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DESIGN OF NEW TECHNICAL DEVELOPMENTS BASED ON ALTERNATIVE ENERGY

Ministry of Higher Education, Science and innovation
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Silicon

Perovskite

Organic

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Nomenclature:

- **CIGS** – Copperindium gallium selenide
- **ITO** – Indium-doped tin oxide
- **DSSC** – Dye-sensitized solar cells
- **FTO** – Fluorine-doped tin oxide
- **MFI** – Metallorganic Frameworks
- **LUMO** - Lower unoccupied molecular orbit
- **HOMO** - Highest occupied molecular Orbital
- **NREL** - National Renewable Energy Laboratory
- **RI** – Refractive Index
- **NCS** – Nanocomposite Solar Cell
- **FAD** – Ferrocenedicarboxylic Acid
- **HTM** – Hole Transport Material
- **PCE** – Power conversion efficiency
- **J_{max}** – Maximum Current Density for Light Exposure
- **AE** – Apparent Efficiency (Photon-to-electricity conversion efficiency)
- **AJ** – I-t Curve Current Efficiency (the ratio of effective current density to J_{light})
- **P_{max}** – Maximum Power under light exposure (W)
- **J_p** – Photon-current per cm² (μA/cm²)
- **I_p** – Probe current (μA)
- **EQE** – External Quantum Efficiency
- **P** – Power (W)
- **IST** – Integrated STC
- **voltage** – Voltage (V)
- **current** – Current (A)
- **FF** – Fill Factor
- **Voc** – Open-circuit Voltage
- **Isc** – Short-circuit Current

Introduction

The twenty-first century marks a decisive shift in the global energy paradigm. The growing demand for electricity, the depletion of fossil fuel reserves, and the worsening effects of climate change have created an urgent need for sustainable, environmentally friendly energy sources. Among the most promising and rapidly developing solutions are **alternative energy systems**, particularly those harnessing solar and wind power. This course, *Design of New Technical Developments Based on Alternative Energy*, introduces students to modern design approaches, materials, and technologies that underpin today's renewable-energy innovations. It unites theoretical foundations with practical engineering principles to prepare students for professional research and development in the field of sustainable technology.

Solar photovoltaic (PV) technology has diversified far beyond traditional silicon panels (Figure 1). Modern PV research spans second-generation *thin-film* devices and emerging materials to improve efficiency, cost, and form-factor. For example, thin-film cells use nanometer-scale absorber layers on glass or polymer, enabling lightweight, flexible modules. Other approaches add novel layers or structures to silicon (see PERC and heterojunction below) or stack semiconductors in *multi-junction* cells to capture more of the solar spectrum. New absorber materials – perovskites, dyes, and organics – promise very low-cost or transparent devices. Bifacial modules harvest light from both front and rear surfaces using reflected ground light. In parallel, wind turbines convert atmospheric motion into power, making wind a mature renewable source. By 2024 wind exceeded 800 GW globally, providing $\approx 8\%$ of electricity. Finally, PV system operation (cleaning, remote monitoring, and sun-tracking) is critical for performance. The sections below introduce these advanced solar technologies and wind energy concepts in turn.

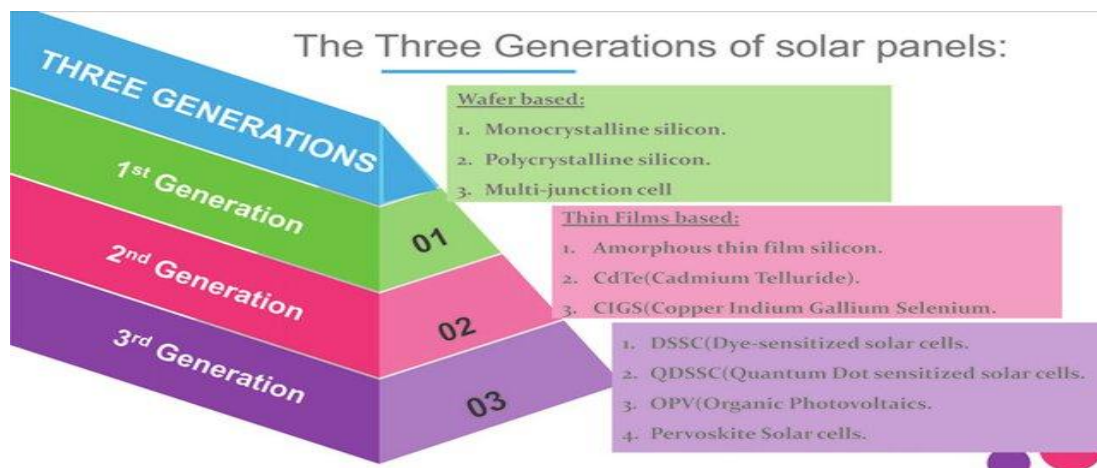


Figure 1. 3 Generations of Solar cells

First Generation (Crystalline Silicon) Solar Cells

First-generation cells are based on thick crystalline silicon wafers, either monocrystalline (mono-Si) or polycrystalline (poly-Si), representing over 90% of global PV installations due to mature manufacturing and reliable performance. **Crystalline silicon** or (**c-Si**) is the crystalline forms of silicon, either polycrystalline silicon (poly-Si, consisting of small crystals), or monocrystalline silicon (mono-Si, a continuous crystal). Crystalline silicon is the dominant semiconducting material used in photovoltaic technology for the production of solar cells. These cells are assembled into solar panels as part of a photovoltaic system to generate solar power from sunlight.

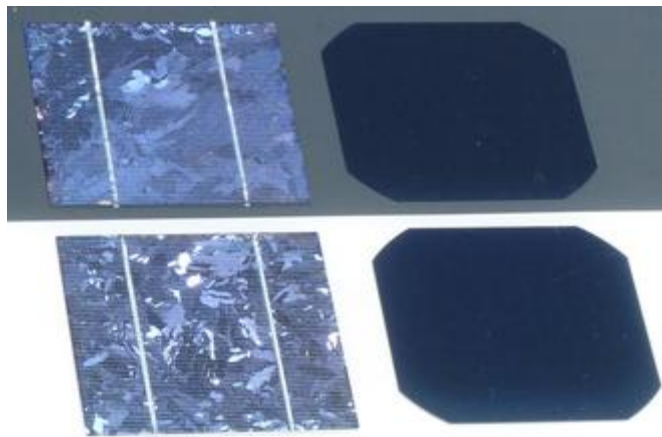


Figure 2. Crystalline-silicon solar cells are made of either Poly Silicon (left side) or Mono Silicon (right side).

Classifications: PV industry

In photovoltaic industry, materials are commonly grouped into the following two categories:

- Crystalline silicon (c-Si), used in conventional wafer-based solar cells.
 - Monocrystalline silicon (mono-Si)
 - Polycrystalline silicon (multi-Si)
 - Ribbon silicon (ribbon-Si), has currently no market
- Other materials, not classified as crystalline silicon, used in thin-film and other solar-cell technologies.
 - Amorphous silicon (a-Si)
 - Nanocrystalline silicon (nc-Si)
 - Protocrystalline silicon (pc-Si)
 - Other established non-silicon materials, such as CdTe, CIGS
 - Emerging photovoltaics
 - Multi-junction solar cells (MJ) com

Structure and Operation

They consist of a p-n junction formed by doping silicon wafers, covered by an anti-reflection coating(SiO_2) and front/rear electrodes. Light absorption in the bulk silicon generates electron-hole pairs separated by the junction's electric field(Figure 3).

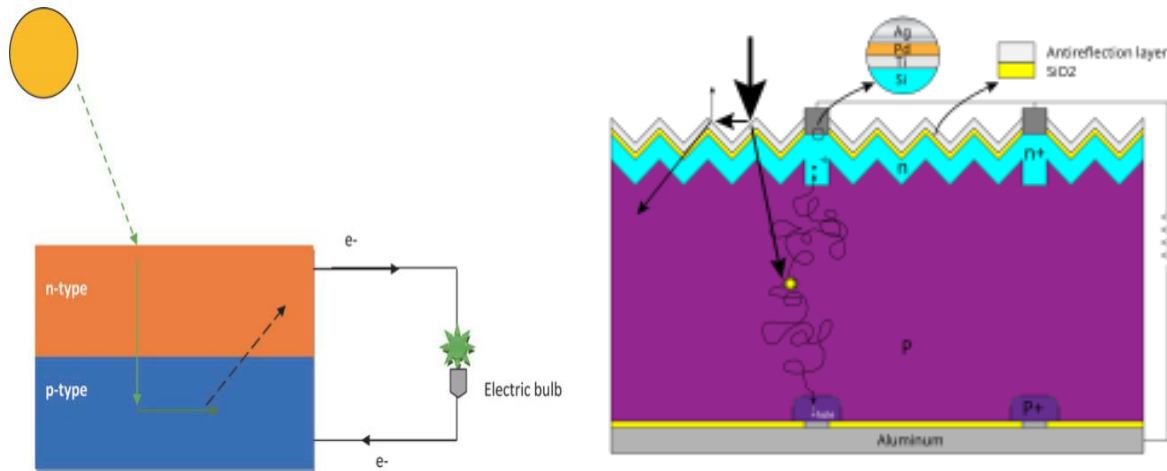


Figure 3. Silicon solar cells

Advantages and Limitations:

Advantages: High stability, well-understood reliability, long service life, dominant supply chain.

Limitations: High material (silicon) consumption, energy-intensive wafer production, higher costs per watt, and constrained by single-junction Shockley-Queisser limit (~31% theoretical).

Passivated Emitter and Rear Contact (PERC) Solar Cells

PERC cells are an enhanced crystalline silicon design that adds a dielectric “passivation” layer and local contacts on the rear surface. In a standard PERC cell (illustrated below), an anti-reflection texture and front grid collect light as usual, but the back side has a thin $\text{SiO}_2/\text{Al}_2\text{O}_3$ film plus tiny openings where aluminum is applied. This structure (seen in the figure) creates a partial rear mirror and electric field that reduces carrier recombination at the back surface. The effect is higher voltage and efficiency. PERC cells were developed in the 1980s and became widely commercialized in the 2010s. Today PERC is the dominant silicon cell technology because it boosts efficiency over conventional *Al*-BSF cells by several percent. Commercial PERC modules regularly exceed 22% efficiency, and record PERC cells (laboratory) have topped 25%. Thus PERC represents a relatively simple retrofit to standard silicon processing that yields significant performance gains.

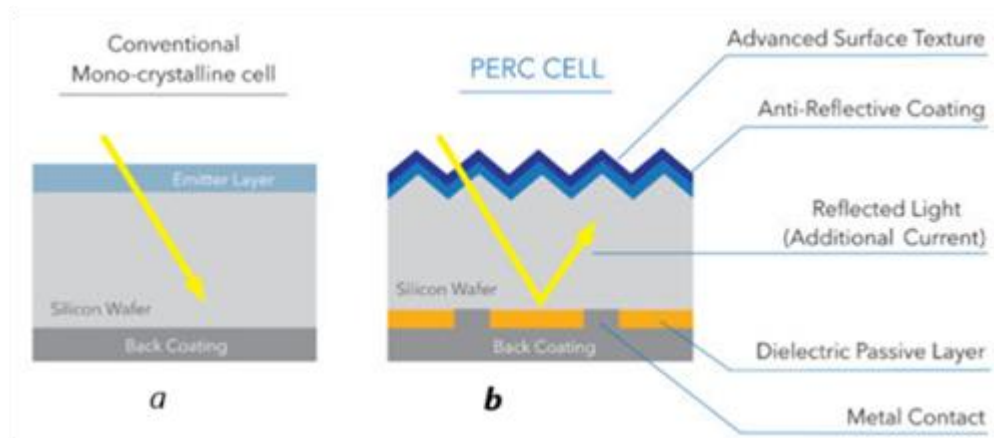


Figure 4. *a*) Conventional crystalline silicon (c-Si) solar cells; *b*) Passivated emitter rear contact (PERC) solar cells

Second Generation (Thin-Film) Solar Cells

Thin-Film Solar Cells

Thin-film solar cells deposit micron- or sub-micron layers of semiconductor on a substrate. This “second-generation” PV uses materials like cadmium telluride (CdTe), copper-indium-gallium-selenide (CIGS), or amorphous silicon (a-Si) in very thin form. The figure (Cadmium Telluride cell cross-section) shows a typical thin-film layer stack: glass, a transparent conductor, the CdSeTe/CdTe absorber, and a metal back contact. Because the absorber is very thin, these cells are lightweight and can be made flexible or semi-transparent. They suit building-integrated photovoltaics or curved surfaces, and their roll-to-roll manufacturing can be simpler and cheaper than crystalline silicon. Modern CdTe thin-film modules have matured: for example, CdTe is now the **second-largest** PV technology after silicon, capturing ~21% of the U.S. market and ~4% globally (2022). Record efficiencies for single-junction thin films (e.g. GaAs) have even exceeded 29%, surpassing the Shockley–Queisser limit for silicon. However, many thin-film cells still lag in durability and long-term stability versus silicon, which has kept their market share (~5% worldwide) relatively low. Overall, thin films offer low cost per watt and design flexibility at the expense of somewhat lower efficiency and longevity compared to first-generation cells.

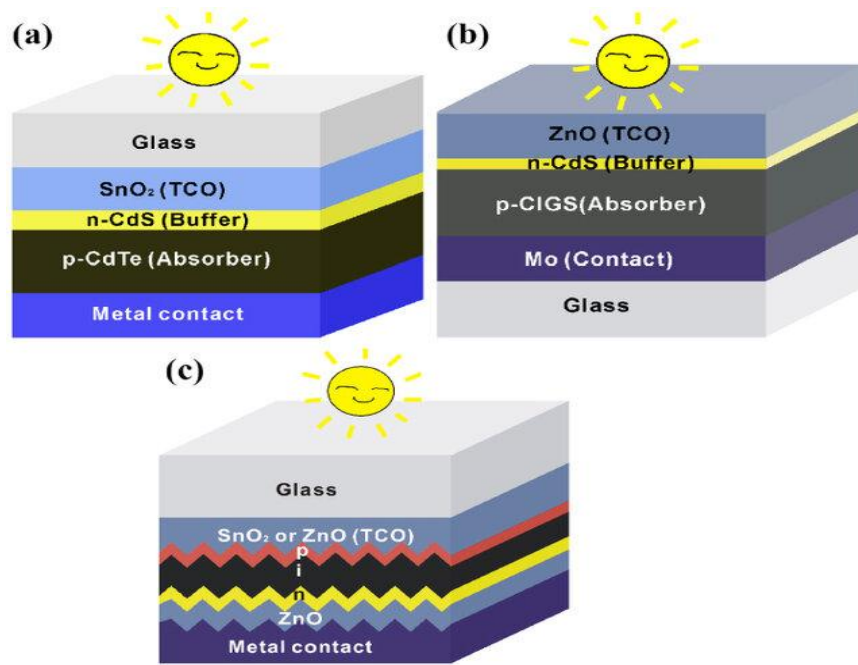


Figure 5. Typical structures of conventional CdTe, CIGS and superstrate-type thin film Si single junction solar cells. (a) CdTe. (b) CIGS. (c) Thin film Si (all not to scale).

Third Generation (Emerging & Advanced) Solar Cells

Heterojunction Solar Cells

Heterojunction (often “HJT” or “SHJ”) cells combine crystalline silicon wafers with thin amorphous silicon layers to form the junction. The schematic below (Figure-6) shows a silicon heterojunction cell: an n-type crystalline Si wafer is sandwiched between intrinsic and doped amorphous-Si layers. This yields extremely good surface passivation and high open-circuit voltage. The amorphous layers create a heterojunction analogous to a p–n interface, so electrons excited in the cell can be collected efficiently. The excellent passivation from the a-Si layers gives heterojunction cells very high performance; indeed, HJT currently holds the world record for mass-produced silicon cell efficiency. In practice, heterojunction modules are nearly bifacial (they naturally capture some light from the rear) and exhibit low temperature coefficient. Their main drawback is more complex fabrication (vacuum deposition of a-Si). Despite that, adoption has surged: by 2022–2024 HJT overtook traditional Al-BSF and now accounts for ~10% of new cell production, reflecting its higher efficiency potential.

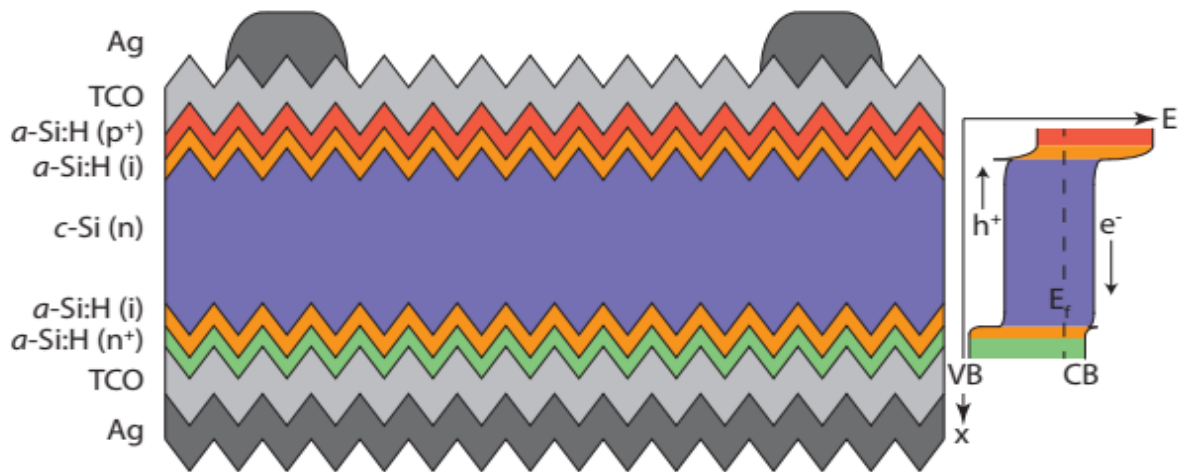


Figure 6. Sketch of a SHJ solar cell as first developed by Sanyo, Japan, including its band diagram. The wafer is n-type. Structure is not drawn to scale

Multi-Junction Solar Cells

Multi-junction (tandem) cells stack two or more photovoltaic junctions of different bandgaps to absorb a broader spectrum. A typical terrestrial tandem might put a wide-bandgap cell on top of silicon, or use multiple III-V compounds in series. This bypasses the $\sim 33.7\%$ efficiency limit of a single junction under one-sun illumination. In the lab, multi-junction concentrator cells have achieved $>46\%$ under concentration. However, multi-junction devices are complex and costly, so they are mainly used in space and high-concentration PV. Recently, perovskite-on-silicon tandems have attracted interest: lab prototypes exceed 30% efficiency, hinting at future highly efficient panels. In summary, multi-junction technology promises very high efficiency but is still emerging outside niche applications.

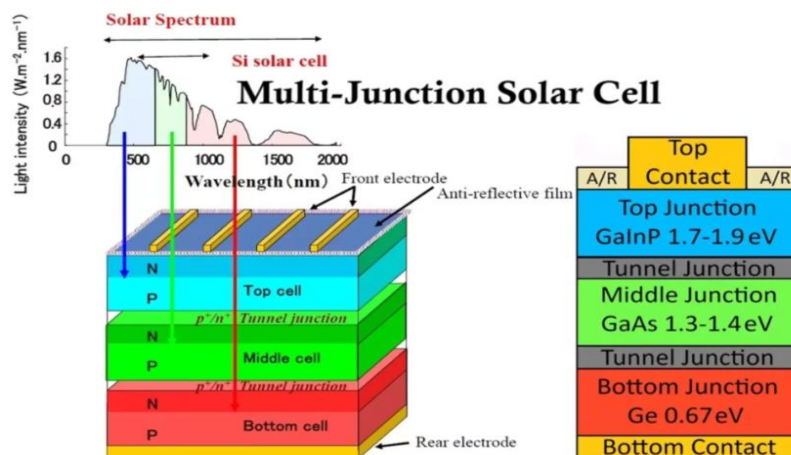


Figure 7. Multi-junction solar cell structure.

<http://large.stanford.edu/courses/2010/ph240/weisse2/>

Bifacial Solar Cells

Bifacial panels generate power from light incident on *both* the front and rear faces. They take advantage of ground-reflected (albedo) or diffuse light that strikes the back surface. For example, on a bright sandy ground or with white rooftops underneath, rear-side generation can add 10–30% more energy compared to a conventional panel. Bifacial cells and modules were developed in the late 20th century but became mainstream in the 2010s. They are well-suited to flat installations (ground or roof) and have the practical benefit of being less affected by dust and soiling (since the rear side also generates). Current predictions suggest bifacial designs will lead PV manufacturing by 2030, due to their higher annual yield and versatile mounting.

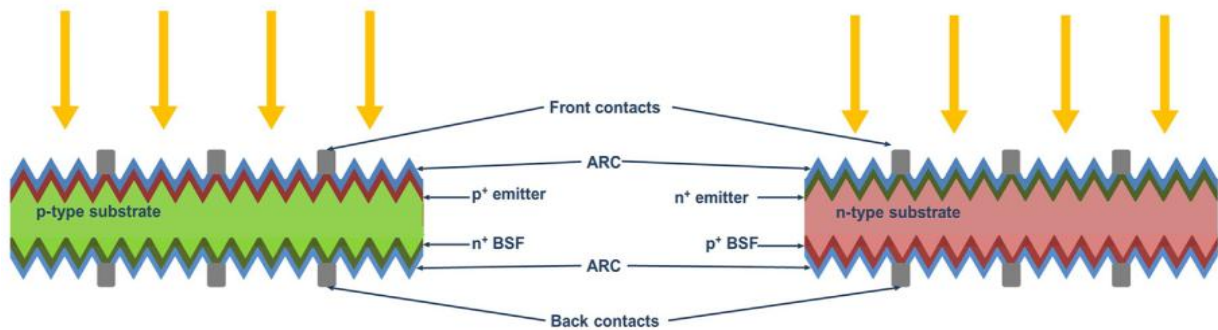


Fig. 8. Cross-section view of standard n-type and p-type bifacial crystalline silicon solar cells.

Perovskite Solar Cells

Perovskite solar cells use a light-absorbing layer with a perovskite crystal structure (often lead-halide perovskites). These materials have extremely high absorption and allow very thin films (~500 nm) to capture most sunlight. They can be processed at low temperature from solution, leading to potentially very low-cost fabrication. Perovskites have skyrocketed in performance: single-junction lab cells now exceed 25% efficiency. Moreover, perovskites combine well with silicon or other bottom cells in tandem architectures. For instance, all-perovskite two-terminal tandems have reached ~31.9% efficiency in the lab. If stability and toxicity issues (lead content, sensitivity to moisture) can be managed, perovskite cells could revolutionize PV by offering thin, light, and even semi-transparent panels with performance rivaling silicon.

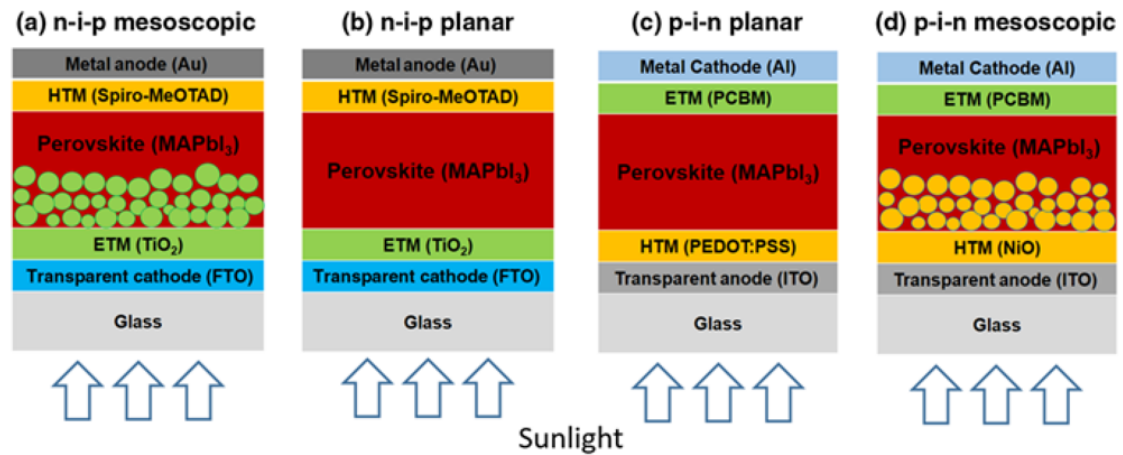


Figure 9. Schematic structure of a typical planar perovskite solar cell (n–i–p configuration)

Dye-Sensitized Solar Cells

Dye-sensitized solar cells (DSSCs, or Grätzel cells) are a type of thin-film PV based on a porous semiconductor (usually TiO_2) coated with a light-absorbing dye. Sunlight excites the dye molecules, injecting electrons into the semiconductor, while the circuit is completed by a liquid (or solid) electrolyte. DSSCs are notable for low-cost materials and simple fabrication (often using printing/coating). They can be made semi-transparent and colorful, suitable for building-integrated applications. However, typical efficiencies ($\sim 5\text{--}10\%$) are well below silicon. Key challenges include the long-term stability of the liquid electrolyte and the use of expensive catalysts (e.g. platinum). Despite these issues, DSSCs remain an important research area, especially for indoor or low-light environments where their diffuse-light response can be favorable.

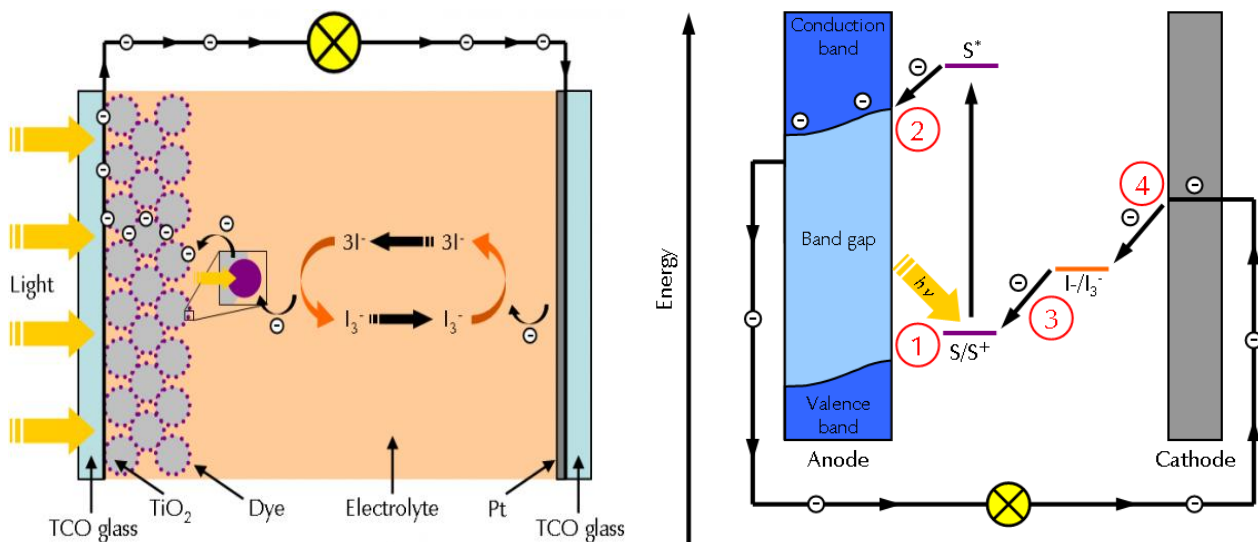


Figure 10. Illustration of the basic structure of a DSSC and its operating mechanism

Organic Solar Cells

Organic solar cells (also called polymer or plastic solar cells) use carbon-based molecules or polymers as the semiconductor. These organic semiconductors can be processed in solution (inkjet or roll-to-roll printing) on flexible substrates, yielding very lightweight and conformable modules. The chemistry can be tuned (via molecular engineering) to adjust bandgaps, enabling multi-color or semi-transparent cells. The high absorption coefficient of organics means only hundreds of nanometers of material are needed to absorb light. The trade-off is that organic PV currently has lower efficiency and stability: typical lab devices are still in the 10–15% range (though records have recently approached 19%). They also degrade faster under sunlight. Nonetheless, organic cells may find niche uses in portable or indoor power where flexibility and low cost outweigh the lower efficiency.

