Understanding the Evolution of Solar Photovoltaic Technology in the Next Decade

Applying the Bending, Blending and Breaking Framework

March 2026

About Us

The Tamil Nadu Infrastructure Fund Management Corporation (TNIFMC) is an asset management company promoted by the Government of Tamil Nadu. It manages multiple thematic funds, registered under the SEBI AIF Regulations, to channel private investments into key sectors of the state's economy.
Tamil Nadu Green Climate Fund (TNGCF), a social impact fund dedicated to investing in enterprises and projects that help mitigate greenhouse gas emissions and enhance climate resilience.

Climate Collective Foundation (CCF) is India's largest non-profit climate tech ecosystem orchestrator, having accelerated 1,457 startups while building a 34,000+ strong community across the Global South since 2016.

CCF bridges the development and private sectors to accelerate the transition to a low-carbon future. It offers entrepreneur education, startup acceleration, venture funding, industrial decarbonization, impact assessment, and community-building.

About Our Collaboration

TNIFMC and CCF are collaborating to undertake investment research and impact assessments across priority sectors being explored by TNIFMC for green investments.

Over the past year, this work has included investment research on solar EPC, water filtration, EV charging and infrastructure, electric vehicle ownership costs, battery recycling (lead and lithium), lubricants recycling, and associated financial models. In parallel, CCF’s impact team developed climate impact assessment methodologies for solar module manufacturing investments.

This paper marks the first in a planned series that builds on this body of work and examines sector-specific technology and investment themes in greater depth.

The Paradox of Progress

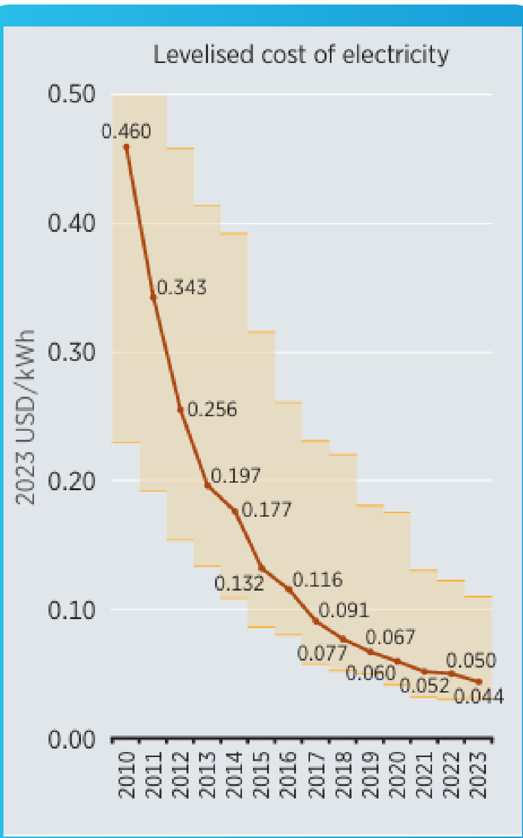


Image Source: IRENA, 2024. This figure shows the trends in global utility-scale solar PV deployment showing weighted average values and observed ranges for levelized cost of electricity between 2010 and 2023.

In 1839, physicist Alexandre-Edmond Becquerel discovered that when light struck a certain material, it generated an electric current. At the time, it was a laboratory-level novelty. Nearly two centuries later, solar photovoltaic (PV) technology has become the fastest-growing renewable energy source. Solar has experienced transformative price declines, with a reduction of over 90% in just the past decade (IRENA, 2024).

This dramatic cost reduction occurred due to a confluence of factors: laboratory breakthroughs in technology & design, which were supplemented in recent years by a self-reinforcing technology development-project deployment cycle that accelerated PV's technology learning curve. In conjunction, efficiency improvements and technological and deployment progress lowered the cost of solar electricity. The lower costs drove wider adoption, and wider adoption enabled scale, which in turn led to further technological and cost improvements (Kavlak, 2017).

Many forces, such as improved conversion efficiency, lowering material, BOM & manufacturing costs, material innovation, cell architecture, and policy support, have contributed to PV progress.

The sustained decline in cost has been the universal and decisive driver. Of all contributing factors, the most durable pathway for cost reduction has been efficiency[1] gains achieved through loss reduction. This is what makes the evolution of photovoltaics so counterintuitive. The best solar cells are those that prevent photons and charge carriers from being wasted in every possible way (Miller O.D,et.al., 2011). This reflects the via negativa of engineering, where each efficiency gain represents less reflection[2], less recombination[3], lower resistance[4], and less entropy lost as heat, all within the immovable limits of thermodynamic law.

