing technologies – **to be significantly reduced** and **sustainability to be improved** by the end of the project.

- At the moment, **considering technology and cost advancements**, the markets in which the conventional modules developed as part of the IBC4EU project will be most valuable are the **distributed segment**, and in particular the **residential** sector. However, if all efficiency and cost objectives are met, then IBC could become the preferred technology across all the PV segments, as investigated in section 6 and mentioned in the last bullet point.

- As a result of slightly higher manufacturing costs and therefore higher module prices, IBC is currently marginaly less competitive than PERC (-12%) and TOPCon (-14%) in the centralised segment in terms of LCOE. Nevertheless, in the targeted segments of distributed residential, and to a lesser extent C&I, modules represent a smaller proportion of the total CAPEX of the installation, which means that **IBC is about as competitive in these BAPV segments as PERC** (-1% for residential, -9% for C&I) **and TOPCon** (-3% for residential, -11% for C&I).

- Based on this observation, the IBC should **at least reach 12%** of the annual market share by 2030 in a business as usual case, which would represent **134 GW of annual installations in 2030**. But thanks to technological improvements, particularly those developed as part of the IBC4EU project, IBC could capture a larger share of the market than other n-type technologies, especially in the target residential markets. This could lead to IBC capturing between 20% and 60% of the annual market by 2030, respectively equivalent to 264 and 668 GW of IBC market demand on an annual basis, depending on the performance achieved, particularly in terms of manufacturing cost.

8 Glossary

Abbreviation	Meaning
Ag	Silver
AgriPV	Agrivoltaics
Al-BSF	Al-Back Surface Field
BAPV	Building Attached Photovoltaics / Building Applied Photovoltaics
BAU	Business as usual
BIPV	Building Integrated Photovoltaics
CIF	Cost, Insurance and Freight
c-Si	Crystalline silicon
FOB	Free On Board
HJT	Heterojunction technology
IBC	Interdigitated Back Contact
IIPV	Infrastructure Integrated Photovoltaics
LCC	Life Cycle Costing
LID	Light Induced Degradation
LCOE	Levelized Cost of Energy
PERC	Passivation Emitter Rear Contact
PVNB	Photovoltaic Noise Barrier
Si	Silicon
TOPCon	Tunnel Oxide Passivated Contact
VIPV	Vehicle Integrated Photovoltaics
WP	Work Package

9 References

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