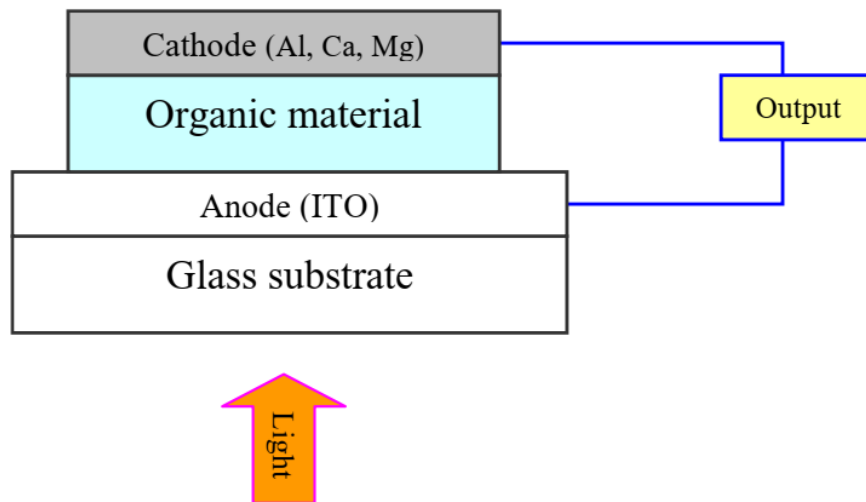


Figure 11. A prototype structure of Organic solar cells OSC device

Transparent Solar Cells

Transparent photovoltaics aim to integrate solar cells into windows, displays, and other surfaces by letting visible light through. One approach (MIT-style) is to make the cell absorb only non-visible wavelengths (UV and IR) while passing visible light. For example, researchers have coated glass with layers that harvest UV/IR but appear clear to the eye. Another approach uses very thin or patterned silicon cells with special micro-optics to achieve a neutral color. Recent breakthroughs have produced *colorless* transparent modules with about 20% visible transparency and $\approx 15\text{--}16\%$ conversion efficiency. Such transparent panels could serve as smart windows or mobile-device screens, generating power without darkening the view. However, a

fundamental trade-off remains: higher transparency generally means lower efficiency, so optimization continues.



Figure 12 Mechanical flexibility organic transparent solar cells

Wind Energy

Wind power captures kinetic energy from moving air using turbines. Modern wind turbines (with blades up to 100+ m long) convert the wind's momentum into electricity with minimal emissions. Wind farms – onshore and offshore – have expanded rapidly. By 2024 global installed wind capacity exceeded 800 GW, generating over 2,500 TWh (roughly 8% of world electricity). Wind energy has very low operating cost and a small carbon footprint compared to fossil fuels. New turbine designs (lighter blades, taller towers) and offshore development continue to improve capacity factors. On the flip side, wind is inherently variable and usually requires backup or storage to smooth supply. Offshore wind, where winds are stronger and steadier, is a major focus despite higher costs of installation. Overall, wind is a mature, low-cost clean energy technology complementary to solar.



Figure 13

Solar Plant Maintenance and Sun-Tracking

Large solar plants require regular maintenance to sustain performance. Panels must be kept clean (dust, dirt, snow can reduce output), so some installations use automated washers or periodic manual cleaning. More importantly, modern PV farms employ sophisticated monitoring (SCADA) and control systems. A distributed SCADA network links inverters, sensors, and even two-axis trackers across the site. Real-time data allows rapid fault detection and performance optimization. Dual-axis sun trackers adjust both tilt and azimuth of the panels throughout the day and year, keeping them aimed toward the sun. This tracking can increase annual energy yield by 15–30% compared to fixed mounts (especially in high-latitude or clear-sky locations). In summary, clean panels, smart monitoring/IT, and dynamic sun-tracking together maximize the energy output and reliability of PV systems.

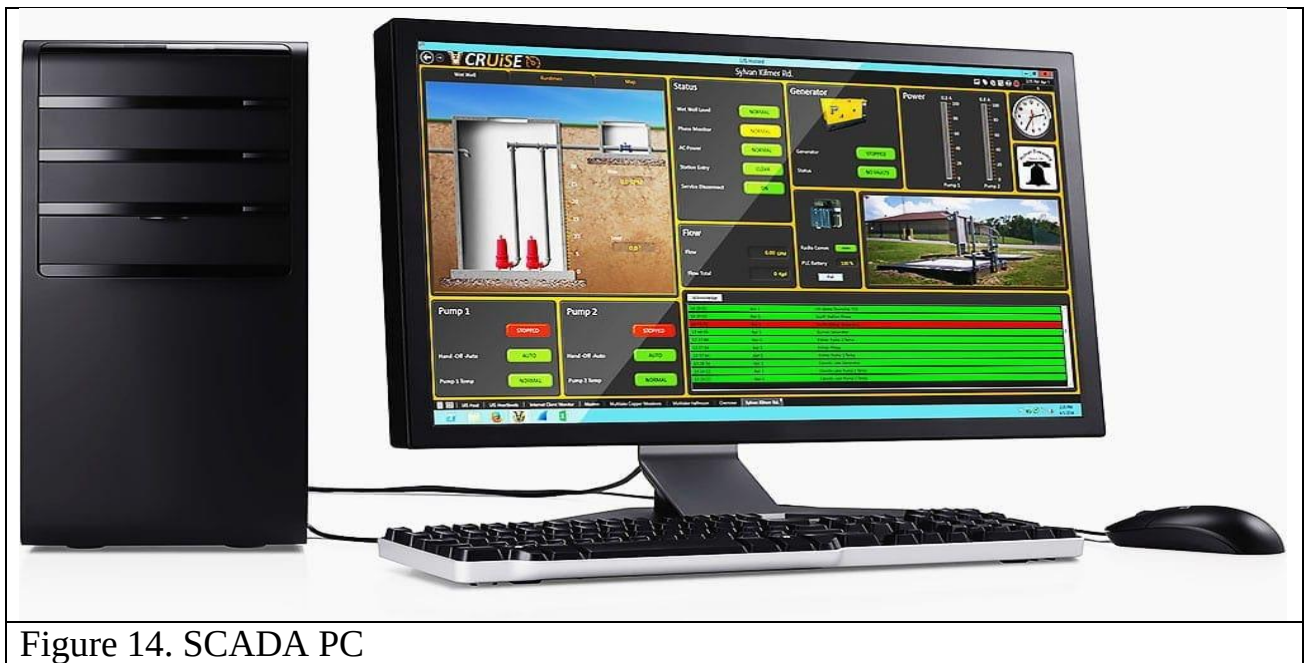


Figure 14. SCADA PC

Educational Objectives and Expected Outcomes

By the end of this course, students are expected to:

- Understand the physical principles and material science underlying major photovoltaic and wind-energy systems.
- Acquire the ability to analyze, model, and design innovative devices based on alternative energy conversion.
- Evaluate the efficiency, cost, and environmental impact of various solar and wind technologies.
- Apply knowledge of automation and digital control (SCADA) to improve the performance and maintenance of renewable installations.
- Develop a research-oriented mindset that fosters creativity, sustainability, and technological innovation.

The course combines **lectures, laboratory experiments, computer simulations, and project-based assignments**, encouraging students to translate theoretical knowledge into real-world design solutions. Through interdisciplinary integration of physics, materials science, electronics, and environmental engineering, this program prepares graduates to participate in global efforts toward decarbonization and energy independence.

Conclusion

The transition to a sustainable energy future relies not only on scientific discovery but also on the intelligent design of new technical developments. By studying alternative energy systems—from thin-film and perovskite solar cells to large-scale wind turbines—students gain both a comprehensive understanding of current technologies

and the innovative mindset required to advance them. This course aims to inspire the next generation of engineers and researchers to transform renewable-energy ideas into practical, efficient, and socially beneficial solutions.

Chapter I

1. THIN-FILM SOLAR CELLS

Thin-film solar cells are made by depositing one or more **nanometer- to micrometer-scale layers** of photovoltaic material on a substrate (glass, metal, or plastic). This contrasts with first-generation wafers (crystalline Si) which are ~100–200 μm thick. Thin films (TF) use far less material, can be flexible or lightweight, and enable new form factors (e.g. building-integrated PV, flexible modules)[1][2]. Major thin-film technologies include amorphous silicon (a-Si:H), cadmium telluride (CdTe), copper–indium–gallium diselenide (CIGS), and various emerging materials (perovskites, organics, dye-sensitized cells, etc.). Thin films are typically classified as “second-generation” PV, with newer materials (perovskite, quantum dot, organic) as third-generation emerging PV[1]. Key advantages of thin films over crystalline Si are lower material use, potential for lower cost, flexibility, lighter weight, and simpler large-area manufacturing[1][3]. However, many thin-film types have historically lower efficiency and shorter lifetimes than wafer cells, which has limited their market share[1].

Historical Development

Research on thin-film PV began in the 1970s. In 1970, Alferov’s team at Ioffe Institute (Russia) made the first GaAs solar cells (later Nobel-winning work)[1]. In 1972, Karl Böer founded Delaware’s Institute of Energy Conversion to study $\text{Cu}_2\text{S}/\text{CdS}$ and Zn_3P_2 and amorphous silicon (a-Si) films[1]. Early efficiency gains followed: by 1980 $\text{Cu}_2\text{S}/\text{CdS}$ reached ~10%[1]. In 1986 ARCO Solar introduced the first commercial a-Si thin-film module (the G-4000, ~4 W)[1]. By the 1990s, several companies and labs pushed thin-film efficiencies higher: e.g. >15% a-Si at Univ. of South Florida (1992)[1], and a 3-junction GaAs cell reached 32% (1999)[1]. Organic (polymeric) thin-film cells emerged in 2001 (Linz)[1]. In 2009 researchers at Univ. of Tokyo made the first perovskite ($\text{CH}_3\text{NH}_3\text{PbI}_3$) thin-film cell (~3% PCE)[1]. In the 2010s, quantum-dot and perovskite cells soared to >20% efficiencies (e.g. perovskites >25% by early 2020s)[2]. Throughout, GaAs thin-film (III–V) set record efficiencies (up to 29.1% for single-junction GaAs[1]).

Thin-film solar cells

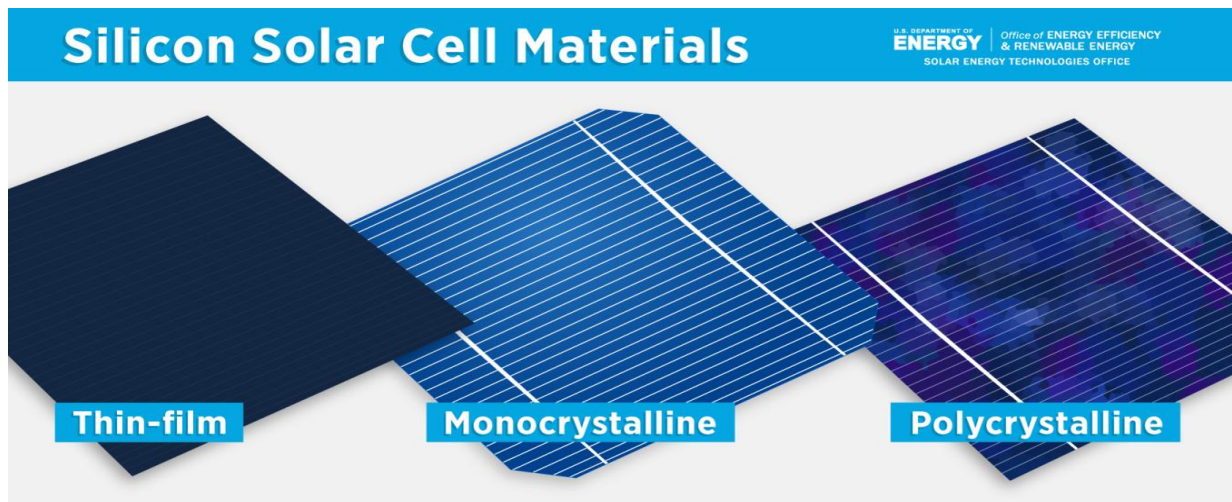


Figure 1. Types of solar cells

Photovoltaic technologies: wafer-based cells vs thin film cells.

The present PV technologies could be classified in two categories: (1) wafer-based (2) thin film cells (Figure 2). Wafer-based cells are fabricated on semiconducting wafers and could be handled without an additional substrate, while modules are typically covered with glass for improving the mechanical stability and more protection. Thin film cells consist of semiconducting layers which can be deposited onto various substrates such as plastic, glass or metal. Further division of thin films into commercial and emerging thin film technologies is presented in Figure 2.

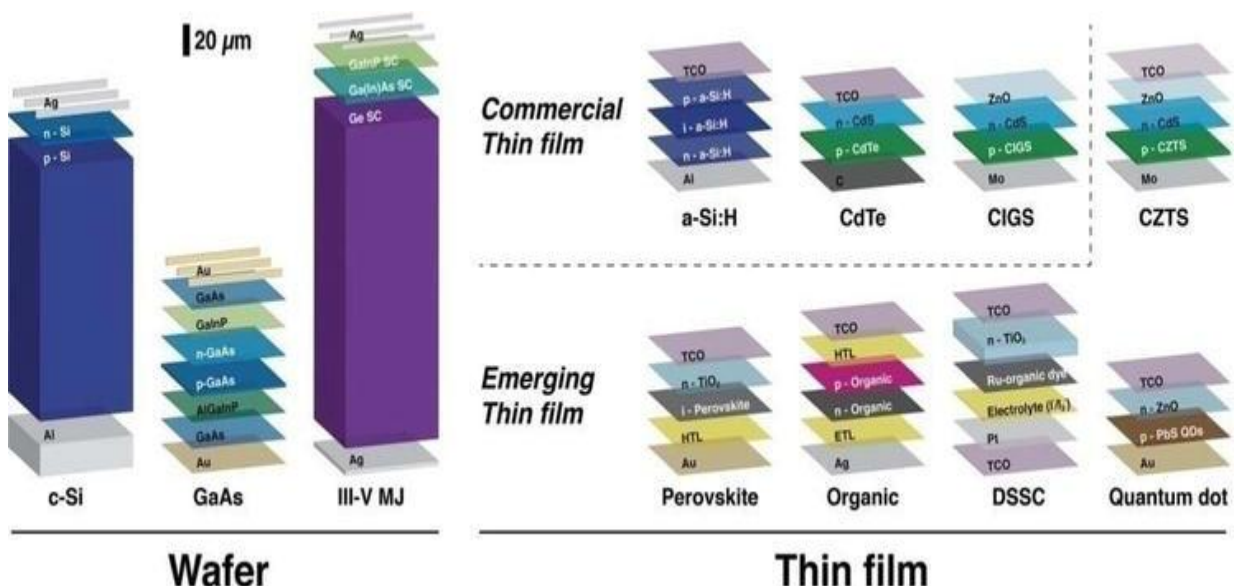


Figure 2. Typical PV device structures, divided into thin film and wafer-based technologies. Primary absorber layers are labeled in white color, and thicknesses are shown to scale (<http://xlink.rsc.org/?DOI=C4EE04073B>).

Three primary wafer-based technologies exist in the market containing: (1) Crystalline Silicon (c-Si), (2) Gallium Arsenide (GaAs) and (3) III-V multijunction (MJ). Among these types, c-Si PVs have occupied ~90% of present global manufacturing capacity and are the most mature of all PV technologies. Silicon solar cells are divided as single-crystalline (sc-Si) or multicrystalline (mc-Si)

PV Fundamentals: Efficiency and I–V Characteristics

Solar-cell efficiency η is the ratio of electrical power out to incident solar power in. Key parameters on the I–V curve are the short-circuit current I_{SC} (at $V = 0$), open-circuit voltage V_{OC} (at $I = 0$), and the maximum-power point (V_m , I_m). The **fill factor** is defined as $FF = (V_m \cdot I_m) / (V_{OC} \cdot I_{SC})$ [16]. The output efficiency is then

$$\eta = \frac{P_{\max}}{P_{\text{in}}} = \frac{V_m I_m}{P_{\text{in}}} = \frac{V_{OC} I_{SC} FF}{P_{\text{in}}}.$$

Here P_{in} is the incident irradiance times cell area (standard test conditions). Thus one can calculate η if V_{OC} , I_{SC} , and FF are known[16]. In practice, I–V curves of different solar-cell technologies (e.g. thin-film vs crystalline) have similar shape but different parameter values.

Thin-film cells tend to have **lower open-circuit voltage and current** than crystalline Si, because thinner absorbers generate less photovoltage or current (especially long-wavelength light may pass through). Their fill factors can also be slightly lower. As a result, typical lab-cell efficiencies are lower (often 10–20% for thin films vs 20–27% for crystalline Si). For example, the best laboratory GaAs thin-film cell reaches 29.1%[1] (higher than any c-Si, 26.7%) but cost of III–V is very high. More commonly, record efficiencies are: **mono-Si ~26.7%**, **multi-Si ~23%**, **CIGS ~23.6%**, **CdTe ~22%**, **perovskite ~25.7%**, and **a-Si ~13%**[2][5][6]. (See Table 1.) In deployed modules, record commercial efficiencies are a bit lower (e.g. 25.4% for top Si modules vs ~19.9% for CdTe modules[5]). A global efficiency chart by NREL confirms this hierarchy[1][5].

Table 1. Record efficiencies of various solar cell technologies[1][2] [5][6]. (These are research-cell records, not necessarily commercial modules.)

Solar cell type	Highest confirmed efficiency (%)	Source
Crystalline Si (mono)	26.7%[2]	NREL data[2]

Solar cell type	Highest confirmed efficiency (%)	Source
GaAs (III–V thin film)	29.1% [1]	(single-junction)
CIGS (copper-indium-gallium-selenide)	~23.6% [6]	(2024 record claim)
CdTe (cadmium telluride)	~19.9% [5]	(module record)
Perovskite (single-junction)	25.7% [2]	(2022 research)

Thin films generally have lower efficiency and larger temperature coefficients than crystalline cells[\[1\]](#), but they can use simpler manufacturing and lighter/flexible substrates. In any case, efficiency comparisons must note cell vs module (module always lower due to losses) and record vs mass-production. As of 2023, CdTe thin films (dominant US thin-film PV) account for ~21% of US PV installations[\[7\]](#), while crystalline silicon still holds ~80–90% of the global market.

Figure 3 illustrates a typical solar cell I – V (current–voltage) curve, defining key parameters used to calculate efficiency (see below).

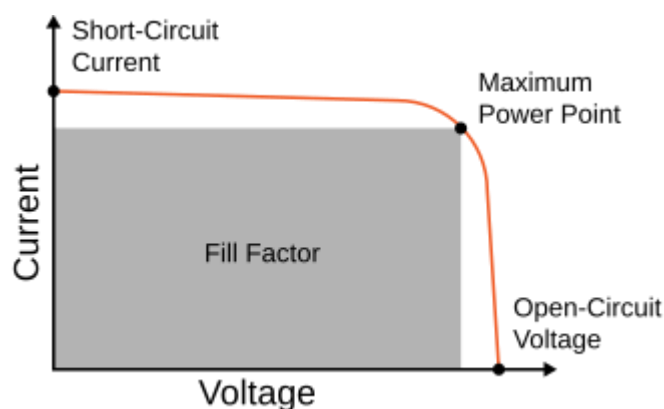


Figure 3. Illustration a typical solar cell I – V (current–voltage) curve. (Image: Fourmatter, CC BY-SA 4.0)

Figure 3: Typical I – V curve of a solar cell (schematic). The short-circuit current I_{SC} (vertical intercept), open-circuit voltage V_{OC} (horizontal intercept), maximum-power point (V_m , I_m), and fill factor (FF) determine the cell’s power and efficiency.

Fabrication and Materials

Thin-film solar cells are typically manufactured by depositing the semiconductor layers onto a substrate. There are two broad approaches: vacuum-based deposition and solution (wet) deposition[\[2\]](#).

- **Vacuum/PVD methods:** These include sputtering, evaporation, molecular beam epitaxy (MBE), and pulsed-laser deposition. For example, CIGS absorbers are often made by co-evaporation of Cu, In, Ga, Se, or by sputtering a metal precursor followed by selenization[6]. CdTe layers are typically deposited by vapor transport or sputtering onto conductive glass[7]. These vacuum methods yield high-quality films but require expensive equipment.
- **Solution-based methods:** These include spin-coating, doctor-blading, spray-coating, chemical bath deposition (CBD), electrodeposition, and printing. For instance, perovskite layers are commonly spin-coated from solution; CdS buffer layers are made by CBD; organics are often printed. These methods are simpler and lower-cost but can suffer from lower uniformity or stability[2].

In a typical thin-film stack, the sequence is: substrate → back contact (metal or TCO) → absorber (semiconductor) → transparent front contact (TCO)[6]. Glass substrates are common (it's cheap and can tolerate high temperature), but flexible substrates (metal foil or polyimide) are also used for bendable modules. Each material imposes constraints: e.g. CIGS is often deposited on soda-lime glass to supply beneficial sodium, whereas some GaAs or organic cells can use plastic.

Amorphous and Microcrystalline Silicon (a-Si, μ c-Si): Amorphous silicon (a-Si:H) was one of the first practical thin-film PV materials. It is simply silicon with a disordered atomic structure, often hydrogenated (a-Si:H) to passivate defects[3]. Hydrogenation was introduced in 1969 (Chittick et al.) to reduce dangling bonds[3]. a-Si:H typically forms a p-i-n junction: a thin p-type layer, an intrinsic absorber (~300 nm thick), and an n-type window layer, all sandwiched between transparent conductive oxide (TCO) contacts[3]. The schematic diagrams in **Figure 4** and **Figure 5** represent the simple architecture of a-Si SC in superstrate and substrate configuration.

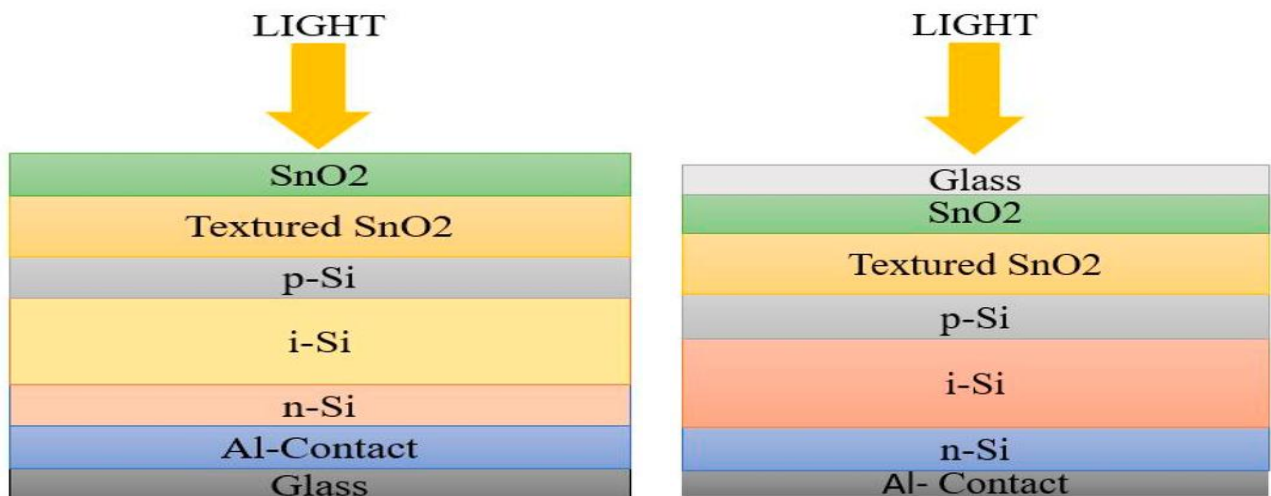


Figure 4. Superstrate configuration.
(<https://doi.org/10.3390/en15228688>)

Figure 5. Substrate configuration.
(<https://doi.org/10.3390/en15228688>)

Advantages: a-Si cells can be made very thin ($<1\ \mu\text{m}$) and on flexible substrates, so they are lightweight and have lower material cost. They also have relatively low manufacturing temperature. Light absorption per thickness is high (amorphous Si has higher bandgap $\sim 1.7\ \text{eV}$, absorbing blue light well)[3].

Alternatively, a “micromorph” cell stacks a-Si over $\mu\text{c-Si}$ (microcrystalline silicon)(Figure 6) to capture longer wavelengths.

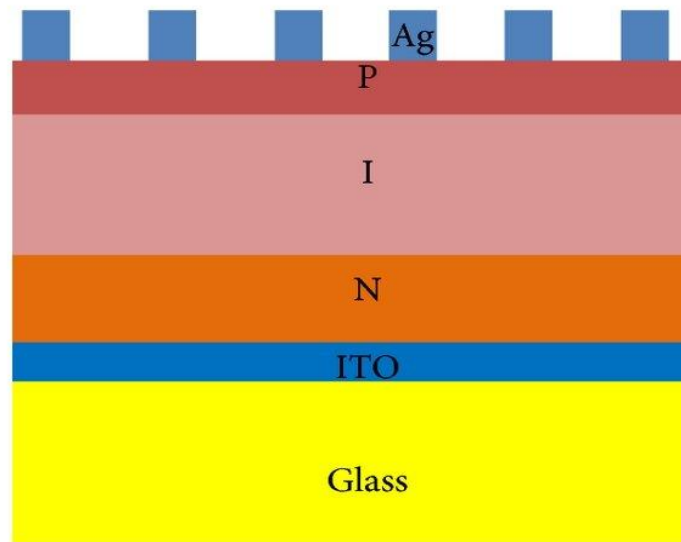


Figure 6. Schematic view of $\mu\text{c-Si:H}$ thin film solar cell.(DOI: [10.1155/2015/327596](https://doi.org/10.1155/2015/327596))

Challenges: a-Si exhibits the Staebler–Wronski effect: efficiency degrades under light exposure (creating metastable defects). Also its bandgap is larger, so less infrared is absorbed. Typical single-junction a-Si cells peak around $\sim 10\%$ efficiency in lab conditions[3], and production modules are $\sim 6\text{--}8\%$. Research combinations (a-Si/ $\mu\text{c-Si}$ tandem, adding Ge or carbon) (Figure 7) seek to overcome this[3]. Table 1 shows record a-Si ($\sim 13\%$, which is a multijunction cell) vs c-Si.

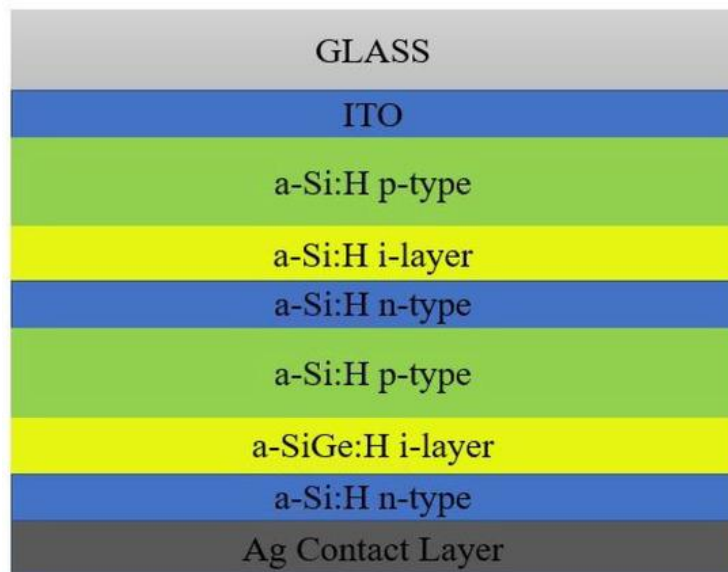


Figure 7. a-Si:H&a-SiGe:H heterojunction SC. .(DOI: [10.1155/2015/327596](https://doi.org/10.1155/2015/327596))

Manufacturing: a-Si films are normally deposited by plasma-enhanced chemical vapor deposition (PECVD) at low temperatures ($\sim 200\text{--}300\text{ }^{\circ}\text{C}$) onto glass/TCO[3]. A typical cell stack is glass/TCO/p-a-SiH/i-a-SiH/n-a-SiH/TCO (or metal)[3]. Cells can be made in “superstrate” (light enters through glass) or “substrate” (light enters through film side) configurations[2]. Adding microcrystalline or polymorphous layers ($\mu\text{c-Si}$, pm-Si) can extend absorption. Heterojunction solar cells (HJT) on Si wafers exploit a-Si layers on crystalline Si; these are discussed below.