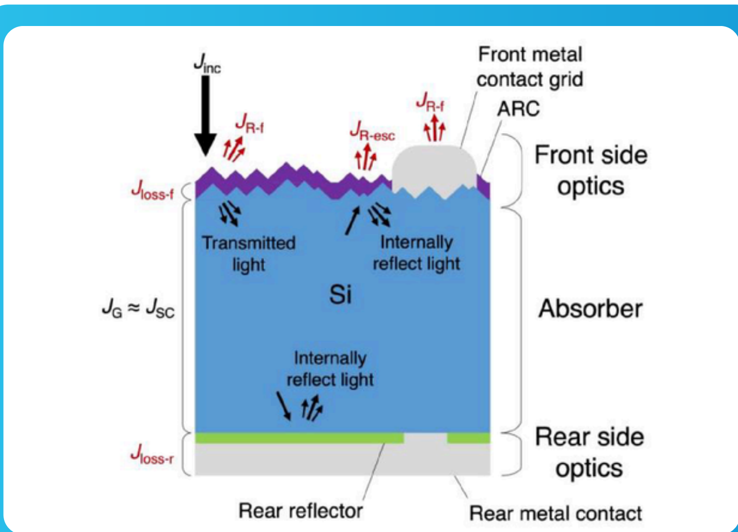


Image Source: M. J. Hossain et al., 2023: This figure shows how light travels through a silicon PV cell and where energy density is lost. Highlighted in red are the loss mechanisms: JR–f, where light is reflected at the front surface; JR–esc, where light escapes after multiple internal reflections; and Jloss–f and Jloss–r, where light is absorbed at the front and rear surfaces without contributing to electricity generation.

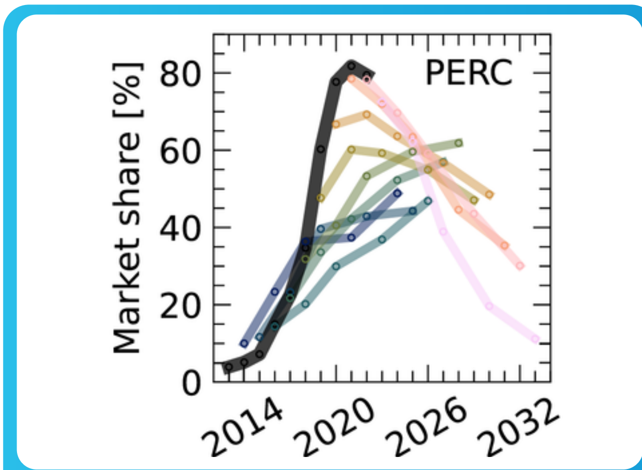


Image Source: Stefani V et al., 2023: The black shows the estimated market share for PERC and the coloured one's show the projected market shares based on International Technology Roadmap for Photovoltaics (ITRPV) annual reports.

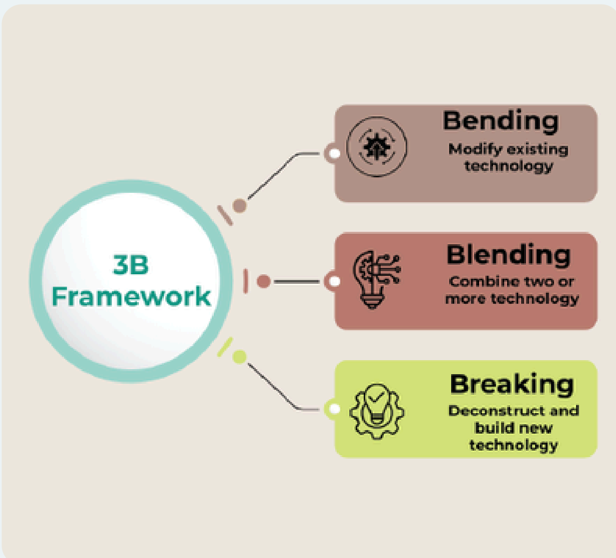
But what happens when a cell architecture reaches its efficiency limits?