Cadmium Telluride (CdTe)

CdTe is the most commercial thin-film PV (First Solar, etc.). The first CdTe cell was made in 1969[7] and 1980s research reached $>10\%$ [7]. Today, CdTe modules have $\sim 19\text{--}20\%$ efficiency[5]. CdTe has a direct bandgap $\sim 1.48\text{ eV}$, ideal for single junction, and an exceptionally high absorption coefficient. A CdTe layer only $\sim 2\text{--}3\text{ }\mu\text{m}$ thick can absorb most sunlight[7].

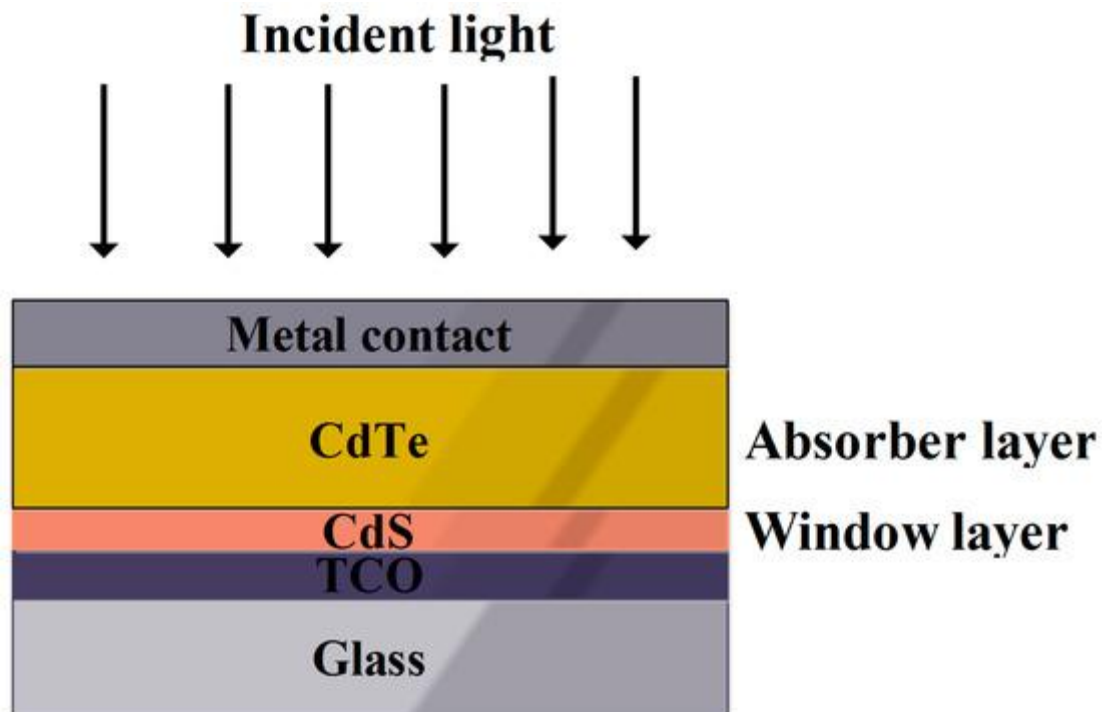


Figure 8. Pictorial representation of simple CdTe SC.
<https://doi.org/10.3390/en15228688>

Structure: Typical CdTe modules use glass/Mo back-contact/CdTe absorber/CdS buffer/TCO front-contact (Figure 8) [6][7]. Fabrication often involves close-spaced sublimation or vapor transport of CdTe onto a substrate, with sequential laser scribing to define cells[7]. A thin CdS layer (~100 nm) is deposited (via chemical bath) as an n-type window/buffer, then a transparent TCO (like ZnO:Al) as front contact[6][7]. Cadmium exposure is a concern, so some processes eliminate CdS buffer (using ZnMgO window instead).

Performance: CdTe modules have lower V_{OC} (~800 mV) than Si cells, but high J_{SC} due to strong absorption. They have low manufacturing cost per area. The world-record CdTe cell efficiency is ~22.1% (small cell)[5], while mass-production modules reach ~19–20%[5]. CdTe PV has dominated utility-scale in the US (e.g. ~29% of new US PV in 2021 was CdTe)[1].

Copper–Indium–Gallium Selenide (CIGS)

CIGS ($\text{Cu}(\text{In,Ga})\text{Se}_2$) is a chalcopyrite material with a tunable bandgap (1.0–1.7 eV depending on Ga content)[6]. Its absorption coefficient is extremely high ($>10^5/\text{cm}$) for visible light[6], so only ~1–2 μm of CIGS can absorb most sunlight. The typical structure is glass/Mo back contact/CIGS absorber/CdS buffer/ZnO window[6], similar to CdTe except the absorber composition(Figure 9).

Under illumination, photons generate electron–hole pairs in the absorber. Electrons are collected via the buffer and TCO, while holes are drawn to the Mo back contact(as shown in Figure 9b).

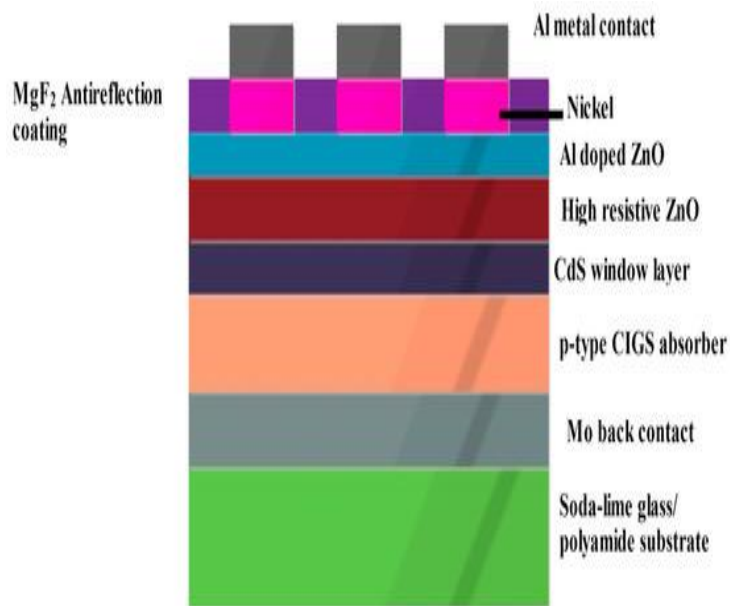


Figure 9a. Diagrammatic representation of CIGS cell architecture.
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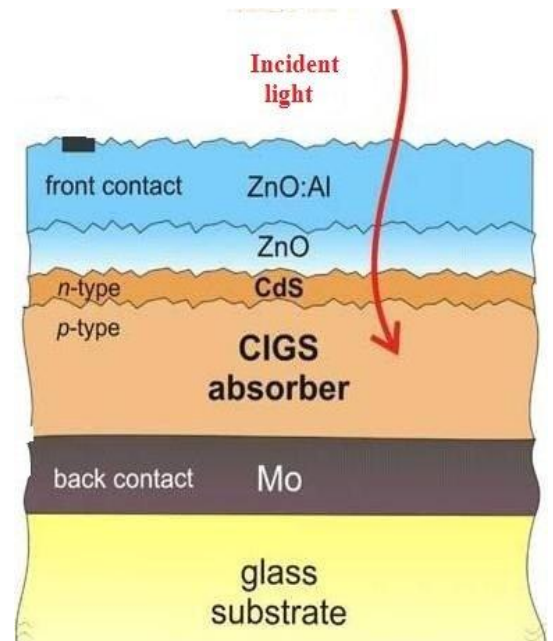


Figure 9b. Operation of CIGS solar cells **European Scientific Journal 11(6)**

Manufacturing: CIGS layers can be deposited by co-evaporation (evaporate Cu, In, Ga and Se simultaneously), or by sputtering metallic precursors then “selenizing” (annealing in Se vapor)[6]. In production, a soda-lime glass substrate (with Na) is common because sodium diffuses into CIGS and improves grain growth and doping[6]. After CIGS deposition, a thin CdS layer is applied (chemical bath), then intrinsic ZnO and Al-doped ZnO as transparent electrodes[21]. Some companies avoid cadmium by using alternative buffer layers.

Efficiency: CIGS cells hold the highest non-concentrator efficiency of any thin film: about **23.6%** as of 2024. For example, labs (NREL, ZSW, etc.) have long demonstrated ~20% CIGS cell efficiencies[6]. Typical CIGS V_{OC} is around 0.6–0.7 V, and J_{SC} about 35–40 mA/cm². CIGS modules in production (e.g. Solar Frontier) achieve ~17–20% efficiency. Its advantages are high absorption (hence thin layer), flexibility (on foils), and absence of toxic elements (no Cd if using cadmium-free buffer)[6].

Other Thin-Film Technologies

Beyond the big three, several other thin-film or “emerging” PVs exist:

GaAs and other III–V cells: Very high efficiency (>25%), but extremely costly. Often made as multi-junction cells for space or concentrators. (Single-junction GaAs is a thin-film technology with 29.1% record[1].)

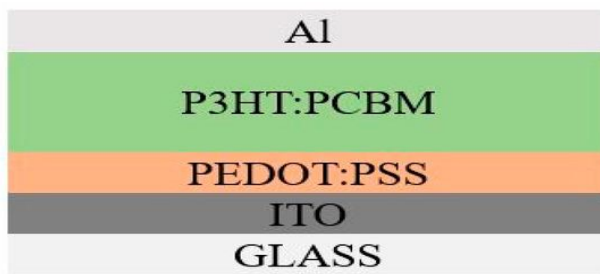
Copper Indium Sulfide (CIS) / CZTS: Related chalcopyrites (CuInSe_2 , $\text{Cu}_2\text{ZnSnS}_4$). These use Earth-abundant elements (no Ga, no Cd). CIS (no Ga) cells have reached ~22% record; CZTS records are ~12–13%. Still R&D stage.

Dye-Sensitized Solar Cells (DSSC): Photoactive dye on nanostructured oxide. Typical efficiencies ~10–12%. Advantage: low cost, easy fabrication; disadvantage: stability and low voltage.



Figure 10. Simple cell architecture of DSSC. (<https://doi.org/10.3390/en15228688>)

Organic photovoltaics (OPV): Carbon-based semiconductors (polymers, small molecules). Flexibility and very low cost potential. Lab efficiencies now ~18–19%; but lifetime is short (months). Two-terminal and tandem OPVs (combining different polymers) have been demonstrated up to ~17–18%[1]. The example of polymer-based cell architectures in normal and inverted structures are diagrammatically represented in **Figure 11** and **Figure 12**.



↑↑↑↑↑↑↑↑
LIGHT



↑↑↑↑↑↑↑↑
LIGHT

Figure 11. Actual Architecture.

(<https://doi.org/10.3390/en15228688>)

Figure 12. Inverted Architecture.

(<https://doi.org/10.3390/en15228688>)

Perovskite Solar Cells: Lead-halide perovskites (e.g. $\text{CH}_3\text{NH}_3\text{PbI}_3$) have revolutionized thin-film PV. From their debut in 2009 at 3% efficiency, single-junction perovskite cells have climbed to about 25.7%^[2] (2022 records) and continue to improve. They can be deposited by low-temperature solution processes (spin-coating, etc.). Perovskites have high absorption and long carrier diffusion lengths, but face stability challenges. Perovskites are often used in tandem (see below).



Figure 13. A schematic diagram represents the simple Perovskite Architecture.

(<https://doi.org/10.3390/en15228688>)

Quantum-dot and Nanocrystal Cells: PbS or lead-halide perovskite QDs offer solution processing and tunable bandgaps. Record ~16% for all-inorganic perovskite QD, ~11–12% for colloidal nanocrystal devices. Mostly lab research.

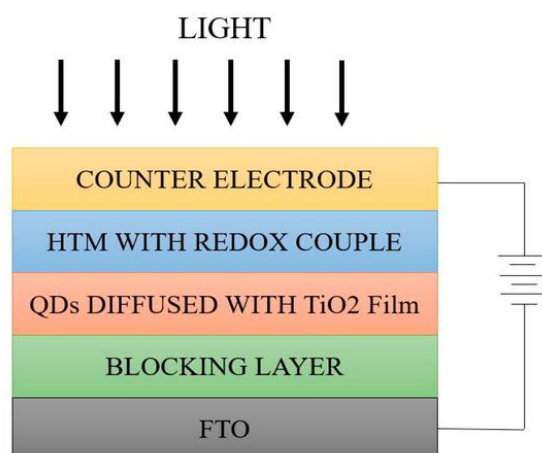


Figure 14. Device architecture of QD SC (<https://doi.org/10.3390/en15228688>)

Figure 14 shows the simple QD based SC structure. Here, the light entering through the counter electrode mainly assists the hole transportation [11]. Then HTM adheres to the redox couple (I-/I³⁺ couple) which is responsible for transfer of the generated holes. Following this phenomenon, QDs adsorbed with the TiO₂ film (photo absorber material) are chosen for exciton generation. The conductive glass substrate, such as FTO glass, is placed next to the photo active material responsible for transfer of generated electrons through the external circuit [12].

Each of these uses similar deposition concepts (thin absorber, buffer, contacts) but with specific materials and processes.

Efficiency Comparison: Thin Film vs. Crystalline Silicon

Thin-film cells typically trade efficiency for cost and form-factor advantages. For example, table 1 shows that highest thin-film efficiencies (20–25%) are below those of crystalline Si cells (≈26–27%). The DOE reported in 2024 that the world-record Si module efficiency is 25.4%, whereas CdTe modules reach only about 19.9%[5]. (Commercial vs lab conditions differ, but this illustrates the gap.) In practice:

Crystalline Si (mono and multi): Modules typically 20–24% (mono higher), lab cells up to ~26–27%.

Thin films: Modules ~15–20% (CdTe, CIGS); lab cells ~20–24% (CIGS ~23.6%, CdTe ~22%, a-Si ~13%, perovskite ~25.7%).

Thin films tend to have lower V_{OC} (e.g. ~0.5–0.7 V vs ~0.7–0.75 V in Si) and slightly lower fill factors, which, combined with thinner absorber, yields lower output power. However, thin films often have better high-temperature performance and lower

embodied energy. The choice depends on application: for rooftop or utility PV where area is limited, crystalline high-efficiency panels dominate. For building integration or flexible applications, thin films (or hybrids like HJT/PERC) can be attractive despite lower efficiency, due to lighter weight and aesthetic (semi-transparency) and potentially lower system cost.

Tandem and Multijunction Thin-Film Cells

Combining thin films with other PV in *tandem cells* is a promising way to overcome the Shockley–Queisser limit (~33% for single junction). The idea is to stack two (or more) p–n junctions of different bandgaps so that each absorbs a portion of the solar spectrum. Many thin-film materials are used as top or bottom cells in tandems:

Perovskite/C-Si Tandem: A perovskite cell (bandgap ~1.6–1.8 eV) is placed on top of a Si cell (~1.1 eV). This takes advantage of perovskite’s high bandgap to harvest blue light and silicon’s lower bandgap for red light. Monolithic (two-terminal) perovskite/Si tandem cells have achieved **33.9%** efficiency (record, Nov 2023 by Longi)[8]. This far exceeds any single-junction cell and illustrates the hybrid of thin-film and wafer technology. Bifacial configurations or four-terminal designs (physically separate cells) are also studied.

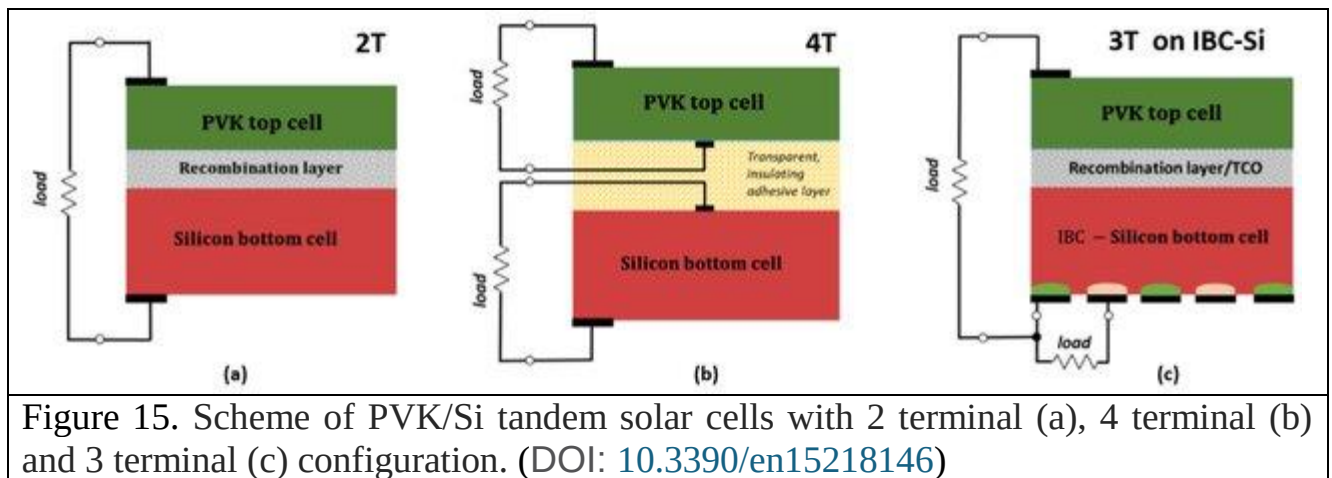
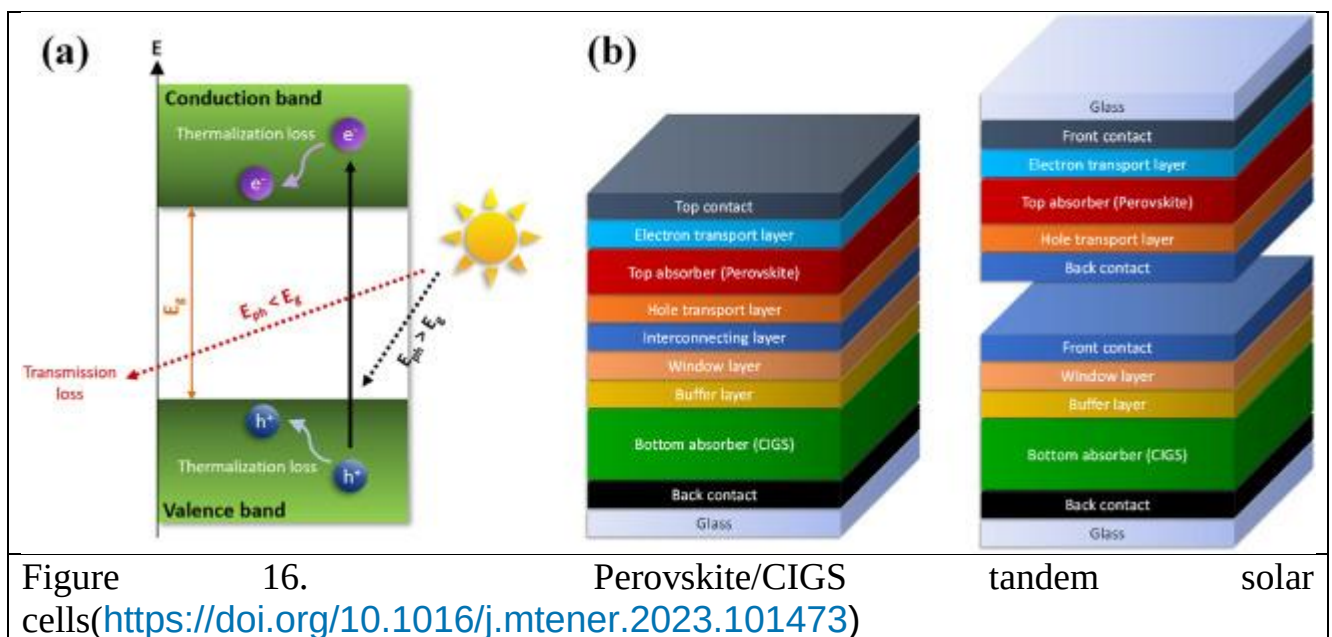
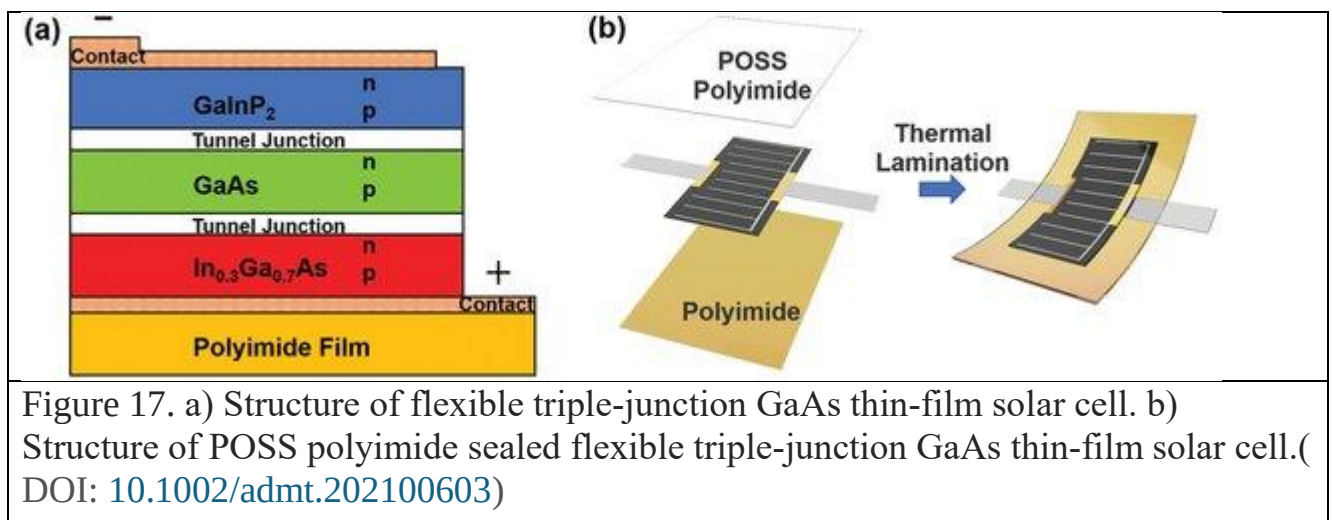


Figure 15. Scheme of PVK/Si tandem solar cells with 2 terminal (a), 4 terminal (b) and 3 terminal (c) configuration. (DOI: [10.3390/en15218146](https://doi.org/10.3390/en15218146))

Perovskite/CIGS Tandem: A perovskite cell can also be stacked on CIGS or another thin-film. Recent research reported a *perovskite/CIGS tandem* at about **24.2%**[1]. Such tandems are all-thin-film, potentially lower weight than perovskite/Si.



Multi-Junction Thin Films: GaAs and other III–V cells are often already multijunction (e.g. GaInP/GaAs/GaInAs stacks at ~44% under concentrators[1]). There are also examples like all-perovskite tandems (wide-gap perovskite on narrow-gap perovskite) reaching ~28% efficiency[9], and organic-organic tandems (record ~14%). However, commercial application of these is still in R&D or limited use (GaAs tandem for space or high-end concentrators).



Heterojunction (HJT) Cells and Tandems

A special case of thin-film integration is the **heterojunction (HJT)** silicon cell. Here, a crystalline Si wafer (n-type or p-type) is coated on both sides with thin

hydrogenated amorphous Si layers (intrinsic plus doped a-Si) that serve as passivating contacts[3][8]. Effectively, HJT blends a-Si thin films with c-Si. These cells combine the high efficiency and stability of crystalline Si with the excellent surface passivation of a-Si.

Modern HJT cells (commercialized by Panasonic, etc.) have reached world-record efficiencies among Si technologies. For example, in 2022 Panasonic achieved 26.61% on a 150 mm SHJ cell (record for commercial Si)[8]. HJT cells also have very high V_{OC} ($\sim 740\text{--}750\text{ mV}$) and high fill factors ($\sim 85\text{--}86\%$). As a result, HJT is now overtaking PERC and TOPCon in market share[8]. In 2023 the average commercial HJT cell efficiency was $\sim 25.0\%$, compared to $\sim 24.9\%$ for TOPCon and 23.3% for PERC[8]. HJT cells are more complex to manufacture (low-temperature processes, dual-sided contacts), but their combination of high efficiency and bifaciality makes them attractive.

HJT is also used in tandem: as in Figure 18, an HJT bottom cell under perovskite yielded a 33.9% tandem record in 2023[8]. The intrinsic a-Si layers in HJT allow excellent passivation, giving the tandem a very high voltage.

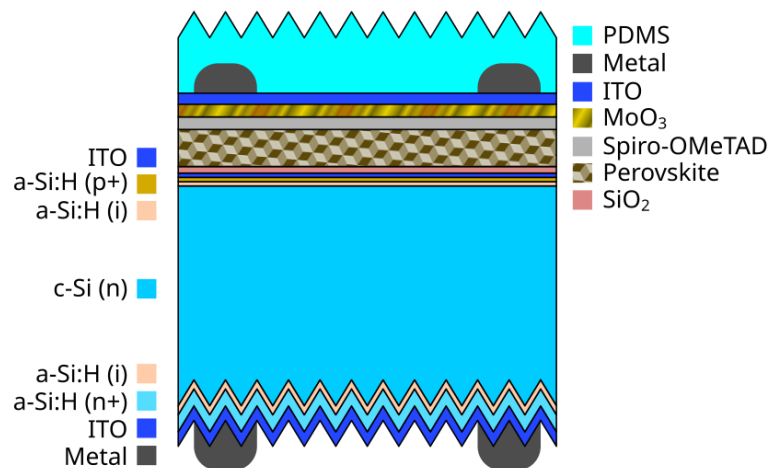


Figure 18. Example tandem structure combining a silicon heterojunction bottom cell with a perovskite top cell. The perovskite (wide bandgap) layer absorbs high-energy photons, while the SHJ (thin-film a-Si layers on c-Si) bottom cell captures the rest. PDMS is an anti-reflection texture. (Image: Radiotrefoil, CC BY-SA 4.0)

Figure 18 shows one possible design of a perovskite/heterojunction tandem cell[10]. In this case the bottom cell is a *silicon heterojunction* (SHJ) – a crystalline Si wafer coated with thin amorphous Si layers – and the top cell is a perovskite film. In general, tandem cells require current matching (in 2T) or separate contacts (4T), and precise bandgap engineering.

Summary: Heterojunction cells exemplify how thin-film layers can enhance traditional cells. They use thin amorphous silicon (a film only a few nm thick) on both sides of crystalline Si to create the junctions and contacts[3]. This yields very low recombination and high voltages, helping achieve world-record results.

Conclusion

Thin-film solar cells span a diverse family of PV technologies. From amorphous silicon and CdTe to CIGS, perovskites, and organics, each has unique materials and manufacturing methods. Thin films generally use simpler, lower-temperature processes and less semiconductor material than wafers. Their efficiencies lag behind crystalline Si, but tandem designs and ongoing improvements (especially in perovskites and HJT) are closing the gap[2][8]. Understanding I–V characteristics (Voc, Isc, FF) and efficiency is key to comparing them. In practice, one chooses technology based on trade-offs: cost vs efficiency vs form factor vs stability. The future of thin-film PV includes tandem cells (e.g. perovskite/Si), new materials (lead-free perovskites, CZTS), and hybrid modules. Overall, thin-film solar cells will continue to be an important complement to crystalline Si in the solar energy landscape[7][8].

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1.1. PRINTING TECHNIQUES FOR DIFFERENT TYPES OF SOLAR CELLS

Overview: Printed solar cells refer to photovoltaic devices fabricated using **printing processes** to deposit functional materials (conductive inks, semiconductor inks, etc.) onto substrates. Modern solar cells can be manufactured using **printing techniques** (additive deposition methods) to form their layers or electrodes. Traditional silicon solar cells rely on **screen-printing** metallic contacts, while newer thin-film cells like **perovskite, organic, dye-sensitized, and quantum dot** cells can employ various printing methods (e.g. inkjet, screen, slot-die, spray) to deposit functional layers[1]. Below we discuss each major solar cell type and how **inkjet printing** (and other printing methods) are used step-by-step in their fabrication, with diagrams illustrating key steps.

History

The first case of printed electronics was seen in 1903 when Albert Hanson filed a patent for "printed" wire. After that the radio drove the industry of printed electronics forward. Until recently inkjet printers have not been used in the printed electronics industry. Industry has decided to move towards inkjet printing because of its low cost and flexibility of use. One of these used is the inkjet solar cell. The first instance of constructing a solar cell with an inkjet printer was by Konarka in 2008. In 2011 Oregon State University was able to discover a way to create CIGS solar cells using an inkjet printer. In the same year MIT was able to create a solar cell using an inkjet printer on paper. The use of an inkjet printer to make solar cells is very new and is still being researched. In 2014, Olga Malinkiewicz presented her inkjet printing manufacturing process for perovskite sheets in Boston (USA) during the MRS fall meeting - for which she received MIT Technology review's innovators under 35 award.

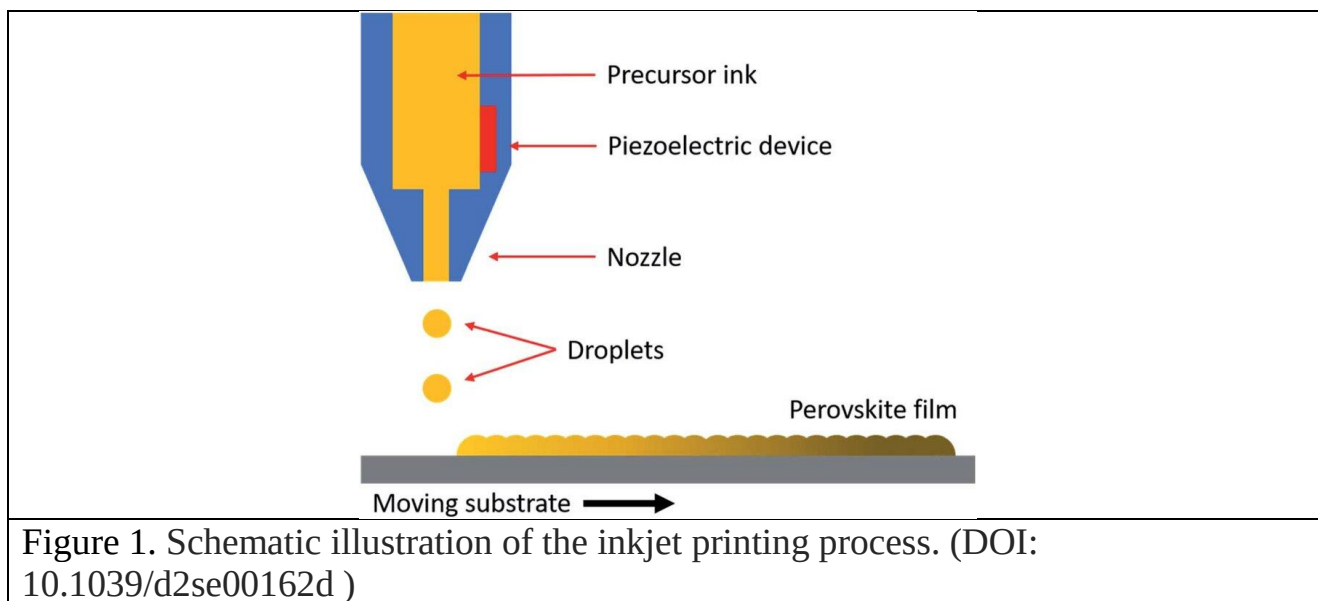
What Are Inkjet-Printed Solar Cells?

Inkjet-printed solar cells utilize a digital, non-contact printing technique to deposit photovoltaic materials onto substrates. This approach allows for precise patterning, minimal material wastage, and compatibility with flexible or unconventional surfaces. The technology is particularly advantageous for producing lightweight, flexible, and customizable solar panels.

How they are made

In general inkjet solar cells are made by using an inkjet printer to put down the semiconductor material and electrodes onto a solar cell substrate. Both organic and

inorganic solar cells can be made using the inkjet method. Inkjet printed inorganic solar cells used to be CIGS solar cells. The organic solar cells are polymer solar cells. The inkjet printing of hybrid perovskite solar cells is also possible, and is now a primary focus. Inkjet printing is even being explored as a method to add the other cell components to silicon based solar cells. The most important component of the ink is the functional material: a metal salt mixture (CIGS), a polymer fullerene blend (polymer solar cells) or a precursor of mixed organic and inorganic salts (perovskite solar cells). These components are dissolved in an appropriate solvent. Additional components might be added to affect the viscosity and the surface tension of the ink for improved printability and wetting on the substrate. The ink is contained in a cartridge from where it is transferred onto a substrate which can vary. The printing is accomplished usually by a piezoelectric driver in the nozzles of the printhead, that is programmed to apply pre-set patterns of pressure to eject droplets (Figure 1). In most cases several layers of functional materials are deposited on top of each other to generate a working solar cell. The entire printing process can be done in ambient conditions, though in most cases further heat treatments are needed. Important factors for the efficiency of inkjet printed organic solar cells are the inkjet latency time, the inkjet printing table temperature, and the effect of the chemical properties of the polymer donor.



Silicon-Based Solar Cells (Crystalline Silicon)

Conventional crystalline silicon cells are made on silicon wafers and use **screen printing** to form the metal electrodes. After creating a p-n junction by doping, manufacturers apply an anti-reflective coating and then **screen-print silver paste** in a grid pattern on the front side and aluminum paste on the back side[2]. These printed

metal films are then **fired (co-fired)** at high temperature to sinter the metals and form ohmic contacts through the anti-reflection layer[3]. The typical step-by-step process is:

1. **Junction Formation:** Diffuse dopants to create a p–n junction in the silicon wafer (not a printing step).
2. **Anti-Reflective Coating:** Deposit a silicon nitride (SiN_x) layer to reduce reflection (also not printed).
3. **Front Electrode Printing:** Align a screen mask and *screen-print* a conductive silver paste grid on the front (n-type) side[2]. The paste is a mixture of silver particles, glass frit, and binders which will form the contact fingers and busbars.
4. **Rear Electrode Printing:** Similarly, screen-print an aluminum (and sometimes silver) paste layer on the back (p-type) side as the rear contact[3].
5. **Drying and Firing:** Dry the printed pastes, then fire the wafer in a furnace ($\sim 750\text{--}850\text{ }^\circ\text{C}$ peak) to burn off organics and alloy the metal contacts with silicon[3]. This firing step drives the silver through the SiN_x layer and forms a low-resistance contact.
6. **Encapsulation:** Solder cell connectors to the printed busbars and encapsulate the cell in a protective module (post-printing assembly).

Screen printing is the **dominant metallization method** in silicon PV manufacturing due to its low cost and high throughput[2]. In fact, over 89% of silicon solar cell factories use screen-printed contacts[2]. The process is optimized for fine-line printing (fingers $\sim 50\text{--}70\text{ }\mu\text{m}$ wide) and sometimes uses double-printing to increase metal height without widening the lines[3]. *Inkjet printing* is less common for silicon cells, but research is exploring it for high-precision doping or seed layers. Overall, **printed contacts** have enabled silicon cells to achieve reliable performance at low cost, solidifying silicon's $\sim 96\%$ market share in PV[2].

Inkjet Printing for Copper Indium Gallium Selenide Solar Cell (CIGS)

Inkjet printing techniques have been explored for the manufacturing of thin-film CIGS solar cells, and are of particular interest due to the extremely low waste from material deposition. Sputtering techniques are often used to deposit the CIGS layer in these cells which is a relatively low-waste technique; however, inkjet printing offers an even lower waste option by allowing for the deposition of the material in only the exact desired locations on the surface that is being coated. Reducing waste in the production process of CIGS cells is important because the costs of the light absorbing layer's components (copper, indium, gallium, and selenide) is comparatively much higher than other types of solar cells, mainly due to the rarity of In, Ga, and Se. CIGS solar panels are appealing mainly because they function as a thin film solar cell (and so require much less materials) and they have a similar

efficiency (23.6%) compared to the traditional crystalline silicon solar panels (26.7%) although CIGS solar cells tend to realistically operate at higher efficiencies than their Si counterparts. Inkjet printing methods can also offer a more environmentally friendly option, because it does not require the use of toxic chemicals to prepare the solar cell like other methods do. Inkjet printing is also being explored for use in depositing the front contact layer for CIGS cells.

Perovskite Solar Cells

Perovskite solar cells (PSCs) are thin-film cells that can be made entirely by solution processing, so they are excellent candidates for **inkjet printing and other printing techniques**[\[1\]](#)(Figure 2). A typical perovskite cell has layers: a transparent electrode (ITO-coated glass), an electron transport layer (ETL, e.g. TiO_2), the perovskite light-absorbing layer, a hole transport layer (HTL), and a top electrode. Many of these layers can be deposited by printing:

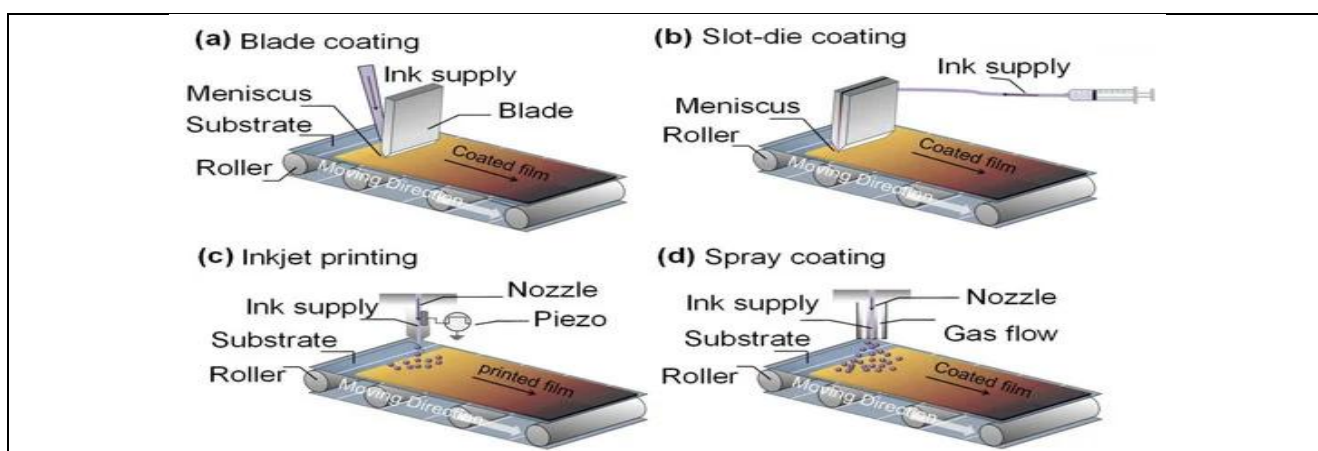


Figure 2: Common printing techniques for thin-film solar cell fabrication, illustrated: (a) blade coating, (b) slot-die coating, (c) inkjet printing, and (d) spray coating. These additive methods can deposit uniform thin films from solution inks[\[1\]](#). Inkjet printing (c) uses a drop-on-demand nozzle to eject perovskite precursor ink droplets with precise patterning.

Printing techniques offer fine control over layer thickness and composition, and allow **patterning** of sub-cells and interconnects directly by design (for monolithic module integration). Recent milestones show the viability of printed perovskites: researchers have demonstrated **partially inkjet-printed perovskite cells** with efficiencies over 20% [\[13\]](#), nearly closing the gap with spin-coated lab cells. Furthermore, fully printed **perovskite modules** have been produced using roll-to-roll processes under ambient conditions – for example, a 2024 study made multi-cell modules entirely by industrial printing (including a printed carbon back electrode) and achieved about 11% efficiency for a 50 cm² module[\[14\]](#). These results highlight that high efficiency is achievable with scalable printing methods. Inkjet printing in particular enables **digital fabrication**: one can print custom patterns (even artwork or

different shapes) by simply using a digital design file[13], offering design adaptability for applications like building-integrated PV. The main challenges for printed perovskites remain achieving uniform large-area films and long-term stability, but ongoing research is rapidly improving ink formulations and processing. Device of printing perovskite solar cells is shown in Figure 3.

Overall, perovskite solar cells are at the forefront of printable PV technology, showcasing how **inkjet and other printing techniques** can revolutionize solar manufacturing by combining *high performance* with *low-cost, scalable production*.

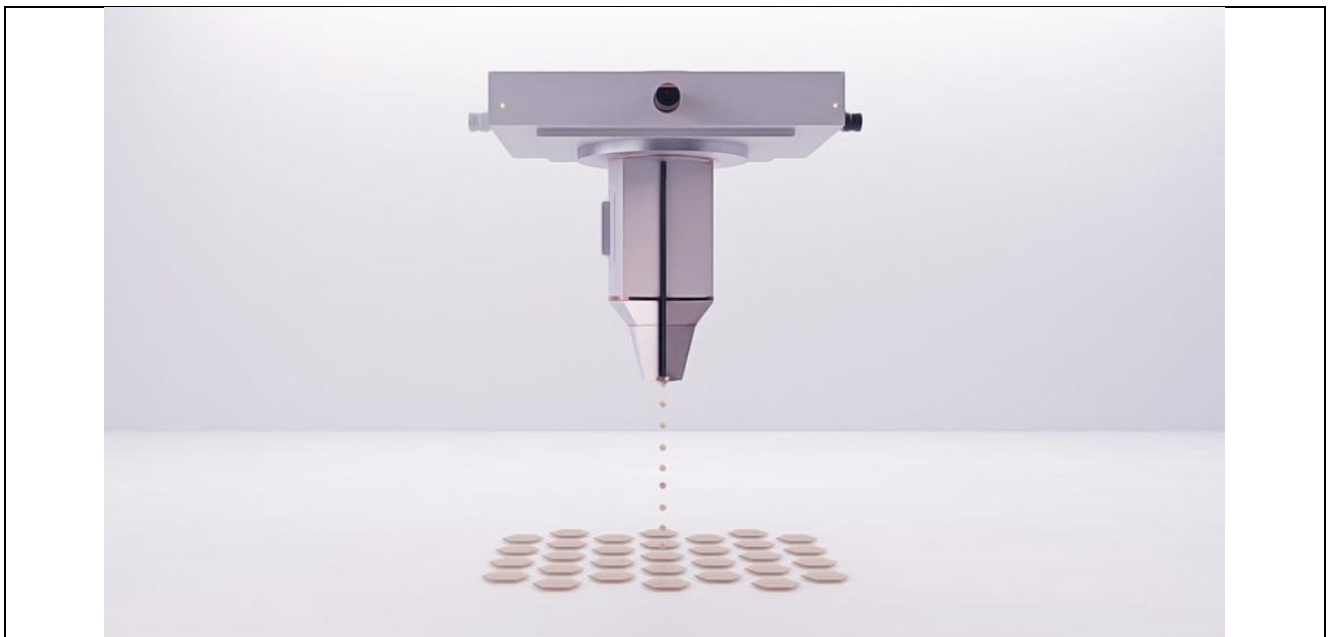


Figure 3: Schematic of the inkjet printing process depositing a solar ink. Inkjet printers eject picoliter droplets of a solution-based ink in a precise pattern without contact. This digital, mask-free method is used to deposit perovskite semiconductor films and patterned electrodes. It is highly scalable and material-efficient, allowing easy modification of the printed design via software[16].

Inkjet printing process for a perovskite cell:

1. **Substrate Preparation**(Figure 4): Start with a glass substrate coated with **ITO** (transparent electrode). Print or coat a thin compact TiO_2 layer as the electron transport layer (this layer can be deposited by methods like spray or spin coating, or even screen-printed and sintered in some cases). Often a mesoporous TiO_2 layer is also printed or coated to help perovskite infiltration[1].
2. **Perovskite Inkjet Printing**: Load a **perovskite precursor ink** (containing metal halide salts and organic cations in solvent) into an inkjet printhead. The printer

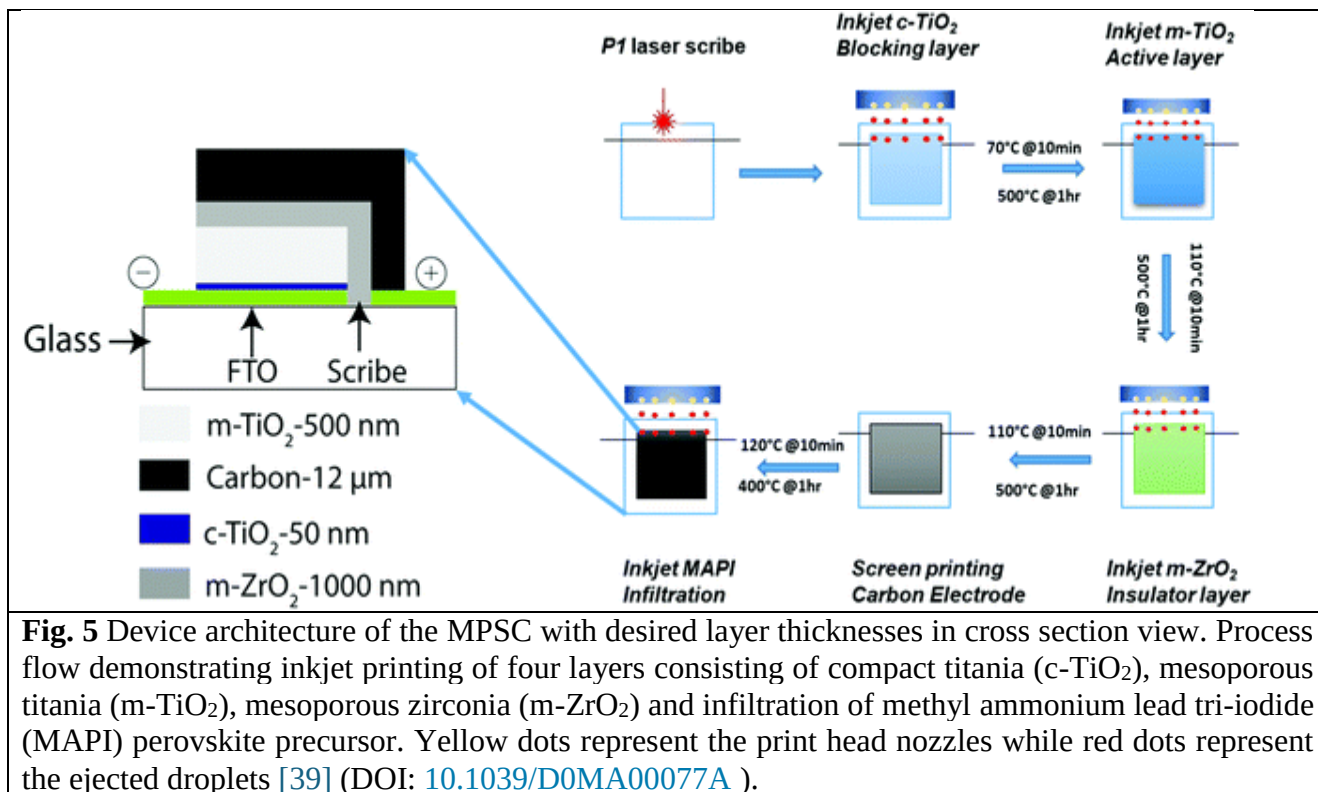
deposits tiny droplets in a raster pattern onto the substrate to form a wet film[4]. After printing, a **drying/annealing** step (often on a hotplate or via controlled heating) is used to evaporate solvents and crystallize the perovskite layer. This printing can be done in a single pass or multiple passes to achieve the desired thickness[1]. Researchers sometimes use techniques like vacuum-assisted drying to improve film quality during this step.

3. **Hole Transport Layer:** Deposit the HTL (e.g. spiro-OMeTAD or a polymer like PTAA) on top of the perovskite. This might be done by spin coating in lab settings, but it can also be printed (for example, *inkjet printing* or *blade coating* the HTL ink)[1]. Each layer's ink formulation (viscosity, drying behavior) must be tuned for printing.
4. **Electrode Printing:** Finally, add a top electrode. In many printable PSCs, a **carbon electrode** (carbon paste) is **screen-printed** as a cost-effective replacement for gold or silver electrodes[1]. The carbon paste is printed in the desired pattern and then dried. (Alternatively, metallic grids or films can be printed or thermally evaporated; carbon and printable conductive inks avoid needing vacuum deposition.)
5. **Post-processing:** Allow the printed stack to fully dry/anneal. The result is a multi-layer printed device. In some architectures (like fully printable **mesoscopic PSCs**), a porous carbon top layer and mesoporous $\text{TiO}_2/\text{ZrO}_2$ scaffolds are all screen-printed, and then the perovskite is introduced by dripping or inkjet-printing into the pores[1].



Figure 4: Conceptual illustration depicting an inkjet-printing process of sacrificial layer of polystyrene (PS) particles for nanoarchitecturing perovskite solar cell with carbonbased electrodes with solar cell structure depicted on the left(DOI: [10.48550/arXiv.2211.09424](https://doi.org/10.48550/arXiv.2211.09424)).

Among the various perovskite device architectures, the so-called triple layer mesoporous metal-oxide monolithic architecture using a porous carbon back contact (MPSC) presents considerable advantages for inkjet printing the active perovskite absorber (Fig. 5).

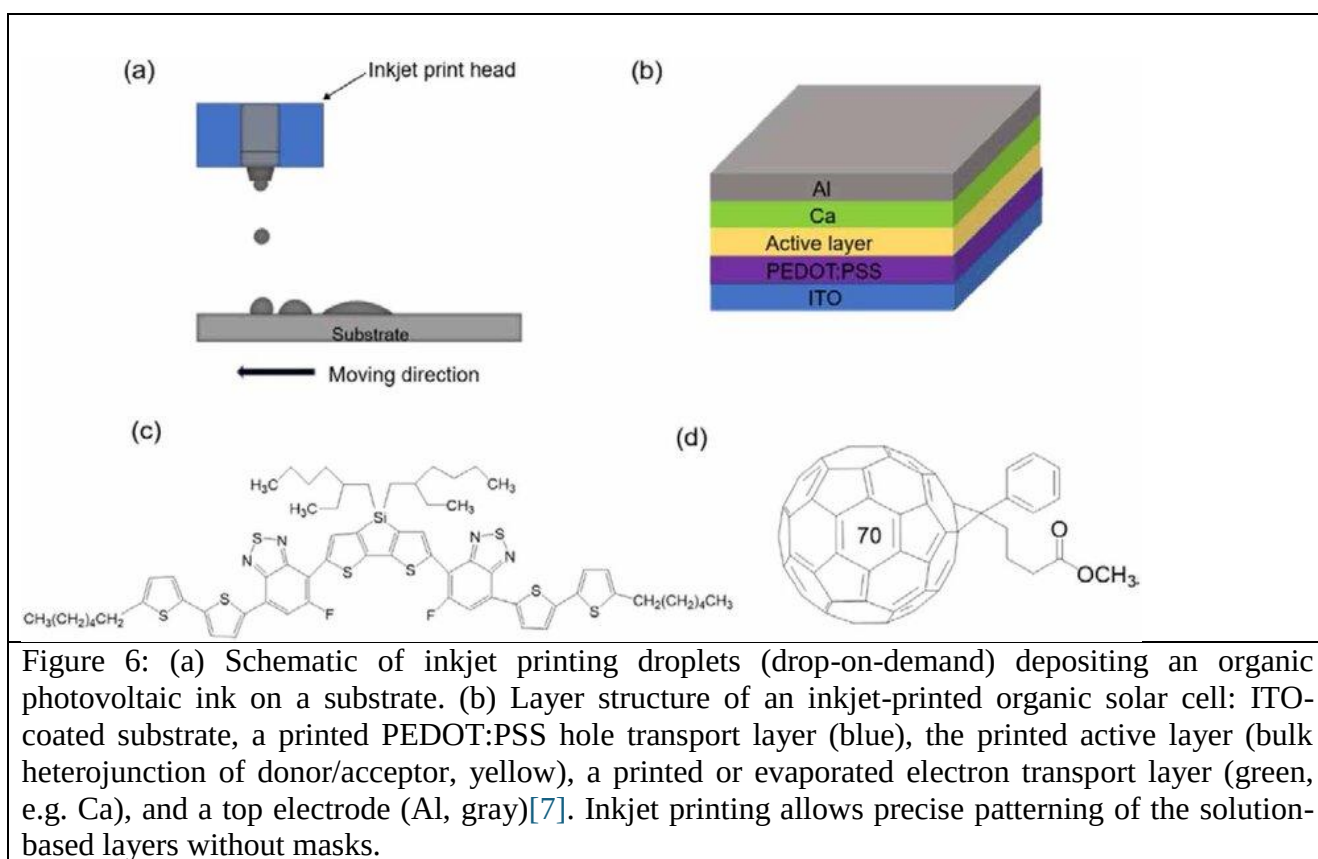


In those types of cells, a porous scaffold consisting of a mesoporous TiO₂ layer (m-TiO₂), a mesoporous ZrO₂ (m-ZrO₂) layer followed by a porous carbon layer presents an excellent texture for infiltrating the lead-halide salt ink droplets. Furthermore, the robust and rather thick cell architecture is defect tolerant and promises straightforward large area scale-up. The extremely thick hydrophobic carbon layer prevents water ingress to the active layer and therefore warrants long lifetime(15) and prevents washing out the lead salt in the case of fragmentation. It has been demonstrated that the active perovskite absorber can be infiltrated by inkjet printing, leading to stable MPSC cells with an average efficiency of 7% (16) . If however the customizability of digital drop-on-demand DOD technology shall be exploited, all stacks of the MPSC must be printed by inkjet. As reviewed by Peng *et al.*(17) and Karunakaran *et al.*,(18) most of the efforts so far have focused on inkjet printing the absorber layer or one of the device electrodes. To the best of our knowledge, there has been no work reporting on the fabrication of perovskite solar cells by inkjet printing all active layers.

Printing advantages: Inkjet and similar techniques enable **digital patterning** of perovskite layers with minimal waste, important for scaling up manufacturing[1][5]. They offer fine control over film thickness and uniformity, leading to high performance when optimized[1]. For example, studies have shown that fully inkjet-printed perovskite cells (with all layers printed) can reach efficiencies comparable to spin-coated devices[1]. Researchers Alharbi *et al.* review numerous printing methods for PSCs – **blade coating, slot-die, inkjet, screen, spray, gravure, flexography** – all of which have been used to fabricate perovskite solar cells[1]. Printing has been key in producing large-area perovskite modules while maintaining good efficiency. One demonstration achieved over 15% efficiency using doctor-blade coating for the perovskite layer[1], and inkjet-printed perovskite layers have exceeded 11% efficiency in research cells[1]. Overall, **inkjet printing** allows precise deposition of perovskite inks, but care must be taken to mitigate issues like the coffee-ring effect (non-uniform drying) – strategies like ink chemistry optimization are employed to get uniform films[4]. The result is a promising route to **low-cost, roll-to-roll printable solar cells** where every layer can be deposited in ambient conditions.

Organic Solar Cells (OPVs)

Organic photovoltaic cells use carbon-based polymers or molecules as the active layer, and they are well-suited to **printing techniques** because they can be made from liquid inks on flexible substrates. In fact, inkjet printing is emerging as an important fabrication method for organic solar cells due to its additive, mask-free deposition and high material utilization[6]. A typical organic solar cell has a structure like: transparent substrate (ITO on plastic or glass), a hole transport layer (e.g. PEDOT:PSS), an **active layer** (a blend of electron-donor and acceptor organic semiconductors), and a top electrode. Here's how printing is applied step-by-step(Figure 6):



Hole Transport Layer Printing: Start with an ITO-coated substrate (often a flexible PET film or glass). The substrate is cleaned, then an ink of **PEDOT:PSS** (conductive polymer) can be **inkjet-printed** or slot-die coated as a thin hole transport layer (HTL) on the ITO[7]. This layer smooths the surface and improves hole collection. It's usually dried at low heat to remove solvents.

Active Layer Inkjet Printing: Prepare a **bulk heterojunction (BHJ)** ink – a solution containing a donor polymer (e.g. P3HT or a modern low-bandgap polymer) and an acceptor material (like PCBM or non-fullerene acceptors) in an organic solvent. This ink is loaded into an inkjet printer, which deposits it as an array of droplets that merge into a continuous film on top of the HTL[7]. The printing parameters (drop spacing, substrate temperature, ink viscosity) are tuned to control the film morphology. After printing, the film is dried (often on a heated substrate) to form the photoactive layer. *Example:* Sumaiya *et al.* note that inkjet-printed P3HT:PCBM active layers have been successfully demonstrated, showing that inkjet can produce films as good as spin coating for large-area cells[6].