This is what's happening to the dominant technology today, i.e. the Passivated Emitter and Rear Cell (PERC) technology. At around 24% efficiency, it is approaching the practical limits of what its architecture can achieve (Min.B et.al, 2017). As a result, the market position of the technology is beginning to change (Stefani V et al., 2023). What comes next will shape which cell architectures gain traction, which nations will lead in manufacturing, and how quickly clean energy can be deployed at the scale demanded by the climate and net-zero transition.
In this context, a conceptual framework that can describe technological transitions and development pathways is valuable, even if it does not provide precise predictions.

A Conceptual Framework for Interpreting PV Innovation Pathways

David Eagleman, a neuroscientist, and Anthony Brandt, a composer and author, developed the **Bending, Blending and Breaking framework (3B Framework)** to explain creativity and innovation. This framework was originally used to describe how creative output emerges across arts, music, language, and science (Eagleman.D, et.al, 2017). It has been adopted by researchers as an interpretive lens for analyzing the complexity and rapid change associated with the fourth industrial revolution and for examining how project managers approach innovation trajectories (Erivan D.R.S, 2019). The framework defines the three strategies: Bending, which modifies something for a new use; blending, which combines two or more new ideas; and breaking, which involves disassembling an idea and reassembling it in a different way.

In this work, the 3B framework is applied as one possible interpretive lens to study the evolution of PV cell technologies. The analysis is limited to efficiency improvements achieved through the reduction of losses, which have been one of the primary drivers of performance gain in PV systems. These pathways are analyzed retrospectively to identify recurring patterns in technological transitions and are compared with industry predictions and market outlooks. The interpretations broadly align with PV market projections. This suggests that the framework can be used as a heuristic tool that, to a large extent, explains historical efficiency improvements.



Mapping and Interpreting the 3B Framework in PV Technologies

The 3B can be interpreted through the lens of loss reduction as follows: Bending strategy modifies existing technology to redirect losses; Blending combines two or more technologies to offset losses that cannot be solved individually; and Breaking develops new architectures that eliminate losses at the structural level.

Bending is about improving existing technology. It represents incremental optimization of the core architecture without changing its fundamentals. In the case of solar PV, Bending answers a simple question: 'How do we stop photons and electrons from getting away?'

Bifaciality is one of the clearest examples. Instead of allowing transmitted light to disappear after hitting the ground or roof, the rear side of the cell converts reflected light into useful electricity (Dullweber, T. 2019). The cell itself does not change. The same principle explains why PERC became the global workhorse of the last decade (Dullweber, T. 2019). By adding rear reflectors and passivation layers, PERC keeps photons circulating longer inside the silicon and prevents electrons from recombining prematurely (Dullweber, T. 2019).

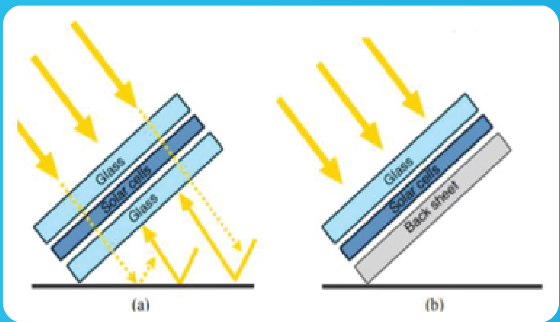


Image Source: Institute of solar technology
Shows In (a) a Bifacial PV module
(b) a standard PV module

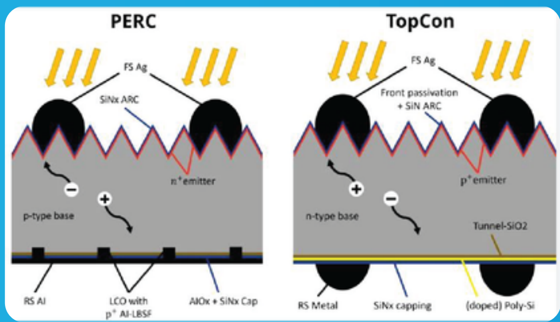


Image Source: Heaven Designs
Illustrates the architecture of PERC and TOPCon

Now the next 'bend' in crystalline silicon (c-Si) is underway, with Tunnel Oxide Passivated Contact (TOPCon). By inserting an ultrathin oxide layer between the silicon and metal contacts, TOPCon further suppresses contact recombination and pushes efficiencies toward 25–26% (Moldovan. A, et.al, 2015). It is a continuation of the silicon architecture rather than a departure from it. Manufacturers can adopt it quickly because it uses similar materials and compatible production lines, enabling rapid scaling without a major redesign of the factory or replacement of machinery (Preu.R,et.al, 2020).