Electron Transport Layer and Electrode: Once the active layer is printed and dried, an electron transport layer (ETL) like ZnO or a thin LiF can be added. This might be deposited by solution too (e.g. printing a ZnO nanoparticle ink or by spray coating). Finally, the **top electrode** (usually a low-work-function metal like aluminum

or a conductive ink) is applied. In fully printed approaches, a **silver nanoparticle ink** can be **screen-printed or inkjet-printed** as the top electrode grid[7], then sintered at low temperature (or a conductive PEDOT/CNT ink can be printed as a transparent electrode). However, many lab OPVs still evaporate an aluminum electrode for convenience (printing of metals is an active area of research to enable *all-printed* devices[7]).

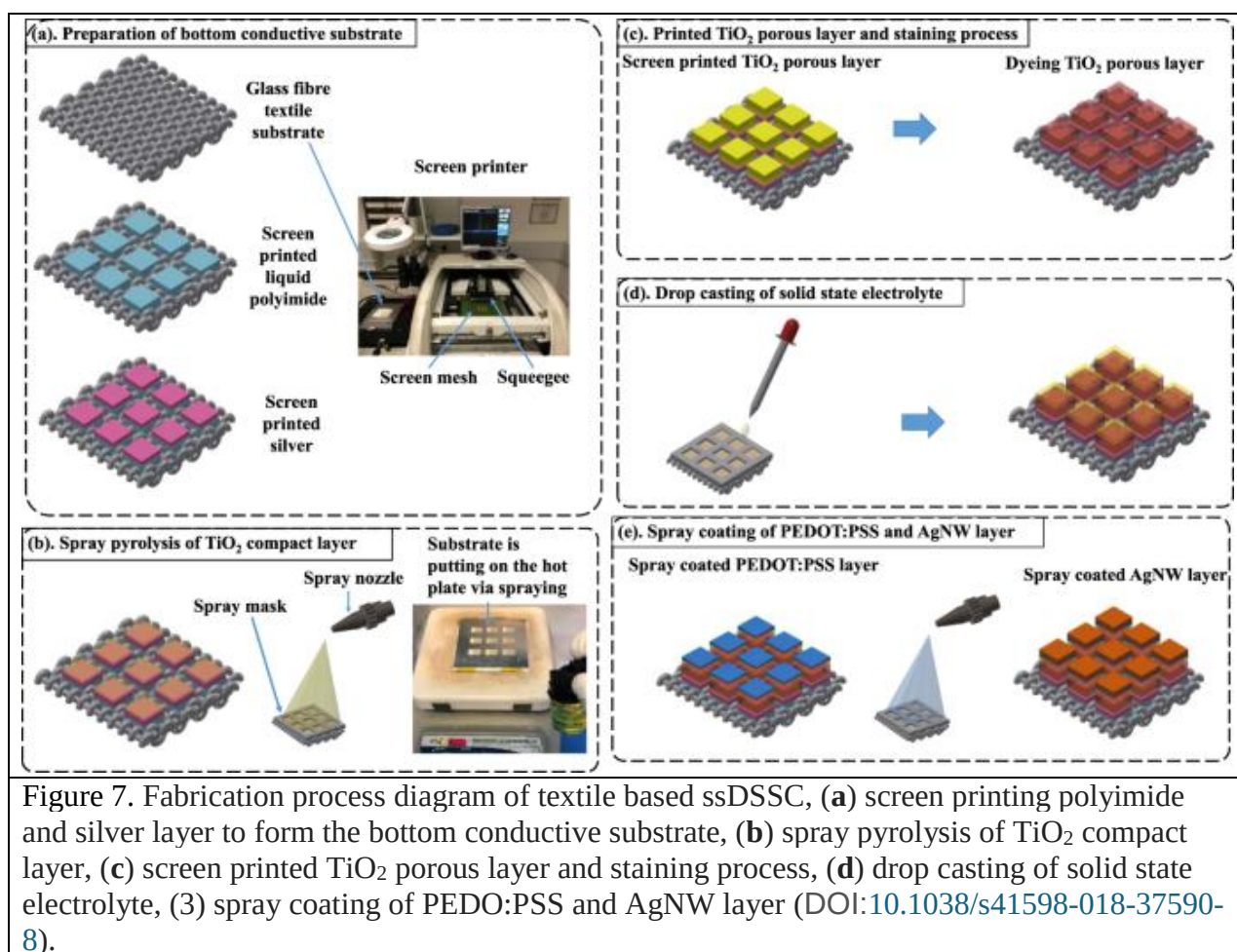
Inkjet printing in particular gives organic solar manufacturing **flexibility**: patterns can be easily changed via software, enabling customized module designs (even aesthetic patterns or “solar wallpaper” designs). It’s also compatible with **roll-to-roll** processes for high throughput[6]. Other printing methods like **gravure printing, flexography, screen printing, and slot-die coating** have all been successfully used for organic PVs as well[7]. For instance, large-area organic modules have been made by roll-to-roll gravure printing of all layers except the electrode. Each method has its niche: screen printing can lay down thicker films (e.g. for electrodes), while inkjet excels at high resolution patterns and prototyping. The main challenges for inkjet-printed OSCs are ensuring uniform drying (avoiding coffee-ring patterns), achieving good layer interfaces, and preventing nozzle clogging with some organic inks[6]. Ongoing research addresses these by tweaking ink formulations (e.g. adding solvent additives to control drying) [7]. Impressively, recent organic cells printed via optimized inkjet processes have reached power conversion efficiencies above 7–9%, and new materials and printing strategies continue to push this higher[7]. In summary, **inject printing** (inkjet) allows the **step-by-step fabrication of organic solar cells** in ambient conditions, offering a pathway to low-cost, flexible solar panels produced almost like “printed electronics.”

Dye-Sensitized Solar Cells (DSSCs)

Dye-sensitized solar cells are another type of thin-film cell where printing techniques play a major role, especially in scalable fabrication. A DSSC consists of a porous nanocrystalline **TiO₂ layer** coated with a light-absorbing dye, a liquid or solid electrolyte, and a counter electrode (often platinum or carbon). Many of these components can be deposited by printing(Figure 7):

- **Photoanode (TiO₂) Printing(Figure 7,8):** The porous TiO₂ layer on the transparent conducting glass can be made by **screen printing a TiO₂ nanoparticle paste** onto the FTO glass and then sintering it[39]. This yields a several-micron thick TiO₂ film for dye adsorption. Researchers have shown that screen-printing multiple TiO₂ layers or using different particle sizes can improve pore structure and performance. Inkjet printing of TiO₂ is also possible – Raissi *et al.* demonstrated inkjet-printed TiO₂ films (using a digital deposition method) that were more porous and achieved higher efficiency than traditionally screen-printed films[4].

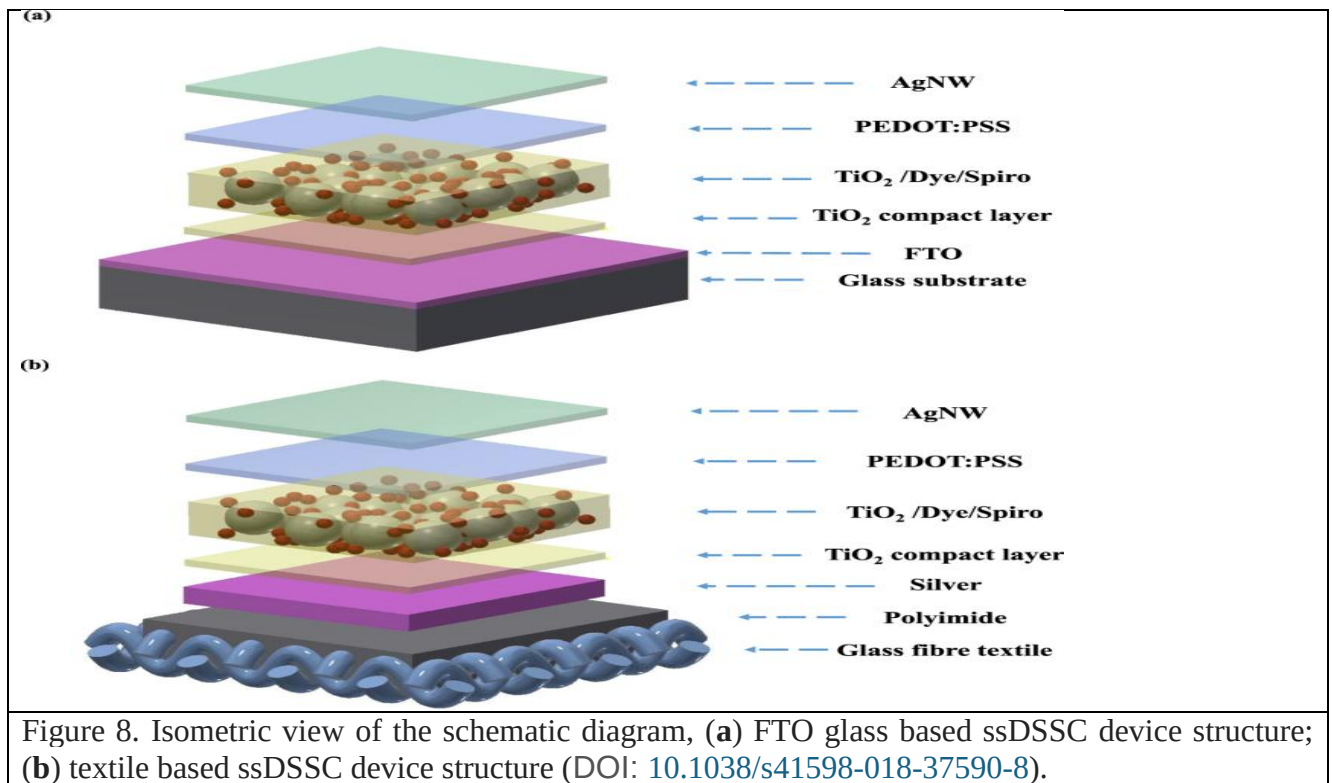
- **Dye Application:** In the conventional lab setup, the TiO_2 layer is soaked in a dye solution (e.g. N719 ruthenium dye) for hours. However, this **sensitization step** can be accelerated by **inkjet printing the dye solution** onto the TiO_2 film[8]. Inkjet printing allows the dye to be deposited precisely where needed without waste. For example, research from Aalto University showed inkjet-printed dye can achieve equivalent or better dye uptake compared to dipping, and can even create patterns or multi-dye designs on the photoanode[9]. The step-by-step process here would involve filling an inkjet cartridge with a concentrated dye solution and printing it evenly across the TiO_2 surface, then rinsing and drying.
- **Electrolyte and Seal:** DSSCs often use a liquid iodide/triiodide electrolyte. This can be introduced by vacuum backfilling after assembling the cells, or by printing if a solid-state electrolyte or gel is used. Some printable solid electrolytes exist (e.g. printable polymer gels). These would be deposited by doctor blade or inkjet in a controlled manner onto the dye-coated TiO_2 before sealing the cell.
- **Counter Electrode Printing:** The counter electrode can be a **screen-printed layer of platinum catalyst** or carbon. In scalable DSSC production, a common approach is to **screen print a carbon paste** on a substrate to form the counter electrode (which doubles as a current collector)[10]. Alternatively, one can screen print a platinum precursor ink and then heat it to form a thin Pt layer. Carbon-based printable electrodes (graphite or carbon black in a binder) are attractive for low-cost DSSCs – these are simply printed and dried on the second glass electrode. Finally, the cell is assembled by sandwiching the dyed TiO_2 electrode and the counter electrode, and sealing the edges (often with a thermal sealant).



Fully printed DSSCs: Impressively, companies and labs have developed all-screen-printed DSSC modules, where every layer (transparent conductor, TiO_2 , optional ZrO_2 insulating layer, carbon catalyst layer) is deposited by screen printing on large areas[10]. For instance, Meyer *et al.* demonstrated a 10×10 cm DSSC module with all layers printed and low-cost materials (glass, TiO_2 , carbon, polymer electrolyte)[10]. The printing sequence in that case was: print porous TiO_2 layer $\rightarrow$ print a porous ZrO_2 spacer layer (to prevent direct contact between electrode and dye layer) $\rightarrow$ print a carbon layer as the counter electrode. After printing and sintering these layers, the dye and electrolyte are introduced, and the module is sealed. The result is a fully printed solar module that can be made quickly and cheaply.

Printing improves the scalability of DSSCs by allowing patterning and deposition without expensive vacuum tools. For example, using digital inkjet printing for the TiO_2 photoanode and even the dye can simplify manufacturing and was shown to boost performance – one study reported inkjet-printed TiO_2 /dye cells achieving $\sim 7.4\%$ efficiency vs $\sim 5.5\%$ for the equivalent screen-printed cells[4]. In summary, step-by-step inkjet or screen printing in DSSCs involves printing the porous oxide layer, printing or soaking the dye, and printing the counter electrode, followed by assembly.

This approach produces efficient DSSCs with relatively low-cost equipment, suitable for education and prototyping (indeed, screen-printing a DSSC is a common undergraduate lab project due to its simplicity).



Quantum Dot Solar Cells

Quantum dot solar cells (QDSCs) use semiconductor nanocrystals (quantum dots) as the light absorber. They can be constructed in architectures similar to DSSCs (quantum dots adsorbed on TiO_2 , known as “quantum dot sensitized solar cells”) or as thin-film devices with thick quantum dot layers (e.g. PbS colloidal quantum dot solar cells). Printing techniques are increasingly used here as well, especially since quantum dot inks can be synthesized and processed in solution. Key printing-related steps include (Figure 9):

- **Quantum Dot Ink Preparation:** Colloidal quantum dots (like PbS, PbSe, or perovskite quantum dots) are dispersed in a solvent with appropriate ligands to form a stable **QD ink**. Researchers have developed formulations that remain stable for large-area printing (e.g. by controlling surface chemistry to prevent aggregation)[11]. These inks can then be deposited by printing methods such as inkjet, spray coating, or slot-die coating.

- **Active Layer Printing:** In a typical thin-film QD solar cell, one would coat or print the quantum dot ink onto a substrate (which has an electrode and maybe a buffer layer). For instance, a PbS QD solar cell might use a glass/ITO substrate, a ZnO or TiO₂ electron transport layer (often spin-coated or could be printed), and then an inkjet-printed QD layer as the photoactive absorber. Inkjet can deposit the QD solution in a controlled pattern; multiple passes with intermediate drying are sometimes used to build up a thicker film. Alternatively, high-throughput methods like **slot-die coating** (a type of printing where ink is continuously applied through a slit onto a moving substrate) have been used successfully for quantum dot films[11]. After depositing the QD layer, a mild thermal or chemical treatment is done to solidify the film and sometimes to exchange ligands for better charge transport.
- **Electrode Printing:** The top contact in QD cells can be a printed grid or a transparent conductive ink. For example, a conductive silver grid can be **screen-printed** on larger-area QD solar modules to collect current, if a flexible device is made on plastic. In lab devices, often an evaporated metal like gold or a printed carbon layer may serve as the back electrode.

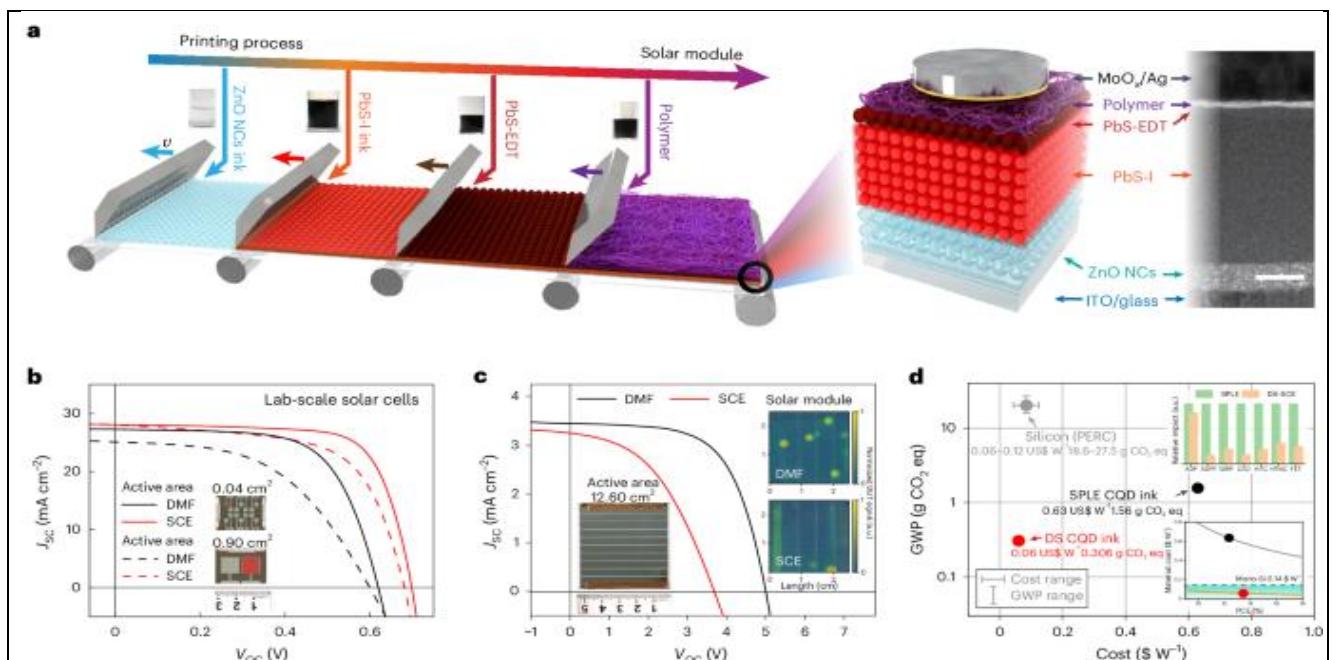


Figure 9. Quantum Dot Ink Preparation <https://doi.org/10.1038/s41560-025-01746-4>

Example achievements: A recent breakthrough reported by Liu *et al.* (2025) demonstrated **large-area printable quantum dot solar modules** by slot-die coating a PbS CQD ink, achieving a certified ~10% efficiency on a 12.6 cm² device[11]. Their lab-scale cells reached 13.4% efficiency using the same printed QD layer approach[11]. The process involved a one-step **slot-die printing** of the QD layer in

air, without the need for spin-coating, showing the viability of scaling up. Similarly, researchers have inkjet-printed patterns of Si quantum dots onto silicon cells to create spectral conversion layers, and have used inkjet to print CdTe quantum dot inks for hybrid solar cells[47].

Overall, **inkjet printing in QD solar cells** allows precise control of film uniformity and composition, which is crucial because quantum dot layers often need multiple treatments (like layer-by-layer deposition with different ligands). The printing approach simplifies manufacturing by avoiding vacuum deposition of absorber layers. The step-by-step printed QD cell fabrication might look like: print a metal-oxide ETL (if used) → dry/anneal → **print the QD absorber layer** (possibly in several sub-layers with drying steps) → chemical treat/anneal the QD film → print or attach a top electrode. Each of these can be done at relatively low temperatures on flexible substrates, making printable QD solar cells promising for wearable or portable applications.

In conclusion, across all these solar cell types – **silicon, perovskite, organic, dye-sensitized, and quantum dot** – **inject/inkjet printing and other printing methods** offer a pathway to more streamlined, scalable production. By depositing functional inks in a precise, additive manner, printing techniques reduce material waste and enable patterning without photolithography. Each solar technology adapts the general idea to its materials (e.g. metal pastes for silicon, solution-processed semiconductors for thin-films). The result is that solar cells can, in many cases, be literally “**printed**” **in a step-by-step fashion**, much like a newspaper – a concept very accessible and exciting for undergraduate students studying renewable energy engineering.



Figure 10: A researcher holds a flexible printed solar cell module. Thin-film solar cells (like organic or perovskite cells) can be fabricated on ultra-thin plastic foils using printable “solar inks.” These inks are deposited in layers onto flexible substrates via techniques such as micro-gravure coating, slot-die coating, and screen printing, producing lightweight, semi-transparent solar panels[19].

Future Prospects

The integration of inkjet printing in solar cell manufacturing holds promise for:

- **Tandem Solar Cells:** Combining different perovskite compositions to capture a broader spectrum of sunlight.
- **Building-Integrated Photovoltaics (BIPV):** Embedding solar cells into building materials for seamless energy generation.
- **Wearable Electronics:** Developing lightweight and flexible solar panels for portable devices.

Continued research and development are expected to enhance the efficiency, stability, and commercial viability of inkjet-printed solar cells, contributing to the advancement of sustainable energy technologies.

The information above is drawn from recent literature and reviews on printed solar cell manufacturing[1][2] [4] [7] [11], which provide deeper insight into the evolution from screen-printed silicon cells to fully inkjet-printed next-generation solar cells. Each printing technique has unique advantages, but all serve the common goal of lowering cost and enabling high-throughput production of solar panels.

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Chapter II

2. PASSIVATED EMITTER AND REAR CELL (PERC) SOLAR CELLS

Introduction

Passivated Emitter and Rear Cell (**PERC**) solar cells are high-efficiency silicon photovoltaic cells that improve upon the traditional aluminum back-surface field (Al-BSF) cell design. Introduced in the 1980s, PERC technology adds a dielectric passivation layer on the rear of the cell and uses local rear contacts, dramatically reducing electron recombination and increasing light capture[1]. This innovation allows PERC cells to generate more power from the same sunlight compared to conventional cells. By the 2020s, PERC became the dominant silicon solar cell architecture worldwide, accounting for the majority of solar cell production[2]. The success of PERC lies in its balance of improved efficiency and relatively low added manufacturing complexity, enabling widespread industrial adoption.

How PERC Works

In a standard silicon solar cell, the front side has an n-type emitter and metallic grid contacts, while the p-type silicon base has a full-area aluminum contact forming a back-surface field (BSF). PERC modifies this by introducing a thin **dielectric passivation layer** (commonly alumina or silica with a silicon nitride capping) on the rear surface, between the silicon and the metal contact[4]. Tiny openings are then laser-ablated in this dielectric so that metal contacts can be locally applied to the silicon (passivated emitter and rear *contact*). The passivation layer serves two key functions: (1) it *reduces carrier recombination* at the rear surface by chemically passivating dangling bonds and by providing field-effect passivation via fixed charges, and (2) it *improves light trapping* by acting as a mirror that reflects unabsorbed light back into the silicon cell[1]. Figure 1 schematically compares a conventional Al-BSF cell versus a modern PERC cell, highlighting the added rear passivation and local contacts.

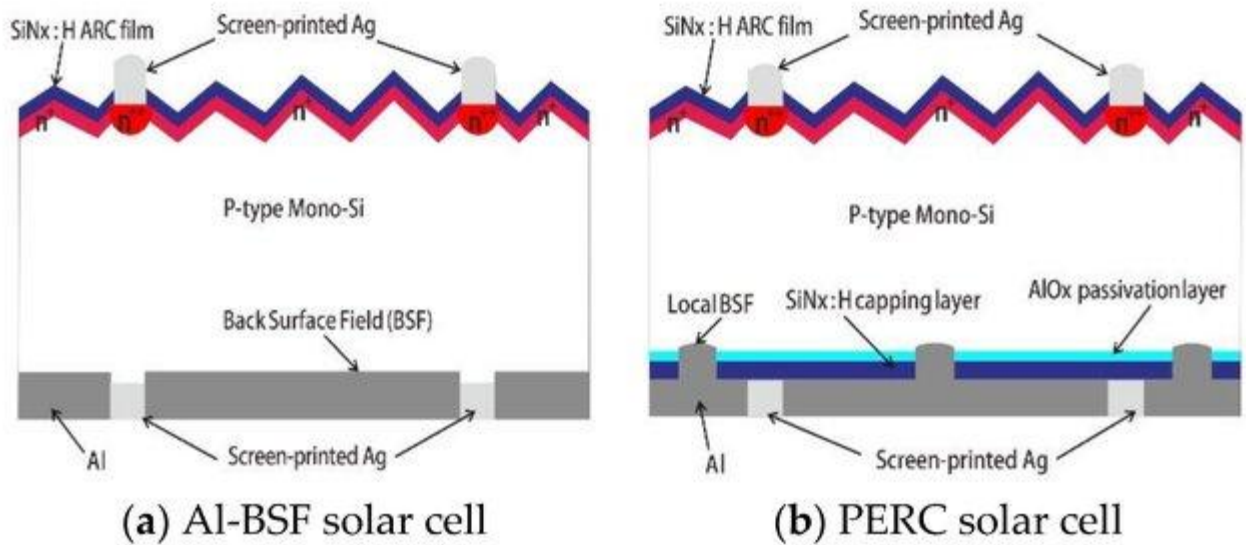


Figure 1: (a) Cross-sectional view of a traditional Al-BSF silicon solar cell. (b) versus a PERC solar cell

Figure 1: Cross-sectional view of a traditional Al-BSF silicon solar cell (right side of left diagram) versus a PERC solar cell (left). The PERC architecture uses a rear dielectric passivation layer with local aluminum contacts, which increases efficiency by reducing rear surface recombination and reflecting unused light[3]. In both cases, the front side has an n^+ emitter, antireflection coating, and metallic grid.

The PERC concept(Figure 2. b) adds a dielectric “passivation” layer on the rear to both reduce recombination and act as a mirror for unabsorbed light, first proposed in the 1980s and commercialized in the 2010s .

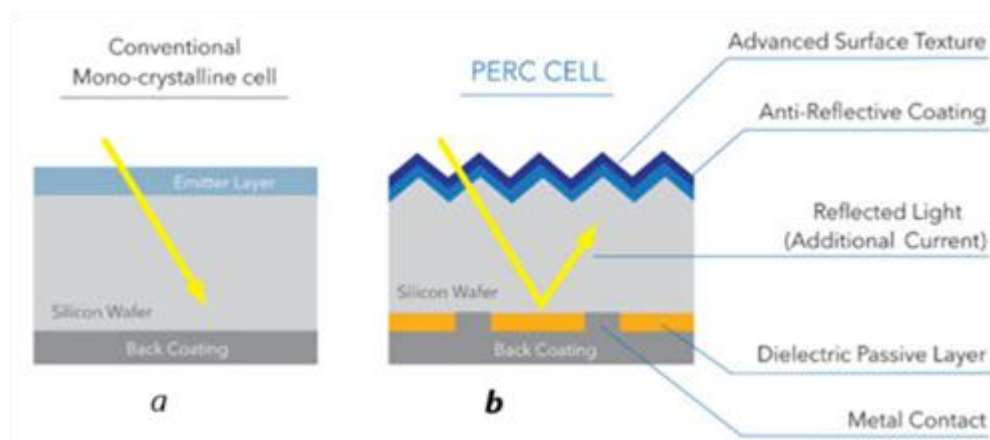


Figure 2. a) Conventional crystalline silicon (c-Si) solar cells; b) Passivated emitter rear contact (PERC) solar cells

By reducing recombination at both the front emitter and rear interface, PERC cells allow charge carriers (electrons and holes) to remain in an excited state longer

and be collected more efficiently[2]. Compared to early 1980s cells (~16% efficient), the PERC design boosted lab efficiencies by over 50% in relative terms – reaching about 25% efficiency on silicon by the early 2000s[2]. Today’s commercial mono-crystalline PERC panels typically achieve ~20–22% module efficiency, about 1–2% (absolute) higher than conventional BSF panels[1]. Moreover, PERC cells maintain stronger performance under low-light and high-temperature conditions, thanks to their enhanced light trapping and reduced recombination losses[1]. These advantages have made PERC a workhorse of the solar industry.

Typical silicon solar cells

The diagram below shows a cross section of a typical solar cell built into a module. These are the layers, from top to bottom:

- Front contact
- Anti-reflective glass
- Negative (n-type) silicon layer
- Positive (p-type) silicon layer
- Back surface field (BSF)
- Rear contact

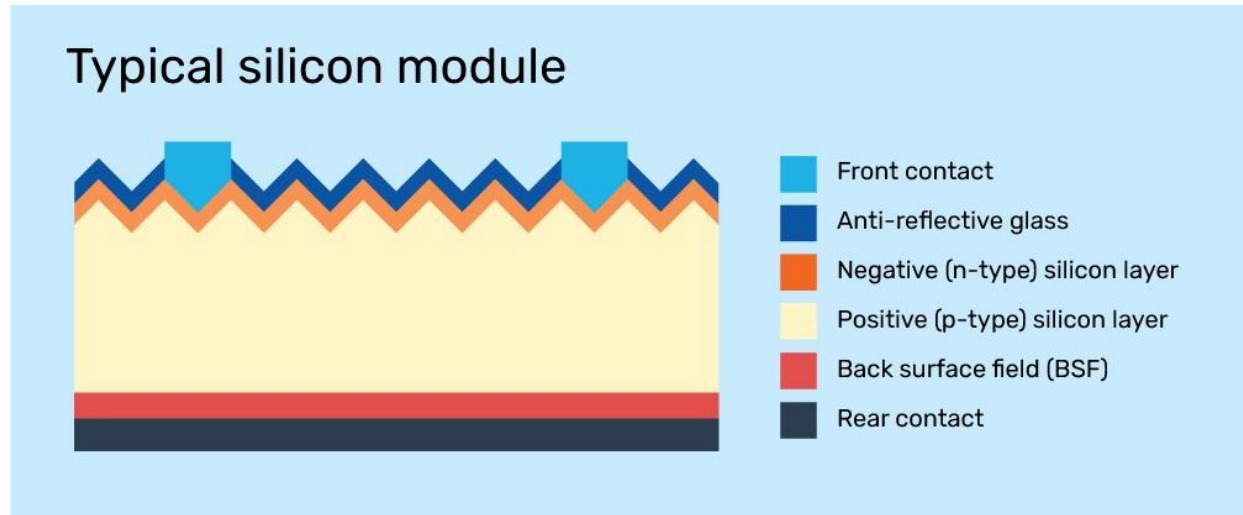


Figure 3. Typical silicon module

PERC solar cell

The figure 4 shows a cross section of a PERC solar cell built into a module. These are the layers, from top to bottom:

- Front contact

- Anti-reflective glass
- Negative (n-type) silicon layer
- Positive (p-type) silicon layer
- Local back surface fields
- Passivation layer
- Dielectric capping layer
- Rear contact

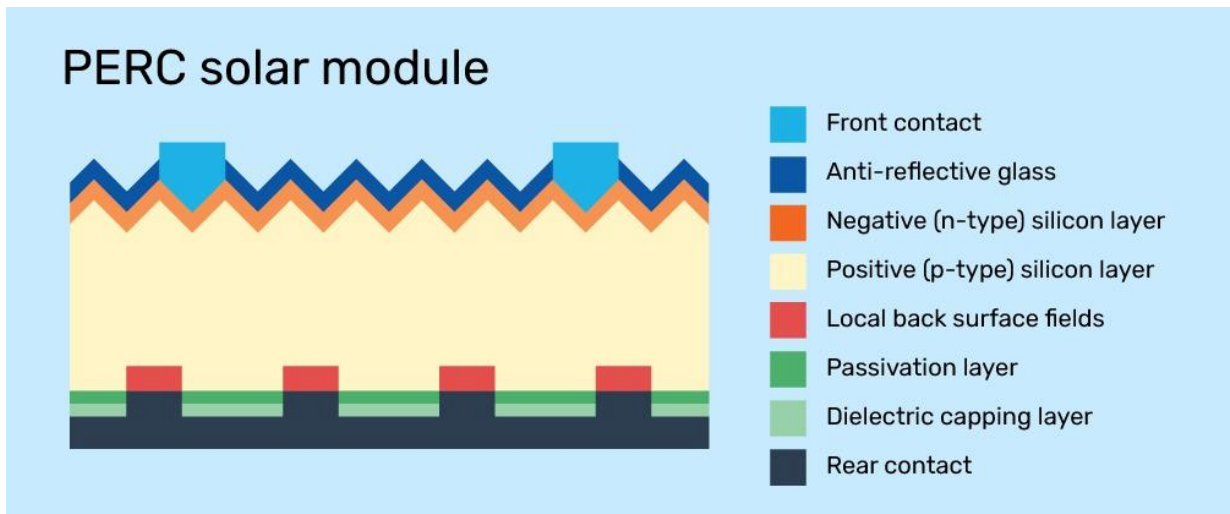


Figure 4. PERC solar module

Historical Development of PERC Cells

1983–1989: Conception and First High-Efficiency Cells – The PERC concept was first conceived in 1983 by Professor Martin Green and colleagues at UNSW Australia[3][4]. Green’s team recognized that improving both the top emitter passivation and the rear surface of silicon cells could dramatically boost efficiency. The first scientific publication on PERC appeared in 1989, when Blakers *et al.* reported a 22.8% efficient cell using passivated emitter and rear techniques[16]. This device – essentially a **PERL** cell (Passivated Emitter, Rear Locally diffused) – set a world record at the time (Appl. Phys. Lett. 55, 1363 (1989), Blakers *et al.*). In the PERL design, the rear contact areas were **locally** heavily diffused (p^+ regions under the metal), minimizing recombination at the metal/silicon interface while maintaining good contact[5]. Through the late 1980s and 1990s, Green’s UNSW group continually improved such cells. By 1999, Zhao *et al.* achieved ~24–25% efficiency on both p-type and n-type silicon using passivated emitter, rear totally diffused (**PERT**)

structures[4]. These lab results approached the theoretical efficiency limits for single-junction silicon at the time.

1990s–2000s: Competing Technologies – Despite PERC’s efficiency potential, industrial solar cell production in the 1990s remained focused on simpler designs. Two rival high-efficiency concepts emerged: **back-contact** cells (popularized by SunPower, featuring all contacts on the rear to eliminate front grid shading) and **heterojunction** cells (HIT/HJT, commercialized by Sanyo/Panasonic, using amorphous silicon layers for passivation)[4]. PERC was largely confined to laboratories in this era, as manufacturing challenges (e.g. precise deposition of rear dielectrics and laser-contact formation) limited its commercialization[4]. Instead, industry incrementally improved the standard Al-BSF cells through better metallization, surface texturing, and anti-reflection coatings in the 1990s and early 2000s[4]. By the early 2000s, those incremental tweaks pushed commercial Al-BSF cells near their practical efficiency limits (~18–19% in mass production, ~20% in the best cases)[3]. PERC, meanwhile, continued to set efficiency records in research, reaching 25% in 2008–2009 (Green *et al.*, Prog. Photovolt. 2008) and holding the single-junction silicon record of 25.0% for several years[25].

2010–2015: Transition to Mass Production – It took roughly 25–30 years from conception for PERC to transition into industrial production[6][4]. Around 2010–2012, pilot manufacturing lines began adopting PERC processes as new laser and deposition tools became available. The turning point came by **2014–2015**, when the economics tipped in favor of PERC: the efficiency gain (~1% absolute) justified the slightly higher processing cost because higher-efficiency panels reduce system-level costs (fewer panels for the same power)[4]. According to industry reports, much of the new cell manufacturing capacity added in 2014 was PERC-based, making it the second-largest cell technology by that time[7]. By 2015, PERC had “emerged as the new viable platform to manufacture high power, high efficiency panels”[4]. A key factor was that existing cell production lines could be **retrofitted** for PERC with a few extra steps (rear passivation deposition and laser contact opening)[4][8]. This ability to leverage standard p-type silicon and screen-printing technology greatly accelerated PERC’s rollout. *FuturaSun (2023) notes that starting from 2015, PERC spread rapidly and was crowned the new king of the PV industry*[8].

2016–2022: Market Dominance – In the second half of the 2010s, PERC became the dominant crystalline silicon cell type. Manufacturers worldwide (especially in China, e.g. LONGi, JA Solar, Jinko) switched their production to mono-PERC and multi-PERC cells. The global market share of PERC/PERL/PERT designs climbed dramatically, while older Al-BSF lines were phased out[4]. By 2019, large-scale mass production of p-type PERC cells had achieved ~22% average cell efficiency with leading production lines exceeding 23%[9]. In 2021–2022, **over 50%** of all solar cells produced globally were PERC-type p-type cells, and if one includes n-PERT and other variants, PERC-family cells represented an even larger majority[10][2]. In fact, PERC’s impact was so profound that Martin Green was

awarded the 2022 Millennium Technology Prize for this innovation, with the award committee noting that PERC had become the most commercially viable and efficient silicon cell, accounting for almost 90% of the world market by that point[2].

2023 and Beyond: PERC’s Legacy and Succession – As of 2023–2025, PERC technology is approaching its practical limits, with champion large-area cells around 24.5% efficiency (p-type) and mass-produced cells ~23%[11]. To achieve further gains, the industry is transitioning to new cell architectures on n-type silicon such as TOPCon, heterojunction (HJT), and interdigitated back contact (IBC) cells[8]. These next-generation cells build on PERC’s concepts of passivation and light trapping, pushing efficiencies to 26–27% in the lab. Notably, tunnel oxide passivated contact (**TOPCon**) cells – essentially an evolution of PERC with an advanced rear contact – began overtaking PERC in new production capacity by 2024[12]. Nevertheless, PERC is expected to remain in high-volume production through the mid-2020s, especially for cost-sensitive applications, and its design serves as the foundation for many tandem cell experiments. For instance, researchers have successfully used **PERC cells as the silicon bottom sub-cell** in tandem configurations with perovskite top cells, reaching over 30% efficiency in 2025[13] (more on tandem PERC in a later section). In summary, PERC solar cells played a pivotal role in the last decade’s efficiency leap of silicon PV, and they continue to influence the direction of photovoltaic research and manufacturing.

Table 1 – Key Milestones in PERC Solar Cell Development

Year	Milestone/Development	Reference
1983	Martin Green (UNSW) sketches first PERC cell concept (passivated emitter & rear)	Green (2022)[2]
1989	First PERC-type lab cell demonstrated – 22.8% efficient passivated emitter, rear locally-diffused (PERL) cell (Blakers <i>et al.</i> , UNSW)	Blakers <i>et al.</i> (1989)[4]
1999–2000	UNSW develops 24–25% efficient PERT cells on p-type and n-type silicon (Zhao, Green <i>et al.</i>) – approaching 25% silicon efficiency record	Zhao <i>et al.</i> (2000)[4]
2014	PERC enters mass production; first large-scale adoption as standard cell efficiency nears limit (~19%)[4]. Industry begins retrofitting Al-BSF lines to PERC.	Green (2015)[4]
2015	PERC technology achieves broad commercial rollout – >20% module efficiencies. PERC becomes “new platform” for high-efficiency, cost-effective panels[4].	FuturaSun (2023)[8]
2018	PERC surpasses Al-BSF as the dominant cell type in new production. PERC cell efficiency improving ~0.4% (abs.) per year in mass production[14].	PV-Tech (2018)
2020	PERC cell lab record ~24.5% (p-type, Fraunhofer ISE). Commercial mono-PERC modules exceed 21% efficiency.	(Green <i>et al.</i> , 2020)

Year	Milestone/Development	Reference
2022	PERC accounts for ~80–90% of silicon PV production. Martin Green awarded Millennium Prize for PERC innovation[2]. n-Type TOPCon and HJT begin to challenge PERC's dominance.	Millennium Prize (2022)[2]
2025	Tandem perovskite+PERC cells demonstrated with >30% efficiency (Park <i>et al.</i> , S. Korea)[13]. Industry transition to TOPCon/HJT accelerates; PERC remains widely produced for its cost advantage.	Park <i>et al.</i> (2025)[13]

PERC Cell Structure and Operation

A modern PERC solar cell is built on a crystalline silicon wafer and has a **layered structure** similar in front appearance to a standard cell but fundamentally different at the rear. Figure 5 illustrates the typical structure of a PERC cell and highlights the process flow for fabrication.

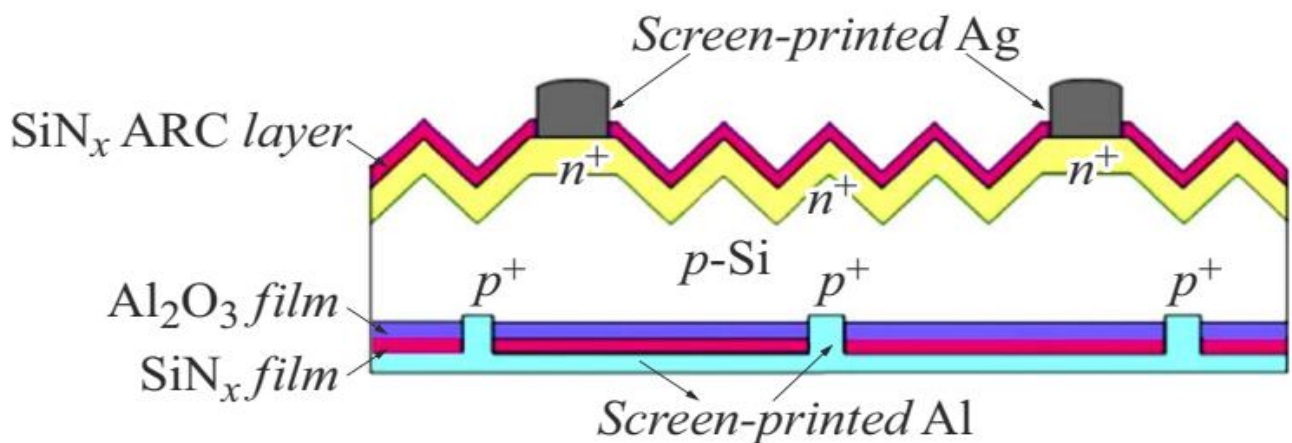


Figure 5 illustrates the typical structure of a PERC cell. (DOI: 10.21883/TP.2022.04.53606.224-21)

Key features of the PERC structure include[39][40]:

Front Side: The sun-facing side of a PERC cell is essentially the same as a conventional cell. It consists of a shallow **n⁺ emitter** layer (formed by diffusing phosphorus into the p-type silicon wafer surface) which creates the p–n junction. The emitter is coated with an **anti-reflective coating (ARC)**, usually silicon nitride (SiN_x), which both reduces reflection and passivates the surface. Metal grid contacts (silver paste fingers and busbars) are screen-printed on the front to collect current[16]. Advanced PERC designs often include a **selective emitter**, where the emitter region under the front contacts is heavily doped to lower contact resistance, while other areas

have lighter doping for reduced recombination[16]. This maintains high open-circuit voltage (V_{oc}) without sacrificing series resistance.

Rear Side Passivation: Unlike a full-area aluminum alloyed back-surface field in older cells, a PERC cell has a **dielectric passivation film** on the entire rear surface of the silicon. Commonly this is a thin layer of aluminum oxide (Al_2O_3 , ~5–20 nm) capped with silicon nitride (SiN_x , ~100 nm)[15]. Al_2O_3 is chosen because it provides excellent chemical passivation (reducing interface defects) and contains a high density of fixed negative charges ($\sim 10^{13} \text{ cm}^{-2}$) at the Si interface, which creates an electric field that repels electrons from the silicon surface (field-effect passivation)[15]. This is beneficial since in a p-type base cell, recombination via electrons at the rear surface is a major loss mechanism – the negative charge in Al_2O_3 mitigates that by pushing electrons away. The SiN_x capping layer serves multiple purposes: it protects the Al_2O_3 from moisture and aluminum paste during firing, provides additional passivation (hydrogen release to saturate dangling bonds), and acts as an optical reflector for longer wavelengths[15]. Overall, the rear passivation stack dramatically lowers the surface recombination velocity, boosting the cell's V_{oc} .

Local Rear Contacts: To collect current, PERC uses **localized rear contacts** instead of a continuous metal layer. After depositing the rear dielectric, small openings (typically 50–100 μm in diameter) are created in the passivation layer by laser ablation in a grid or dot pattern[1]. Through these microscopic holes, a metal (usually screen-printed aluminum paste, sometimes with silver) is applied that alloys with the silicon upon firing, forming a p+ **local back-surface field** under each contact point[17]. These p+-doped regions (created either by the alloying of Al or by a prior boron diffusion in some processes) minimize recombination at the metal-silicon interface while allowing ohmic contact. The metal pads then collect the holes (current carriers in the p-type base) and connect to the external circuit via busbars. The rear metallization in PERC is often a grid of aluminum pads or a full-area aluminum layer that is *discontinuous* due to the dielectric (hence only contacting where laser-opened). This approach, compared to the old full Al-BSF, yields higher V_{oc} and slightly higher photocurrent, because much of the rear surface is still passivated and not in direct contact with metal[17][18].

Light Trapping: The dielectric passivation layer also acts as a back reflector. Silicon is weak at absorbing infrared (long-wavelength) light; in a standard cell, much of that light exits out the back. PERC's rear dielectric (especially Al_2O_3/SiN_x stack) has a lower refractive index than silicon, causing internal reflection of light back into the cell. Additionally, the aluminum metallization behind the dielectric can reflect light that passes through the dielectric openings. The net effect is that infrared photons get a “second chance” to be absorbed in the silicon, increasing the short-circuit current (J_{sc}). This is why PERC cells show improved spectral response in the 800–1100 nm range compared to Al-BSF cells[19]. In essence, PERC combines **optical benefits** (via a dielectric mirror) with **electrical benefits** (via surface passivation).

Manufacturing Process of PERC Cells

The fabrication of PERC solar cells builds on standard crystalline silicon cell manufacturing with a few critical additional steps. To implement PERC, an existing Al-BSF cell production line typically adds a rear surface polishing, rear dielectric deposition, and laser contact opening process[15]. Below is a step-by-step overview of how PERC solar cells are manufactured (for a p-type monocrystalline silicon example), highlighting the differences from a conventional cell:

- **Wafer & Texture:** p-type Si wafer ($\sim 150\ \mu\text{m}$), front side textured (random pyramids) for light trapping, rear side polished for better passivation[15].
- **Emitter Diffusion:** POCl_3 diffusion forms n^+ emitter ($\sim 80\text{--}100\ \Omega/\square$); remove PSG and etch off any n^+ on rear (maintain p-type back) [15].
- **Rear Polish:** Ensure a smooth, flat rear surface (etch off $\sim 1\ \mu\text{m}$ if it was textured) to optimize $\text{Al}_2\text{O}_3/\text{SiN}_x$ passivation coverage[15].
- **Front ARC/Passivation:** Deposit $\sim 75\ \text{nm}$ PECVD SiN_x on the emitter (anti-reflection coating and surface passivation via hydrogenation) [15].
- **Rear Passivation:** Deposit Al_2O_3 ($\sim 10\ \text{nm}$, ALD) + SiN_x ($\sim 100\ \text{nm}$, PECVD) stack on rear (high-quality dielectric passivation); an anneal or firing step activates the Al_2O_3 effect [15].
- **Laser Openings:** Laser ablate small holes in rear dielectric (pattern covering $\sim 1\text{--}5\%$ of area) where contacts will go, balancing low resistance and minimal recombination [20].
- **Metallization:** Screen-print Ag grid on front (fingers and busbars) and full-area Al on rear. (Optional: Ag/Al paste or extra Ag on rear busbars for soldering) [15].
- **Co-Firing:** High-temp belt furnace ($\sim 800\ ^\circ\text{C}$) to sinter metals. Front Ag paste burns through SiN_x to contact emitter; rear Al paste alloys with Si at laser openings, forming local p^+ BSFs and mirror-like Al elsewhere (no electrical contact over dielectric) [17].
- **Test & Sort:** Measure cell efficiency (PERC yields higher V_{oc} , comparable I_{sc} to BSF, overall higher efficiency). Sort cells by efficiency and appearance. PERC cells have a dielectric-coated back (gray/white) and can be made bifacial (transparent rear passivation to capture rear light) for extra yield [1].

The above sequence shows that to go from a standard cell to PERC, the extra **critical steps** are: **rear surface conditioning (etch/polish)**, **rear dielectric deposition**, and **laser opening**[59][60]. Each of these must be executed with precision to get the efficiency boost. The rest of the process (texturing, diffusion, front ARC, metallization) remains largely the same, meaning PERC could leverage the huge manufacturing know-how of the silicon PV industry.

It's worth noting that manufacturers continuously refine PERC process steps. For instance, plasma-based **remote laser doping** can form the local BSF under contacts to improve fill factor. Alternatives to screen printing, like plated

metallization, have been explored to reduce silver usage (e.g. Ni/Cu plating on PERC cells)[21]. However, the mainstream PERC production still relies on affordable printing and firing. With these mature processes, **mass-produced PERC cell efficiencies have increased by ~0.4% (absolute) per year** in recent years[14] – a remarkable pace, reaching ~23% in 2023 for the best producers. This shows the potential still being squeezed out of PERC through manufacturing innovations such as multi-busbar grids, thinner wafers, improved pastes, and advanced process control (often assisted by AI and machine vision for defect control).

Variants and Improvements of PERC Technology

Under the umbrella of “PERC” there exists a family of related high-efficiency cell designs. These include PERL, PERT, and others, which were initially considered separate but are now often grouped as PERC variants[4]. All share the core concept of a passivated emitter and rear, differing mainly in how the rear contact and doping are implemented:

- **PERC (Passivated Emitter and Rear Cell):** The baseline discussed so far – usually implies a p-type base, diffused n+ emitter, rear $\text{AlO}_x/\text{SiN}_x$ passivation, and point aluminum contacts. “Mono-PERC” refers to monocrystalline silicon PERC (highest efficiency), while “Poly-PERC” refers to multicrystalline silicon with PERC architecture (which still gives a boost over poly-BSF cells)[1]. Mono-PERC typically outperforms poly-PERC by a couple of efficiency points, but both benefit from the PERC design. PERC cells today often incorporate **Selective Emitter (SE)** structures and **Multi-Busbar** front grids to further enhance performance[22]. These improvements are sometimes denoted as PERC+ or PERC-SE. A variant called **PERC-ULE** (ultra-low emitter) reduces emitter doping except under contacts, to maximize V_{oc} . However, the fundamental principle remains the same: dielectric rear passivation with local contacts.
- **PERL (Passivated Emitter and Rear Locally-diffused):** This is the lab champion structure pioneered by UNSW. In a PERL cell, the rear contact areas have a heavy boron diffusion (p+), while the areas between contacts are passivated by a thermal oxide[17]. Essentially, PERL uses localized high-low junctions on the rear instead of an aluminum alloy BSF. The front surface of PERL is also highly optimized (thermal oxide + nitride double-layer passivation on the emitter). PERL cells achieved ~25% efficiency under one-sun illumination by minimizing all major loss mechanisms[5]. However, PERL required photolithography and multiple diffusions – steps too expensive for mass production. Many PERL concepts were transferred to industry in simplified forms (e.g. using screen-printed contacts instead of photolithography, as in PERC). PERL remains important in that it showed the ultimate potential of passivated contacts on silicon.

- **PERT (Passivated Emitter, Rear Totally-diffused):** In contrast to PERL, PERT has the entire rear surface diffused (p+ for p-type cells, or n+ for n-type cells). That is, instead of using an Al alloy to create a BSF, PERT cells form the back surface field by diffusion of dopants across the full rear side, and then passivate that diffused surface with a dielectric[5]. For example, on a p-type wafer, one can diffuse a boron p+ layer on the rear, passivate it, and open contacts – this yields a structure similar to PERC but with a boron BSF rather than Al. PERT cells avoid the LID associated with Al-BSF and can be inherently **bifacial** (since both sides are diffused junctions and can generate current)[5]. Notably, many high-efficiency n-type cells are PERT: an n-type wafer with a diffused p+ emitter on front and n+ BSF on rear (both sides passivated) qualifies as PERT. In the late 1990s, Zhao *et al.* used a PERT structure on n-type to reach 24.7% efficiency[4]. Today, PERT is less common in p-type production (because PERC is simpler), but **n-PERT** cells are used by some manufacturers due to n-type silicon’s advantages (no B-O LID, etc.). PERT can be seen as a “dual-diffused” PERC with full-area diffused BSF instead of local Al BSF.
- **PERF:** Occasionally mentioned in literature, PERF might stand for **Passivated Emitter, Rear Floating** junction or **Rear Free** diffusion. It is not as standard a term. In some contexts, PERF has been used to describe a PERC-like cell where the rear contact is point-like and the rear junction is not diffused at all (floating junction). This is essentially a PERC cell (p-type base, diffused emitter, passivated rear) without any intentional BSF doping or with an “undiffused” rear aside from the metal contact regions. The “floating” term implies the rear surface is passivated and not driven into strong inversion or depletion. PERF has not gained broad usage; most people lump it under PERC.
- **BiFacial PERC:** Standard PERC cells can be made bifacial by using a transparent rear sheet in modules and sometimes adapting the rear dielectric to transmit some light. Some manufacturers slightly tweak the rear passivation stack (e.g. using silicon nitride that is less optically dense) so that about 5-10% of rear incident light can be absorbed. Bifacial PERC modules can gain 5–15% more energy yield from reflected light[77]. However, true bifacial optimization often goes with n-type cells (which naturally are bifacial). Still, “PERC bifacial” modules are being sold, indicating the versatility of the PERC design even for bifacial applications[1].
- **PERC/T++:** We also see hybrid naming like **MWT-PERC** (Metal-Wrap-Through PERC) where front busbars are eliminated by wrapping them to the rear through vias[4], or PERC with **shingled** cell interconnections (as in Boviet’s PERC-SE cells, which combine PERC with a shingled-cell layout)[4]. These are more module-level or layout innovations, but they showcase how PERC can integrate with other concepts.

Ongoing Enhancements: The PERC architecture continues to be refined. Researchers are exploring **plated copper contacts** to replace silver for cost reduction[23], advanced **passivating contact** ideas to mitigate metal contact recombination (for instance, local poly-Si on oxide at the rear, sometimes dubbed “POLO-PERC”), and improved dielectric stacks (like adding SiO₂ interlayers). Another area of improvement is addressing PERC-specific degradation: for instance, using **Gallium-doped silicon** wafers largely eliminates B-O related light-induced degradation that was more severe in highly doped PERC cells[4]. Also, manufacturers ensure PERC modules pass strict **PID resistance** tests (IEC 62804) by careful material choices and possibly by including a tiny amount of conductive foil at the module edges to drain leakage currents[4].

In short, PERC is not a single static design but a platform that has sprouted numerous offshoots in the quest for higher efficiency. Many of these variants – PERL, PERT – played crucial roles in demonstrating performance limits, while the baseline industrial PERC incorporated the most practical elements. As we will see next, the latest generation of cells like TOPCon builds directly on PERC by introducing passivating contacts, showing that the evolution is continuous.

Efficiency and Characteristics: PERC vs. TOPCon Solar Cells

One of the most discussed comparisons in modern PV is between PERC and **TOPCon** (Tunnel Oxide Passivated Contact) solar cells. TOPCon can be considered a successor to PERC, especially for n-type silicon. It further reduces recombination by using *passivating contacts* that eliminate the highly recombination-active metal/Si interface on the rear. We outline the differences and performance below:

Structural Difference: A TOPCon cell typically uses an ultra-thin silicon oxide (~1–2 nm) on the silicon surface and a layer of doped polycrystalline silicon on top of that oxide (often on the rear side for an n-type cell)[24]. This poly/oxide stack forms a *tunnel oxide passivated contact* – it allows electrons to quantum tunnel through the oxide to the poly-Si, which then acts as the conducting layer to the metal contact, while still passivating the interface when no bias is applied. In essence, TOPCon replaces PERC’s local aluminum p⁺ contacts with a full-area passivating contact. For an n-type TOPCon cell (which is common), the structure might be: n-type base, p⁺ boron diffused emitter at front, and n⁺ poly-Si/oxide passivated contact at rear (no aluminum BSF needed). In contrast, a PERC cell has localized metal contacts and relies on a dielectric + aluminum pattern for the rear. Figure 6 (below) shows a schematic: the right half was a TOPCon concept, the left a PERC[3]. The TOPCon cell (right) had a continuous n⁺ poly-Si layer across the rear under the metal, as opposed to isolated Al point contacts in PERC.

Efficiency Advantage: TOPCon cells generally achieve higher voltages and fill factors because the passivated contact virtually eliminates metal-Si recombination. According to recent data, TOPCon cell efficiencies in production have reached ~25–25.5%, about 1.5–2% (abs.) higher than mainstream PERC which is ~23%[11]. For

instance, **TOPCon boasts lab efficiencies around 26.0–26.1%**, whereas **PERC cells peak around 22.5–23%** under similar conditions[24]. This ~3.5 percentage point gap is huge in PV terms. Real-world module data also reflect this: TOPCon panels (usually bifacial n-type) are now hitting 22–23% module efficiency, compared to 20–21% for PERC modules of the same era[25]. One source notes “*mass production efficiency of TOPCon has reached 25.2%, surpassing PERC’s 23.2% by 2% absolute*”[11]. The higher efficiency comes from both higher V_{oc} (n-TOPCon cells can reach ~720 mV, vs ~680 mV in p-PERC) and often higher J_{sc} (especially bifacial gain or better blue response due to n-type substrate).