Just like silicon PV's path from PERC to TOPCon, thin-film solar cells show the same bending potential. CdTe cells began with efficiencies of about 6%. Over time, efficiency increased through improvements in the n-layer, more transparent front layers, improved back contacts, and better interface engineering. Today, CdTe solar modules have efficiency greater than 19% (U.S DoE, n.d).

From this, it is clear that that Bending innovations like TOPCon dominate when the industry wants to progress without disruption. This can be seen in action since the market share for TOPCon is growing quickly (Feldman.D, et.al, 2025), and investors are comfortable with betting on this for the next few years.

Blending is about combining complementary technologies or materials that perform better together than either alone. The guiding question of this strategy is, 'What two ideas working together can suppress loss better than either on its own?'

Blending drives efficiency not through incremental changes, but through the synergy of complementary strengths.

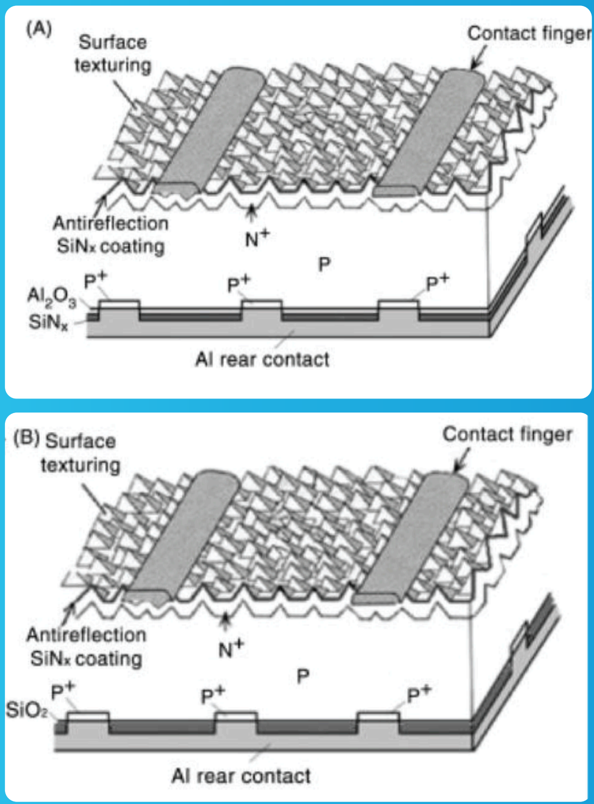


Image Source: Institute of solar technology
Shows In (a) a Bifacial PV module
(b) a standard PV module

In solar PV, a classic example is the pairing of texturing and anti-reflective coating, which blends surface scattering with refractive-index control to trap far more light at the cell surface than either technique could achieve independently (Liu.D, et.al, 2017). Heterojunction Technology (HJT) applies the blending strategy inside the solar cell architecture by combining crystalline silicon, which has strong light absorption, with amorphous silicon, which offers exceptional surface passivation[5]. The result is a massive reduction in recombination losses (Paviet-Salomon, B, 2015). Interdigitated Back Contact (IBC) blends optical optimization with electrical redesign by removing front-side metal shading entirely and shifting all contacts to the rear (Paviet-Salomon, B, 2015).

In thin-films, blending is best illustrated by perovskite–CIGS tandems. Perovskites capture high-energy photons efficiently, while CIGS absorbs lower-energy photons with high defect tolerance. Together, they suppress thermalization and transmission losses more effectively than either material alone (Zhai.J, et.al, 2025).

Blending consistently delivers significant efficiency gains, but it also demands new equipment, skills, and investment. Thus, the blended architectures such as HJT and IBC are expected to scale through the early to mid-2030s, when higher efficiency provides stronger economic returns.

Breaking is about shattering limits and rebuilding the architecture from the ground up. Its guiding question is simple: 'What structural limits must be dismantled even if it means breaking the solar cell apart to keep improving?'

Breaking begins when further gains are no longer possible within the existing architecture, and progress demands reconstruction rather than refinement.

This can be seen with the shift from standard 60 cells and 72 full cells, to 120 and 144 half-cut cells. The industry assumed that each cell had to operate as one large high-current unit. Splitting each cell in half shattered that assumption. Current in each piece dropped by half, slashing resistive (I^2R) losses, cutting heat, and improving shade tolerance. Shingled and tiled modules pushed the concept further by breaking long busbars into overlapping strips, eliminating interconnection losses entirely (Guo.S,et.al, 2013). In both cases, engineers did not optimize the old structure, but they dismantled the part of it that was holding efficiency back.