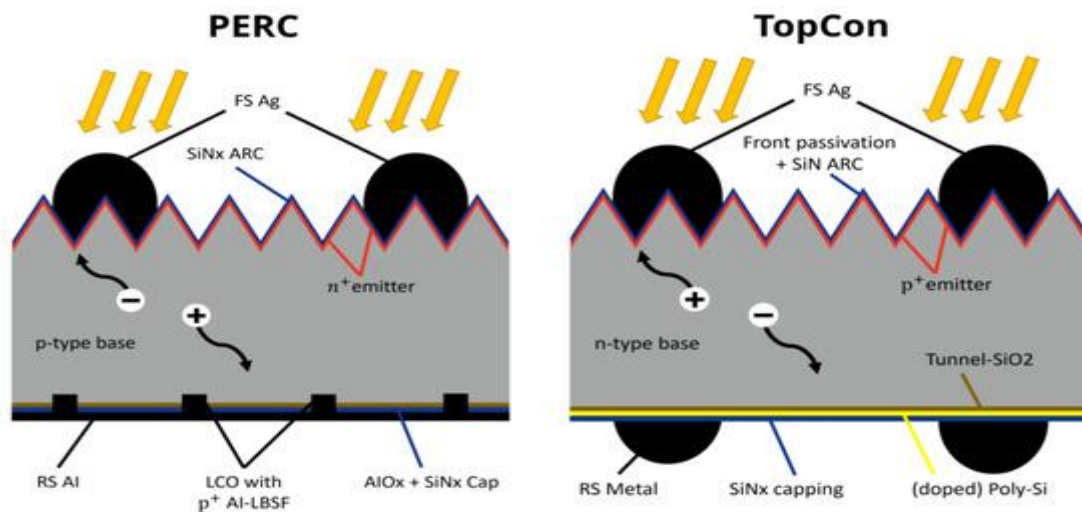


Figure 6. Schematic view of the solar cell architectures of the PERC (**left**) and TOPCon (**right**) cells with an illustration of the sunlight direction on top and charge carrier directions(<https://doi.org/10.3390/cryst14020167>)

Thermal and Bifacial Performance: TOPCon cells, being typically on n-type wafers, have a slightly lower temperature coefficient and no light-induced degradation from B-O defects. They also inherently lend themselves to bifacial designs (the rear passivating contact can be transparent or at least not blocking light). PERC cells on p-type generally have a temperature coefficient around -0.35 to $-0.37\%/^{\circ}\text{C}$ for power, while n-type TOPCon might be -0.30 to $-0.32\%/^{\circ}\text{C}$, meaning TOPCon loses less efficiency on hot days[25]. Additionally, TOPCon modules often achieve bifaciality (ratio of rear to front output) of 75–80%, considerably higher than bifacial PERC which might be ~70% or less. In practical terms, this gives TOPCon an energy yield advantage in installations with reflected light.

Cost and Complexity: Early on, PERC had the clear advantage of lower cost – it was an incremental add-on to existing lines. TOPCon introduces new deposition steps (like depositing poly-Si, which can be done via LPCVD or PECVD) and potentially etching or polishing steps on both sides. However, the industry has rapidly optimized TOPCon such that cost differences are shrinking. PERC’s equipment and processes are fully amortized in many factories, so PERC remains slightly cheaper per wafer.

Some estimates in 2024 showed PERC cell production cost ~10–15% less than TOPCon[24]. Nonetheless, the higher efficiency of TOPCon can yield lower cost per watt at the module level, offsetting the cell cost. As volume grows, TOPCon costs are expected to further drop. Analysts predict TOPCon technology will overtake PERC as the mainstream by 2024–2025 due to this convergence of efficiency gain and manageable cost[36].

Summary of Performance(Practice lesson): In qualitative terms, “*TOPCon offers higher performance (conversion efficiency, especially at high temperatures) while PERC offers simplicity and low cost*”. A concise comparison from an industry Q&A states: “*TOPCon solar cells improve on PERC by adding a tunnel oxide layer and passivated contact, boosting efficiency and reducing recombination. While PERC is more affordable and widely adopted, TOPCon offers higher performance, especially in power conversion and thermal stability.*”[1]. This captures the trade-off well. For a numerical example, consider a standard full-size cell (156 mm): A PERC cell might output ~6.0 A at 0.68 V (I_{sc} ~9.5 A, V_{oc} ~0.68 V, FF ~80%), giving ~5.5 W power. A TOPCon of the same size could output ~6.3 A at 0.72 V (I_{sc} ~10 A, V_{oc} ~0.72 V, FF ~82%), giving ~6.0 W. That is roughly a 9% power increase at the cell level (translating to ~21% vs 23% efficiency). When scaled to modules, these differences persist.

Table 2 – PERC vs. TOPCon Characteristics (Typical values for current technology)

Attribute	PERC (p-type)	TOPCon (n-type)
Cell Efficiency (lab)	~23–24% (best p-type PERC cell)[24]	~26% (best n-type TOPCon cell)[24]
Cell Efficiency (mass)	~22–23% (Mono PERC in production)[11]	~24–25% (Mono TOPCon in production)[11]
Open-Circuit Voltage	~670 mV (p-type, Al-BSF rear)	~710 mV (n-type, passivated rear)
Short-Circuit Current	High; good IR response due to passivation mirror	High; excellent blue and IR response (n-type has no B-O loss)
Fill Factor	~80–81% (screen-printed contacts)	~82–83% (better passivated contacts)
Temp. Coefficient	–0.35%/°C (approx. for mono-PERC)[25]	–0.30%/°C (approx. for mono-TOPCon)[25]
Bifacial Capability	Moderate – some bifacial PERC (~70% bifaciality)	High – naturally bifacial (75–80% bifaciality)
Degradation	Light-induced degradation (LID) unless Ga-doped; some PID risk[4][1]	No B-O LID (n-type); very low LID; PID robust (if well encapsulated)
Process Complexity	+2 steps vs. Al-BSF (AlO_x deposit, laser); uses p-type	+3–4 steps vs. PERC (oxide+poly deposition, possibly diffusion

Attribute	PERC (p-type) wafer	TOPCon (n-type) changes); uses n-type wafer
Relative Cost	Lower capital and process cost; fully amortized lines	~10% higher cell cost (2023) but falling; requires new equipment (LPCVD etc.) [24]
Commercial Status	Very mature, dominant until 2023	Growing fast; expected to be mainstream by 2024–25 [12]

As seen, TOPCon’s main benefits lie in efficiency and n-type wafer advantages, while PERC’s strengths are simplicity and huge existing manufacturing scale. It’s also worth noting that **Heterojunction (HJT)** cells offer even slightly higher potential efficiency (~26–27%) and even lower temperature coefficients, but at a higher cost. The competition between TOPCon and HJT is ongoing, but both are n-type and aim to surpass PERC. Meanwhile, **bifacial PERC** and improved PERC (with better pastes, etc.) are bridging the gap for now.

In practical field conditions, a TOPCon module may deliver ~3-4% more energy than a PERC module of the same nameplate rating, partly due to better high-temperature performance and bifacial gain. However, PERC panels are proven and bankable, and their cost has dropped tremendously. So, both technologies are likely to coexist for some years, with TOPCon increasingly taking premium or high-efficiency market segments and PERC remaining in standard applications until TOPCon’s cost further reduces. Indeed, industry roadmaps (like ITRPV) predict PERC will gradually be phased out in favor of TOPCon and other n-type cells by the late 2020s[\[8\]](#). The **bottom line** is that TOPCon builds upon PERC’s foundation – one can consider it “PERC 2.0” – achieving higher efficiency through a more idealized contact scheme at the expense of some added process complexity[\[1\]](#).

Organic and Tandem Implementations with PERC

(The user request mentioned “easy to understand about organic solar cells” – however PERC is a silicon cell technology, not directly related to organic PV. Likely this was to ensure clarity. We thus focus on tandem combinations involving PERC cells in this section.)

PERC in Tandem Solar Cells: A tandem solar cell stacks two or more sub-cells with different bandgaps to capture more of the solar spectrum and exceed the efficiency limit of single-junction cells (~29% for silicon). Silicon PERC cells, being commercially abundant, have been explored as bottom cells in tandem configurations – especially with perovskite solar cells as the top cell. The idea is to use a high-bandgap perovskite (≈ 1.7 – 1.8 eV) to absorb the visible light, while the silicon (≈ 1.1 eV bandgap) absorbs the red/infrared light that the perovskite lets through. PERC cells provide a cost-effective, already-optimized platform for the silicon bottom

cell[13]. Researchers have demonstrated that using a **commercial PERC** as the base, with minimal modifications, can result in excellent tandem performance[26].

In 2022, a German team (HZB and ISFH) built a proof-of-concept monolithic perovskite/Si tandem on a **p-type PERC** platform, achieving 21.3% efficiency[10]. They used a PERC cell with a specialized front junction (a POLO – poly-silicon on oxide – at the front instead of a diffused emitter, to avoid degrading the perovskite). This design, called “perovskite-POLO-PERC” tandem, kept all the standard PERC rear structure (Al_2O_3 passivation, etc.)[10]. The result was promising, and they estimated potential up to $\sim 29.5\%$ with further optimization[10]. Figure 7 shows a schematic cross-section of such a tandem device, where the bottom cell contains the full PERC structure (rear $\text{Al}_2\text{O}_3/\text{SiN}_x$ and local Al contacts) and the top cell is a thin-film perovskite with transparent contacts.

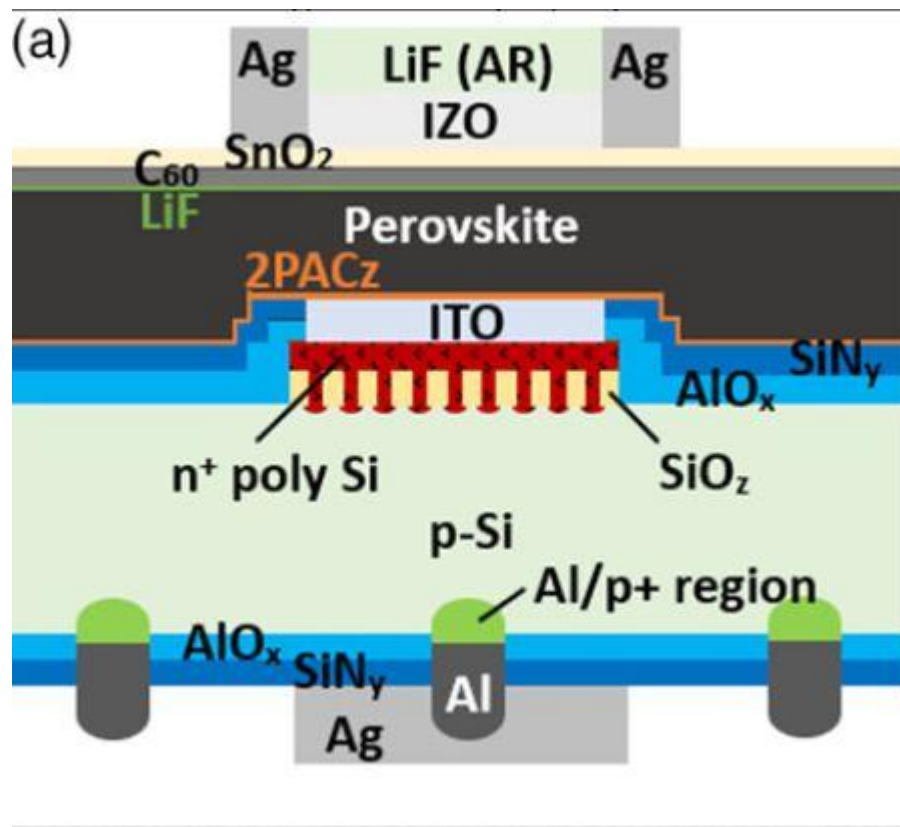


Figure 7. Cross-sectional schematics of the perovskite–POLO–PERC tandem solar cell

Figure 7: Schematic cross-section of a monolithic two-terminal tandem cell combining a perovskite top cell (p–i–n structure) with a silicon bottom cell that uses PERC/POLO technology[10]. The silicon bottom is a p-type PERC cell with a polysilicon (POLO) front junction and the usual passivated rear contact ($\text{Al}_2\text{O}_3/\text{SiN}_x$ + local Al). Such tandems achieved $\sim 21\text{--}23\%$ initially, with paths to $\sim 30\%$ efficiency. (Image credit: HZB/RRL Solar, CC BY 4.0 <https://bit.ly/358rI9p>)

By 2023–2025, significant progress was made: Park *et al.* in South Korea reported a **30.05% efficient** monolithic perovskite/Si tandem using a *commercial p-type PERC cell* as the bottom (with a GaInP passivating contact applied)[13]. They used a self-assembled monolayer to improve the interface and managed to push the tandem's V_{oc} over 1.8 V (since the perovskite top cell provided ~1.1 V and the silicon PERC bottom ~0.7 V). This is notable as it crosses the 30% mark, demonstrating that even **cost-effective PERC bottom cells** can contribute to extremely high efficiencies when paired with a suitable top cell[13]. The appeal of using a PERC (versus a special heterojunction or IBC bottom cell) is cost – PERC cells are cheap and mass-produced, so a tandem on PERC could be more economically attractive if reliability issues are solved.

Challenges: One challenge is that a PERC cell is optimized for single-junction operation. In a tandem, the current through each cell must be matched (series connection). A PERC cell might have more current capacity than needed when paired with a high-bandgap top cell. Strategies to address this include thinning the perovskite to reduce its absorption (so more light goes to silicon)[111], or texturing the silicon front less aggressively (to reflect some light back to perovskite). Also, PERC uses aluminum contacts that might not be ideal for transparent tandem integration (the aluminum on rear is fine, but the front grid and metallization need to avoid shading the perovskite too much). In the perovskite-PERC tandem of 2022, they actually removed the front metal of the PERC cell (replacing it with a transparent conductive oxide and poly-Si contact)[10] – effectively turning it into a POLO cell on the front – to make it tandem-friendly. Thus, strictly speaking, tandem implementations might use a *modified PERC* (with different front structure). Nonetheless, the rear passivation and general p-type nature of PERC can remain unchanged.

Another area is **spectrum utilization**: PERC cells are very good in IR due to the rear reflector; in a tandem, that mirror effect means unused IR bounces in the silicon bottom cell and can be absorbed. That's beneficial. On the other hand, PERC's front might not be ideally transparent to blue light (since PERC's SiN_x front ARC is colored for single junction). But in a tandem the perovskite will take the blue, so some adjustments to front ARC might be done.

Despite these technical tweaks, the message is that **PERC technology is compatible with tandem solar cells** – especially as a drop-in low-cost bottom cell. This opens a pathway to efficiencies well above the single-cell limit. It is conceivable that in the near future, commercial tandem panels could use upgraded PERC cells (perhaps gallium-doped p-type with passivating contacts – a hybrid approach) to deliver 30%+ efficiency at affordable cost, something unattainable by PERC or TOPCon alone. Indeed, companies are actively researching “hybrid” cells like PERC/TopCon or adding inexpensive perovskite layers on top of finished PERC cells.

Organic Solar Cells vs PERC: While the user query mentioned “easy to understand about organic solar cells”, PERC cells are a crystalline silicon technology,

very different from organic PV. It's worth noting that PERC's principles (passivation and light management) also apply generally – even in some organic or thin-film cells, managing recombination and reflection is key. However, organic solar cells use completely different materials (polymers, small molecules) and typically don't have the same kind of pn-junction or carrier-selective contacts as silicon. Therefore, a direct comparison is not very relevant in this context. Still, in an academic textbook style, we might say: PERC cells represent the cutting edge of *inorganic* silicon PV tech, whereas *organic solar cells* belong to a separate “third generation” PV category focusing on low-cost and flexibility, albeit with much lower efficiency (~10–15% lab efficiencies and different stability challenges). Both aim to increase power output from sunlight, but through very different materials science routes.

Performance Characteristics

By virtue of the above design, PERC cells typically exhibit higher **open-circuit voltage** and **fill factor** than equivalent Al-BSF cells, as well as a boost in **short-circuit current** in the near-IR part of the spectrum. For example, a conventional mono-Si cell might have $V_{oc} \approx 0.63$ V, whereas a comparable PERC cell might reach $V_{oc} \approx 0.67$ – 0.70 V due to reduced recombination. The internal quantum efficiency (IQE) at long wavelengths is significantly higher for PERC, translating to ~ 1 mA/cm² greater J_{sc} in many cases[18][19]. These improvements yield about 1% to 1.5% absolute efficiency increase (e.g. from 20% to 21.5%) for monocrystalline silicon, which is quite substantial in the PV industry[1]. PERC cells do, however, introduce some new considerations: the rear passivation must be of high quality and stable, and the laser contact process must be optimized to avoid damaging the wafer or causing shunts. In the early days of mass production, issues like **light-induced degradation** (LID) and **potential-induced degradation** (PID) were observed to be more pronounced in PERC cells – partly due to the higher bulk doping in p-type and the passivation layers. Manufacturers mitigated LID by switching to gallium-doped silicon or new regeneration processes[4], and mitigated PID with better module encapsulation and cell designs[1]. Modern PERC modules now have excellent stability, often warranted for ~ 30 years of operation with minimal additional degradation relative to other cell types.

In summary, the PERC structure can be seen as a natural evolution of the silicon solar cell: by **passivating both surfaces** (emitter/front and rear) and using **selective contacts**, it approaches the theoretical efficiency limits of silicon without a complete departure from traditional cell processing. This ingenious yet practical design is what allowed PERC to revolutionize commercial PV efficiency.

I-V Characteristics and Efficiency Calculation of PERC Cells

Like any solar cell, a PERC cell's performance is characterized by its current–voltage (I–V) curve under illumination. The fundamental equation for a solar cell's I–V curve (for a diode with photocurrent) is:

$$I(V) = I_{ph} - I_0(e^{qV/nkT} - 1) - \frac{V + IR_s}{R_{sh}},$$

where I_{ph} is the photocurrent, I_0 the diode saturation current, R_s series resistance, R_{sh} shunt resistance, and n the ideality factor. A high-quality PERC cell will have a low I_0 (due to excellent passivation), a decent ideality factor close to 1 (for diffusion-dominated current), low R_s (good conductivity and contacts), and high R_{sh} (minimal leakage).

Key Parameters: From the I–V curve we extract:
- **Short-Circuit Current (I_{sc}):** The current at $V=0$. For a PERC cell of standard size ($\sim 244 \text{ cm}^2$), I_{sc} might be on the order of 9–10 A under 1-sun illumination (approximately 39–40 mA/cm² J_{sc} for a high-efficiency mono-PERC). PERC's improved light trapping can increase J_{sc} by $\sim 0.5\text{--}1 \text{ mA/cm}^2$ over BSF cells[1].
- **Open-Circuit Voltage (V_{oc}):** The voltage at $I=0$. As discussed, PERC cells achieve V_{oc} typically in the 0.66–0.71 V range. This is higher than $\sim 0.62\text{--}0.65 \text{ V}$ of older cells because surface recombination (which contributes to I_0) is much lower. V_{oc} is governed by

$$V_{oc} = \frac{nkT}{q} \ln \frac{I_{ph}}{I_0} + 1$$

The passivation in PERC effectively lowers I_0 , hence raising V_{oc} .

- **Fill Factor (FF):** This is the ratio $\frac{P_{max}}{V_{oc}I_{sc}}$, indicating how “square” the I–V curve is. PERC cells have FF typically 79–81% (some laboratory PERC cells with optimized metallization reach 82–83%). Good FF requires low series resistance (thick enough fingers, good conductivity of emitter and wafer) and high shunt resistance (no significant leaks), both of which PERC can maintain. Sometimes the introduction of the rear dielectric slightly increases series resistance (because current must flow laterally to contact openings), but laser openings are optimized to keep the loss minimal. In practice, multi-busbar and half-cell module design have helped raise FF of PERC modules significantly in recent years.

Efficiency (η) Calculation: The efficiency is given by:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{mp} \times I_{mp}}{(1000 \text{ W/m}^2 \times A_{cell})},$$

for cell area A_{cell} . Equivalently, $\eta \approx \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}$, where P_{in} is the incident power ($\sim 100 \text{ mW/cm}^2$ at 1 sun). For example, consider a mono-Si PERC cell with: $I_{sc} = 9.5 \text{ A}$, $V_{oc} = 0.68 \text{ V}$, and $FF = 80\%$, on a full 156 mm pseudo-square ($\approx 243.4 \text{ cm}^2$). Then $P_{max} \approx 0.68 \times 9.5 \times 0.80 = 5.17 \text{ W}$, and $\eta = \frac{5.17 \text{ W}}{24.34 \text{ W}} \approx 21.3\%$. This aligns with typical efficiencies. If that cell was improved to TOPCon with, say, 10 A, 0.72 V, 82% FF, $P_{max} = 0.72 \times 10 \times 0.82 = 5.90 \text{ W}$, $\eta = 24.2\%$. This shows quantitatively how each increment in parameters pushes efficiency.

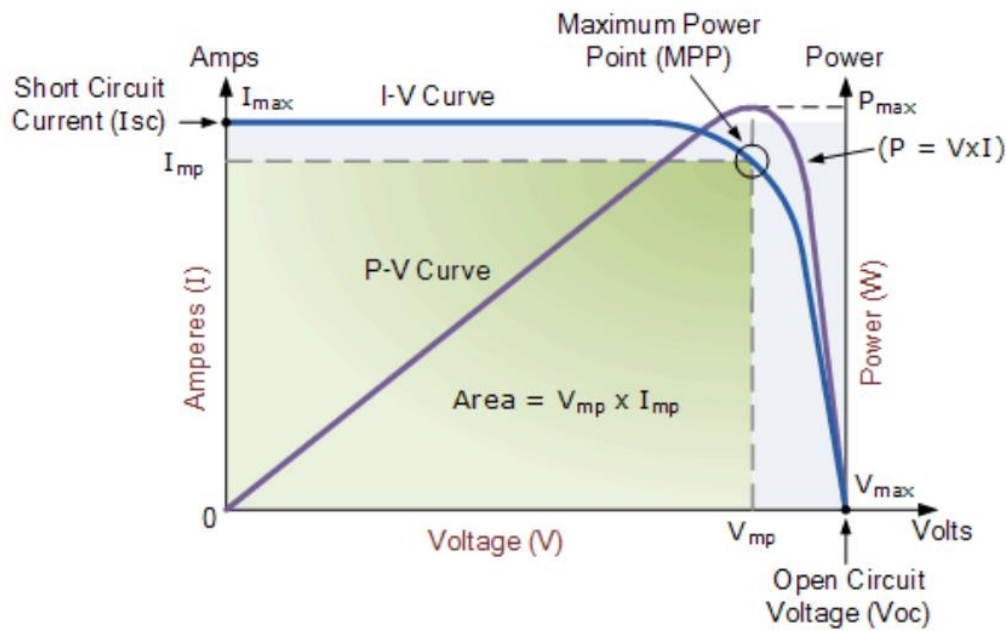


Figure 8. The I–V curve of a solar cell ([115])

I–V Curve Shape: The I–V curve of a solar cell is a rectangular-like curve starting at ($V=0$, $I=I_{SC}$) and ending at ($V=V_{OC}$, $I=0$). A PERC cell’s I–V curve differs from an Al-BSF cell’s primarily by having a higher V_{OC} (shifting the curve to the right) and a slightly steeper “knee” (higher FF). Figure 8 illustrates a typical I–V curve and power curve for a silicon PV device. The maximum power point (MPP) occurs at a voltage V_{mp} near 75–80% of V_{OC} and current I_{mp} ~95% of I_{SC} for a well-behaved cell[27]. In a PERC cell, for example, if $V_{OC} = 680$ mV, the V_{mp} might be ~540–600 mV. If $I_{SC} = 9.5$ A, I_{mp} could be ~9.0 A. Thus $V_{mp} \times I_{mp}$ yields the P_{max} .

The **fill factor** is visually the “squareness” of the I–V curve. PERC’s high FF indicates a nice square shape, owed to its low recombination (diode quality) and decent conductivity. Poor contacts or recombination would round the knee of the curve, lowering FF.

For completeness, **voltage and current are influenced by temperature and irradiance:** Higher cell temperature decreases V_{OC} (≈ -2.2 mV/°C for silicon cells around 0.7 V) and slightly increases I_{SC} ($\sim 0.06\%/^{\circ}\text{C}$ positive coefficient). Thus, efficiency falls as it gets hotter (this is the temperature coefficient mentioned earlier). PERC cells, having slightly higher bandgap voltage potential due to passivation, might have a marginally better temp coeff, but it’s mainly the wafer type (n vs p) that matters there.

Example Characteristic Curves(Practice lesson): If we overlay the I–V curves of a PERC vs an older BSF cell, we’d see at 25 °C, the PERC one reaches a higher voltage at the same current. Moreover, PERC cells maintain higher efficiency at low irradiance. Many module datasheets claim improved *low-light performance* for PERC panels – this is actually more related to module circuitry, but PERC’s slightly

lower diode saturation current can yield better relative efficiency at low-light (since recombination is relatively less at lower generation levels).

In conclusion, analyzing the I–V curve of a PERC cell confirms the benefits of the technology: high V_{OC} from excellent passivation, strong current from enhanced light trapping, and high fill factor from good contact design – all contributing to superior conversion efficiency. The quantification of these gains is essential in academic understanding and industrial quality control, and that’s why PERC’s advent was so significant in raising the performance bar for silicon photovoltaics.

Conclusion and Outlook

PERC solar cells represent a milestone in photovoltaic science and technology. By revisiting the fundamentals of loss reduction (surface passivation and light management) on a device that had been largely unchanged for decades, PERC provided a step-change in efficiency without exorbitant costs. This makes for an excellent case study in how theoretical advances (like those by Green’s team in the 1980s) can eventually reshape an entire industry when manufacturing catches up. In theory, a perfect PERC (with ideal passivation and contacts) could approach ~26% efficiency on p-type silicon[117] – not far from the best TOPCon. In practice, the baton is being passed to new technologies, but often those are extensions of the PERC philosophy (passivating contacts in TOPCon, comprehensive passivation in HJT, etc.).

From a theoretical perspective, PERC taught us the paramount importance of recombination reduction at both surfaces. It validated device models that showed how a simple dielectric could outperform a doped alloy in creating a low-recombination rear interface. PERC also highlighted the balance between optical and electrical optimization – for instance, the trade-off of removing rear texturing to get better passivation, then compensating by dielectric mirror. This balance of considerations is a recurring theme in solar cell R&D.

On the application side, the impact of PERC has been tangible: higher efficiency panels have lowered the cost of solar energy (\$/W) and accelerated the adoption of PV worldwide. Modules based on PERC cells are now ubiquitous, from rooftops to large solar farms. For the end-user or system designer, PERC modules mean needing fewer panels for the same power, slightly better performance on hot days, and strong yields even in diffuse light conditions. Many installations since ~2017 have been deployed with PERC modules, and they are expected to perform reliably over decades, bringing clean energy at lower cost.

As we look ahead, PERC cells are also finding a second life in hybrid configurations – be it as the bottom cells in tandems, or being integrated with new contacting schemes (like maybe a future “polymer/silicon hybrid” where an organic layer could coat a PERC cell to broaden absorption – speculative, but interesting). The combination of PERC with perovskites, as demonstrated by multiple groups, is particularly exciting: it could allow modules exceeding 30% efficiency in a few years,

something once thought exclusive to expensive multi-junctions. If successful, tandem PERC-perovskite modules might extend the dominance of PERC silicon tech well into the 2030s, albeit as part of a multi-junction device.

In summary, PERC solar cells have gone from a laboratory curiosity to the backbone of the solar industry and now to a stepping stone for next-generation PV. The journey from 1983 to 2025 – from 16% efficient cells to 26% and now even 30% in tandems – is a testament to sustained innovation. For a university-level understanding, PERC embodies how improvements in materials (Al_2O_3 films), process (ALD, lasers), and cell design (dielectric passivation) coalesce to break performance barriers in a practical way. Future students and researchers can build upon this knowledge to continue improving solar technologies, whether through further incremental advances or radical new ideas, always remembering the PERC lesson: **manage your losses, and the efficiency will follow.**

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2.1. HETEROJUNCTION (HJT) SOLAR CELLS

Introduction

Heterojunction (HJT) solar cells – also known as silicon heterojunction (SHJ) or HIT (Heterojunction with Intrinsic Thin layer) cells – are advanced photovoltaic devices that combine crystalline silicon with thin amorphous silicon layers to form the solar cell's p-n junction. In a typical HJT cell, a crystalline silicon wafer (usually *n*-type) serves as the main light-absorbing substrate, and ultra-thin amorphous silicon (a-Si:H) layers are deposited on one or both sides of the wafer as emitter and back-surface field, with an intrinsic (undoped) a-Si:H layer in between for surface passivation[1][2]. This heterojunction approach takes advantage of the complementary properties of the two forms of silicon: crystalline silicon provides excellent charge transport and high light absorption in the near-infrared, while amorphous silicon can passivate surface defects and provide a high bandgap “window” that reduces recombination losses[3][4]. The result is a solar cell design capable of very high efficiencies, low temperature coefficients, and improved performance over traditional homojunction silicon cells.