III–V multijunction thin-film cells rebuild the architecture by stacking multiple thin-film layers with different bandgaps to surpass the thermodynamic limit and eliminate the single-junction loss mechanism completely (U.S.DoE, Multijunction III-IV, n.d)

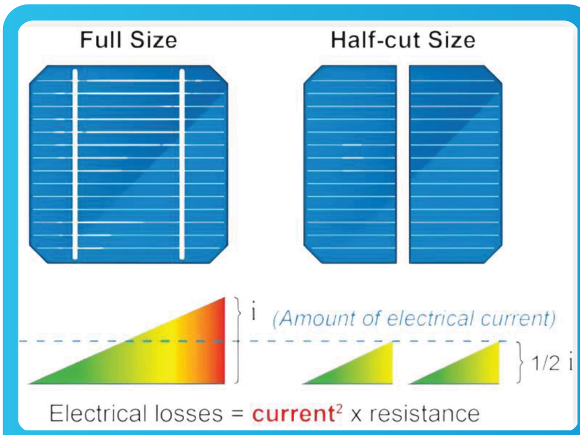


Image Source: [Heaven Designs](#)
Shows the full and half cells

A similar strategy is observed in mainstream PV. Perovskite–silicon tandem cells have already surpassed the Shockley–Queisser limit[6] in laboratory conditions. This is achieved by stacking a perovskite layer over silicon. Silicon has a bandgap[7] of 1.1 eV and absorbs red and infrared light efficiently, but it wastes the excess energy of high-energy blue photons as heat. Perovskites, by contrast, can be engineered to a higher bandgap of around 1.7 eV, which is ideal for capturing blue light while remaining transparent to the wavelength silicon absorbs best. Together, they break through the single-junction efficiency cap (Aydin.E,et.al, 2024).

The grand challenge is not whether tandems will work, but whether they can survive in the real world. Stability under humidity, temperature fluctuations, and UV exposure will remain the key bottlenecks (Aydin.E,et.al, 2024). Encapsulation may slow down degradation but will add cost. The risk for investors lies in how fast the lab success can translate to commercial readiness. Scaling issues, durability uncertainties, and higher production costs could delay or dilute returns.

With current R&D momentum, tandem cells could push commercial module efficiencies past 30% by around 2030. That would mark a fundamental shift for the industry. If tandems establish themselves as the next dominant technology curve, we will see years of Bending and Blending innovations around them until the next breakthrough.

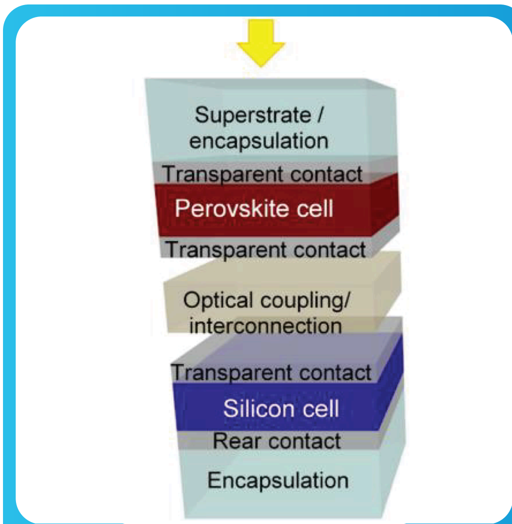


Image Source: Institute of solar technology
Shows In (a) a Bifacial PV module
(b) a standard PV module

The Efficiency Imperative and the Impact of Policymaking

It is clear that efficiency is a vital metric that influences the cost. Higher-efficiency modules generate more revenue per square meter of installation. They reduce the cost of mounting structures, wiring, and inverters. They conserve scarce land resources. They extend the productive lifetime of projects by continuing to deliver higher output even as they degrade. They deepen the climate impact of every dollar invested in clean energy infrastructure.

The manufacturers that successfully navigate the transition from PERC to TOPCon, from TOPCon to HJT, and eventually from HJT to tandems will capture disproportionate value. Those locked into commodity production of legacy architectures will face margin compression from overcapacity and existential pressure from more efficient competitors.

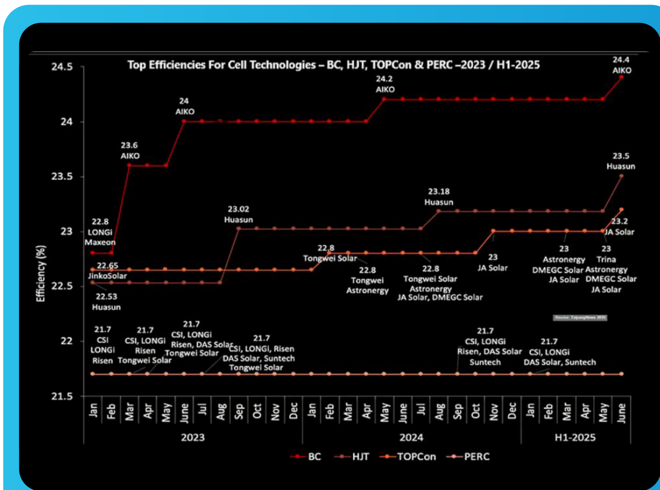


Image source: Taiyang News
This image compares PV technology market share projections from CPIA (China Photovoltaic Industry Association), ITRPV (International Technology Roadmap for Photovoltaics), Exawatt, and S&P Global.

The Decade of Rapid Transition

Solar photovoltaic cells took centuries to reach the current stage. The next phase is expected to progress more rapidly. Viewed through the lens of 3B framework, the following outlook is a reasonable evolution:

1. TOPCon is expected to dominate near-term capacity additions.
2. CdTe is likely to advance through incremental efficiency gains and manufacturing scale-up within the domestic utility PV market.
3. HJT and back-contact architectures may expand from premium segments into mainstream markets.
4. Perovskite-silicon tandems are expected to progress from pilot manufacturing to early commercial deployment.

Limitations of this Study

The Bending, Blending, and Breaking framework is useful for understanding the complexity of solar cell evolution and for making informed interpretations of technological progress. However, it has critical limitations:

It is not a predictive framework and does not identify which technological pathways will ultimately scale. It simply outlines plausible pathways of technological growth rather than definitive outcomes. It is to be noted that bending, blending, and breaking often occur simultaneously and in non-linear ways. The framework focuses primarily on cell level innovation and does not fully capture module level performance, balance-of-system impacts, or system integration considerations that influence real-world deployment.

Accordingly, the 3Bs should be used as a guide for interpreting technological trajectories to understand the logic of efficiency-driven innovation and not as a standalone tool for forecasting market outcomes or deployment timelines.

Scope for Future Work

There are many new research areas in solar cells that can be considered in future papers. Some topics are listed below:

1. How the transition to new PV cell architectures affects existing manufacturing equipment, and whether these can be retrofitted or need to be replaced, and how this transition impacts module costs.
2. The solar cell industry's dependence on specialized manufacturing equipment and the resulting concentration and risks within the supply chain.
3. Recyclability of pv cells and its components, and how these factors influence investment decisions.
4. Comparison of technology choices based on internal rate of return (IRR) versus CO_2 abatement optimization.
5. Methodology for attributing climate impact across the PV value chain.

Key Concepts

[1]Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun (PVeducation.org, n.d).

[2]Reflection at Surface: When sunlight first hits a solar panel, 4-8% bounces right off the surface before it can be converted to electricity (TONGWEI.CO).

[3]Electron Recombination: In a working solar cell, 5-20% of generated electrons never make it to the circuit where they recombine with holes instead of contributing to current (TONGWEI.CO).

[4]Resistance in circuits: Electrical resistance causes 3-8% loss of power output due to resistive losses in busbars, ribbons, and cell interconnections (TONGWEI.CO).

[5]Passivation refers to the treatment of a solar cell's surface to limit electron–hole recombination. By adding a thin passivation layer, surface defect sites are neutralised or shielded, reducing the likelihood that charge carriers recombine before being collected. As a result, more excited electrons reach the contacts and contribute to the generated electrical current (Solarbe Global).

[6]The Shockley–Queisser limit describes the maximum efficiency that a single p–n junction solar cell can achieve. The upper limit is around 33.7% for materials with a bandgap close to 1.34 eV. This constraint comes from losses that occur in a solar cell- such as energy lost as heat, photons that are not absorbed, recombination of charge carriers, and electrical resistance within the device (Ossila).

[7]The bandgap, or energy bandgap, is the minimum energy required for an electron to move from a bound state in the outer shell of an atom to a free, conductive state, leaving behind a corresponding hole (Sino Voltaics).

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