From a theoretical standpoint, HJT cells address one of the key loss mechanisms in conventional silicon solar cells: surface recombination. By introducing a thin intrinsic amorphous silicon layer at the interface, HJT cells dramatically reduce the density of dangling bonds and defects at the silicon surface, which in turn boosts the open-circuit voltage (V_{OC}) and overall efficiency[2]. Moreover, because HJT cells can be manufactured at low temperatures (typically below 200 °C), they avoid the high-temperature diffusion steps of standard cells and exhibit minimal light-induced degradation. These advantages make HJT technology a promising path toward pushing silicon solar cell efficiencies closer to the theoretical single-junction limit (~29.4% for silicon, compared to the ~33.7% Shockley–Queisser limit for an ideal single junction[2]). In the following sections, we will explore the development history of HJT solar cells, their structure and operation, fabrication methods, performance characteristics, and recent advances, as well as compare their efficiency to other leading solar cell technologies.

Historical Development of HJT Solar Cells

The concept of using heterojunctions in silicon solar cells has its roots in research from the 1970s and 1980s. Early pioneers like **Fuhs et al. (1974)** demonstrated heterojunctions between amorphous and crystalline silicon[2], and **Yablonovitch et al. (1985)** achieved an open-circuit voltage over 720 mV using a double heterostructure cell (a silicon device sandwiched between wide-bandgap semiconductors)[2] – a remarkably high V_{OC} for the time. These studies hinted at the potential of heterojunction designs to surpass the performance of traditional diffused-junction cells.

However, the practical development of what we now call HJT (heterojunction with intrinsic thin-layer) solar cells began in the early 1990s. **Sanyo Electric Co.** in Japan was the first to create a viable HJT solar cell device and coined the term “HIT” for this technology. In 1992, *M. Tanaka et al.* reported a heterojunction cell consisting of a thin *p*-type amorphous silicon layer on an *n*-type crystalline silicon wafer, achieving about 12% conversion efficiency[2]. Shortly thereafter, Sanyo researchers discovered that inserting an ultrathin intrinsic a-Si:H layer between the wafer and the doped a-Si layers dramatically improved performance. The intrinsic layer effectively passivated surface defects at the c-Si/a-Si interface. By reducing recombination, it increased all key parameters – V_{OC} , short-circuit current (I_{SC}), and fill factor – raising the efficiency from ~12.3% to about 14.8% in those early cells (with an optimal intrinsic layer thickness around 6–7 nm)[2]. This innovation gave the HIT cell its name and marked the first major milestone in HJT development.

Throughout the late 1990s and 2000s, Sanyo continued to refine the HIT cell technology and brought it into commercial production. By texturing the silicon wafer surface (to form pyramids that trap light) and improving the quality of the amorphous silicon and transparent conductive oxide (TCO) layers, Sanyo steadily pushed efficiencies higher. In 2003, Sanyo reported a HIT cell exceeding 21% efficiency, a world-leading result at that time. By 2009, *Tsunomura et al.* had achieved ~22% efficiency in a HIT cell (with a 100 cm² area), and Sanyo announced a prototype cell with 23% efficiency that same year[2]. These improvements were driven by better surface passivation, enhanced light trapping, and reduced resistive losses in the cells.

In 2010, Panasonic Corporation acquired Sanyo and further advanced the HJT technology. Panasonic’s HIT cells set multiple efficiency records in the early 2010s, thanks to process optimizations and superior material quality. By 2014, researchers at Panasonic (*Masuko et al.*) achieved a landmark efficiency of **25.6%** on a heterojunction cell[2], breaking the 25% barrier that had long been the realm of laboratory silicon cells. This record was accomplished on a full-size cell using an *n*-type CZ silicon wafer and demonstrated the enormous potential of HJT design for high performance.

Another breakthrough came in 2017 when *Yoshikawa et al.* from Kaneka Corporation reported a heterojunction cell with interdigitated back contacts that reached **26.7%** efficiency[2][4]. This cell, combining HJT technology with a back-contact architecture (often termed HBC – heterojunction back-contact), eliminated front grid shading and further improved current collection. It achieved a short-circuit current density J_{SC} of ~42.7 mA/cm² – an exceptionally high value for silicon cells[4]. The Kaneka result highlighted that marrying HJT with other advanced designs (like back-contact layouts) could yield even higher efficiencies.

Recent years (2020s): As patents on the original HIT technology expired (around 2010), many companies and research institutes worldwide began investing in HJT development[5][1]. Manufacturers in China and Europe set up HJT production lines, seeing it as a successor to the now-ubiquitous PERC technology[1]. This has led to rapid efficiency gains through industry R&D. Chinese companies in particular have made headlines by continuously pushing HJT efficiencies in mass production. For example, **LONGi Green Energy** announced a new world record in December 2023 with a 27.09% efficient cell using a heterojunction back-contact design[6]. This surpassed their previous ~26.8% record from 2022 and was independently certified, demonstrating that HJT can reach ~27% efficiency on full-size wafers[6]. Moreover, when combined in tandem with a high-bandgap top cell (such as a perovskite solar cell), HJT bottom cells have helped achieve **tandem efficiencies** well above the single-junction limit – for instance, LONGi also reported a 33.9% efficient silicon-perovskite tandem cell in 2023[4]. Figure 1 below summarizes the basic structure of a modern HJT solar cell, which has evolved from the early Sanyo designs into today’s high-efficiency devices.

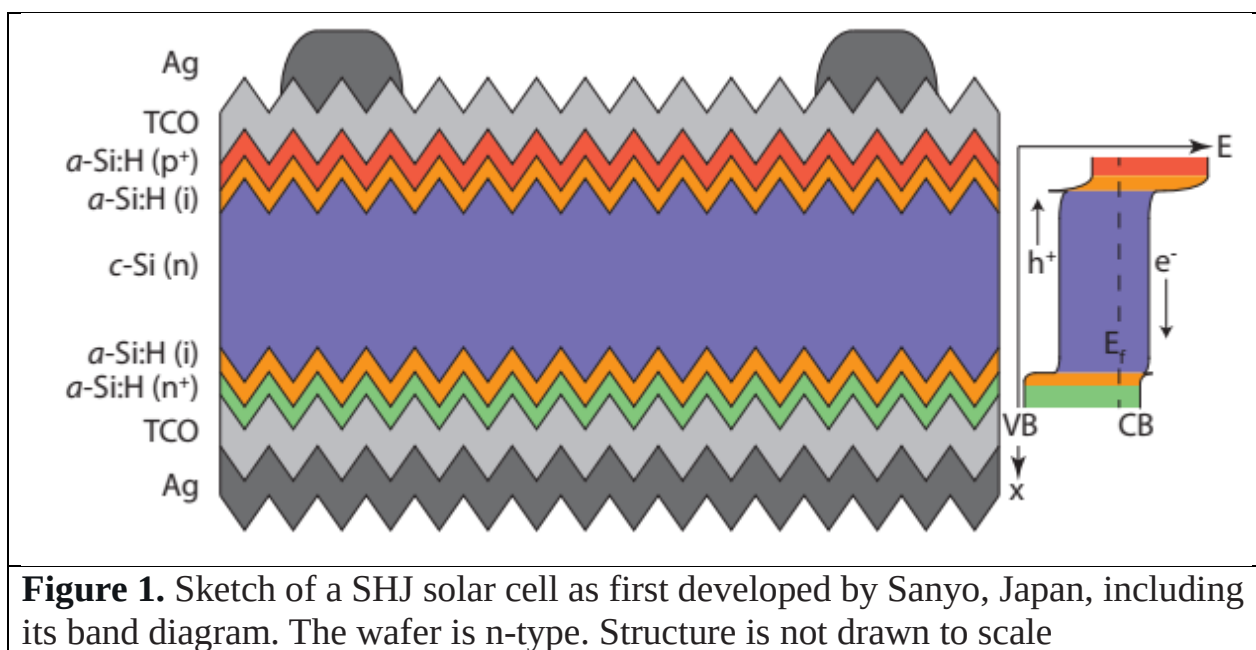


Figure 1: Cross-sectional diagram of a typical silicon heterojunction solar cell (HJT) structure. In this design, an n-type crystalline silicon wafer (blue) is sandwiched between thin amorphous silicon layers: an intrinsic a-Si:H passivation layer (light blue) and p+/n+ doped a-Si:H layers (orange and dark blue) forming the emitter and back surface field. A transparent conductive oxide layer (gray, e.g. indium tin oxide, ITO) coats the a-Si layers, serving as an anti-reflection coating and electrode. Metal contacts (dark gray pads/busbars) collect current. The wafer surfaces are textured with pyramidal features (zig-zag pattern) to enhance light trapping[3]. This combination of

materials and structure yields high efficiency by reducing recombination at surfaces and selectively collecting charge carriers through the heterojunctions.

Structure and Working Principle

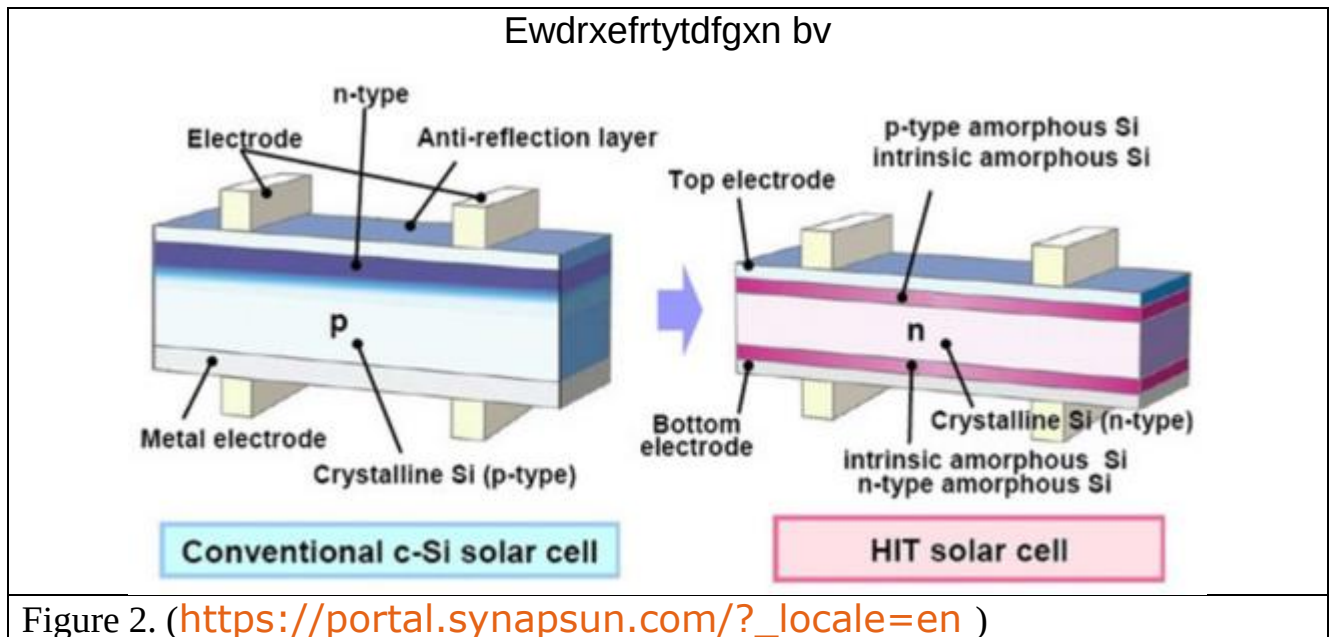


Figure 2. (https://portal.synapsun.com/?_locale=en)

Heterojunction is another type of structure of a solar cell. It is a combination of 2 technologies, a base layer of crystalline polysilicon in between 2 layers or amorphous polysilicon. This structure allows to collect more energy out of the solar radiation. As a result the cells have a higher efficiency. Moreover, it has a lower temperature coefficient allowing better performance at high temperature. On top of that, heterojunctions cells are bifacial.

The HJT solar cell operates on the same fundamental principle as a conventional silicon $p-n$ junction solar cell – converting sunlight into electric current via the photovoltaic effect – but its heterojunction design gives it unique characteristics. In a standard configuration, an HJT cell uses an n -type monocrystalline silicon wafer as the absorber (where most light is absorbed and electron-hole pairs are generated). On the sun-facing side of the wafer, a very thin layer of intrinsic (undoped) amorphous silicon (a-Si:H) is deposited, followed by a thin layer of p -type a-Si:H. These amorphous layers together act as the emitter, forming a heterojunction with the n -type c-Si. Similarly, the rear side of the wafer is coated with intrinsic a-Si:H and then n -type a-Si:H, creating the back surface field (BSF) and collector for holes. The intrinsic a-Si:H layers are typically only on the order of 5–10 nm thick, just enough to passivate the crystalline silicon surface without introducing too many defects of their own[2]. The doped a-Si:H layers ($p \sim 10$ nm, $n \sim 20$ nm thick) are kept very thin as well. Covering these silicon layers is a transparent conducting oxide (such as ITO or indium-zinc oxide) ~ 75 – 100 nm thick, which serves as a low-resistance contact layer that allows light to enter. Finally, metal electrodes

(usually fine silver or copper grid lines) are applied on the front and rear to collect the generated current.

The **heterojunction** refers to the interface between the crystalline silicon and the amorphous silicon. Because amorphous silicon has a wider bandgap (~ 1.7 eV) than crystalline silicon (~ 1.12 eV)[4], the p -a-Si:H/ n -c-Si junction behaves differently than a homojunction. The band diagram features discontinuities (offsets) in both the conduction and valence bands at the interface. Importantly, the intrinsic a-Si:H layer helps align these bands by creating a graded transition and by reducing defect states. In operation, when sunlight enters the cell, the c-Si wafer absorbs the majority of photons (especially longer wavelengths) and generates electron-hole pairs. The built-in electric field of the heterojunction (a depletion region forms primarily in the c-Si near the interface) drives electrons toward the n -type side and holes toward the p -type side. The amorphous emitter layer, despite being only ~ 10 nm, is sufficiently doped to provide selectivity for holes: it allows holes to pass but blocks most electrons, thus working as a “hole-selective contact”. The opposite occurs at the back n -type a-Si:H layer, which is selective for electrons. Meanwhile, the intrinsic a-Si:H layers at both interfaces dramatically reduce surface recombination by “passivating” dangling bonds on the c-Si surface (hydrogen in the a-Si:H bonds to silicon surface atoms, mitigating defect states)[3]. This passivation is what enables HJT cells to reach very high open-circuit voltages V_{OC} (~ 0.73 – 0.75 V in state-of-the-art devices, compared to ~ 0.65 V for typical diffused junction silicon cells)[4].

Another advantage is that the amorphous silicon layers serve as excellent emitters even without high-temperature processing. Traditional solar cells form a p - n junction by diffusing dopants into the silicon wafer at temperatures > 800 °C (e.g. creating a p -diffused emitter on an n -type wafer). In HJT, the junction is formed at low temperature by deposition of p -type a-Si:H (~ 200 °C), which is much gentler on the wafer and avoids thermal damage. Moreover, because HJT cells typically use n -type silicon wafers, they do not suffer from light-induced degradation mechanisms like the boron-oxygen complexes that plague p -type PERC cells. The use of n -type wafers, coupled with excellent surface passivation, gives HJT cells very stable performance over time and under illumination[1].

Better Bifacial Performance

HJT cells are often designed to be **bifacial** as well(Figure 3) – meaning they can collect light from both front and rear surfaces. Since both sides of the cell have a symmetric structure (silicon wafer with a-Si layers and transparent conductive coating), an HJT cell naturally lends itself to generating current from light that strikes the rear side (for instance, reflected light from the ground).

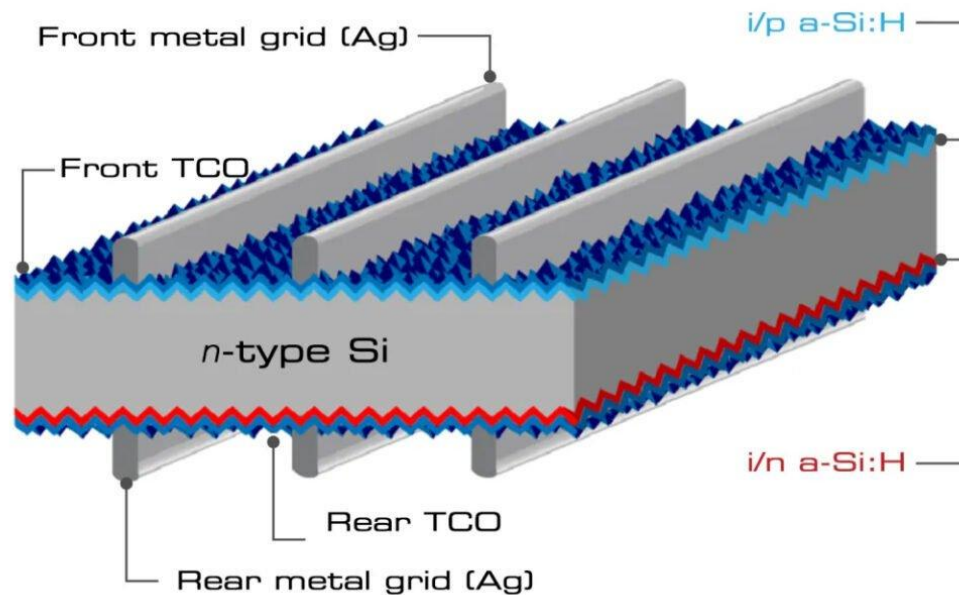


Figure 3. Typical bifacial HJT solar cells scheme in front junction configuration.
([10.13140/RG.2.2.29803.25124](#))

HJT solar cells have a unique design with symmetrical front and back structures, enhancing their bifacial power generation. These cells achieve over 95% efficiency on the rear side, significantly boosting overall energy output. Their transparent dual-glass design allows light to pass through, improving rear-side generation, and making them ideal for applications like fences and carports. Compared to PERC and TopCon technologies, HJT cells can produce over 30% more energy, making them highly effective for installations where both sides of the panel receive sunlight.

Bifacial HJT modules can therefore produce additional energy (the “bifaciality factor” of HJT cells is typically ~90%, indicating the rear side current is about 90% of the front side under equal illumination[7]). This is significantly higher than bifacial PERC cells, due to HJT’s transparent rear structure and superior surface passivation on both sides.

In summary, the structure of HJT solar cells integrates multiple design innovations: a high-quality *n*-type silicon absorber, ultrathin intrinsic and doped amorphous silicon layers for passivation and charge selectivity, and transparent conductive coatings for light coupling and current collection. Together, these enable high efficiency by

maximizing the collection of photogenerated carriers while minimizing recombination losses. The next section will discuss how these cells are manufactured in practice.

Fabrication Methods of HJT Solar Cells

One of the attractive aspects of HJT technology is that it can be manufactured with relatively few processing steps, all at low temperatures, compared to conventional silicon cells. However, it does require specialized equipment for depositing the thin-film layers and careful handling of wafer surfaces. Below is a step-by-step overview of the typical fabrication process for a silicon HJT solar cell:

Wafer Preparation (Texturing & Cleaning): The process starts with *n*-type monocrystalline silicon wafers (commonly Cz-Si). The wafers are chemically *textured* to create a pyramid pattern on the surface for light trapping. This is usually done by anisotropic etching in an alkaline solution (e.g. potassium hydroxide, KOH) which etches the silicon in a crystallographically selective way, forming microscopic pyramids[3]. After texturing, a rigorous cleaning sequence is performed because HJT cells are very sensitive to surface contamination. Standard RCA cleaning steps are used (acid cleans to remove organic residues and metal ions, oxide etch to remove the native oxide) to ensure an atomically clean, hydrophobic silicon surface[4]. Any remaining oxide is typically etched just before deposition of the amorphous silicon to ensure good electronic contact.

Intrinsic and Doped Amorphous Silicon Deposition: Next, the wafer is loaded into a plasma-enhanced chemical vapor deposition (**PECVD**) system. PECVD is used to deposit the hydrogenated amorphous silicon layers. First, a thin intrinsic a-Si:H layer is deposited on both sides of the wafer (one side at a time, or in some tools, both sides sequentially without breaking vacuum). This intrinsic layer might be only ~5–10 nm thick, requiring precise control. Immediately following, a *p*-type a-Si:H layer (containing dopants like trimethylboron for *p*-type) is deposited on the sun-facing side, and an *n*-type a-Si:H layer (doped with phosphine for *n*-type) on the rear side. Deposition temperatures are on the order of 180–200 °C[2] – a key advantage of HJT is avoiding high-temperature diffusions. The PECVD process parameters (gas mixtures, RF power, pressure) are tuned to produce amorphous films with low defect density and the desired thickness. Because the amorphous layers are so thin, deposition must be uniform and well-controlled to avoid pinholes or thickness non-uniformity that could affect performance.

Transparent Conductive Oxide (TCO) Coating: After the silicon layers, a transparent conductive oxide layer is added to each side. Commonly, indium tin oxide (ITO) is used due to its high conductivity and transparency. TCO deposition is often done by sputtering (a physical vapor deposition technique) at low temperatures. The TCO serves multiple purposes: it acts as an anti-reflection coating (reducing surface reflection of light), provides lateral electrical conductivity to collect current from the amorphous layers, and also adds additional passivation by field effect. Recent developments have also explored indium-free TCOs (like doped zinc oxide or indium-

zinc oxide) to reduce cost, as well as very thin TCOs in back-contact designs[6]. The thickness of the TCO is typically ~75–100 nm on the front (optimized for anti-reflection at ~600–800 nm wavelengths) and similar on the rear if bifacial.

Metallization (Grid Electrode Formation): The final step is to form the metal contacts that will carry current out of the cell. Traditional screen-printing of silver paste can be used, but standard high-temperature Ag pastes (fired at ~750 °C in PERC cells) cannot be used on HJT because such temperatures would damage the a-Si:H layers. Instead, **low-temperature silver pastes** or alternative metallization techniques are required[4]. One approach is screen-printing a specially formulated silver paste that can be cured at around 200 °C. Another approach that has gained traction is **electroplating**: first, a seed layer of metal is applied (for example, by inkjet printing a nanoparticle ink or light-induced plating), then a thicker copper or silver layer is plated to form the fingers. This can dramatically reduce silver consumption (since copper can replace most of the finger volume)[4]. Some companies use *smart-wire* interconnection where many thin wires are laminated onto the cell, eliminating conventional busbars[1]. In any case, the front grid is made very fine (to reduce shading losses), often with multi-busbar designs or even *zero busbar* (busbar-less) configurations using wires. The rear side of a bifacial HJT cell also has a grid, usually aluminum or silver, but these can cover a larger area since rear shading is less critical than front shading. After metallization, the cell is essentially complete and ready for testing and assembly into modules.

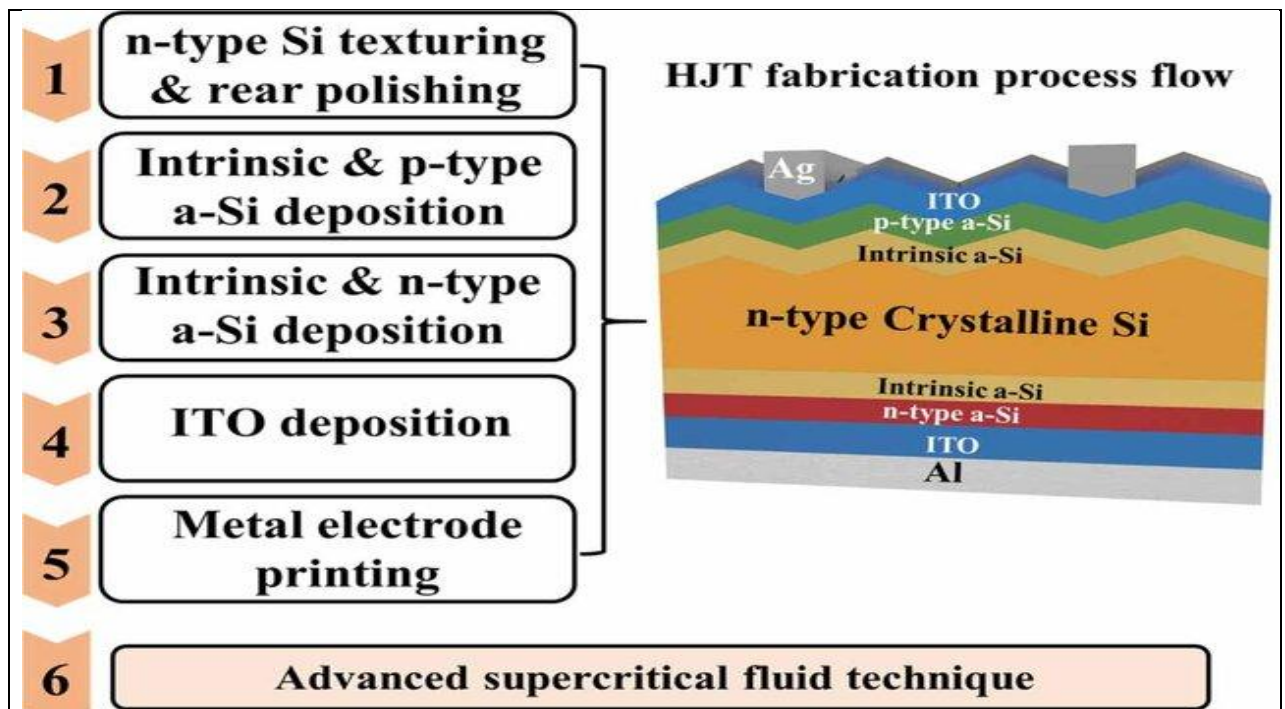


Figure 4. Heterojunction (HJT) solar cell fabrication process flow and device structure.

Throughout fabrication, maintaining low thermal budget is crucial – the entire HJT process flow keeps temperatures typically below $\sim 250^\circ\text{C}$. This low-temperature processing preserves the excellent electronic quality of the n -type silicon wafer (no thermal degradation or impurity diffusion from furnace steps) and retains hydrogen in the amorphous silicon for passivation. It also means HJT lines could potentially use thinner silicon wafers without warping them (in fact, HJT cells can be made on $\sim 100\ \mu\text{m}$ or thinner wafers, whereas conventional cells $\sim 160\text{--}180\ \mu\text{m}$, because HJT doesn't subject them to high heat)[4]. On the flip side, the requirement for new equipment (PECVD, sputtering, low-temp metallization) and the use of expensive materials (like indium for ITO, and more silver per cell due to screen printing limitations) have historically made HJT manufacturing more costly than PERC cell manufacturing[4]. As of around 2018, producing HJT modules was estimated to cost a few cents per watt more than PERC, though this gap has been shrinking with economies of scale and technology improvements. For instance, advancements in paste and plating are reducing silver usage, and newer high-throughput tools have lowered the capital expenditure for HJT factories significantly by 2020[4].

In summary, HJT fabrication involves a mix of silicon wafer processing and thin-film deposition techniques. The process flow is relatively short (no diffusion, no high-temperature anneals) but demands high precision and cleanliness. The resulting cell is a multilayer structure (c-Si/a-Si/TCO/metals) that embodies the strengths of both crystalline and thin-film PV technologies.

Performance and Characteristics of HJT Cells

Heterojunction solar cells are among the top performers in the field of photovoltaics. They are notable for their **high efficiency**, excellent temperature performance, and stable operation. Let us consider some key performance metrics and how HJT cells compare:

Conversion Efficiency: This is the percentage of incident solar power that the cell converts to electrical power. Commercial HJT modules today achieve efficiencies around 22–24%, and laboratory HJT cells have reached nearly 27% efficiency (as noted earlier)[4][6]. Such high efficiencies result from the combination of a high V_{OC} , high J_{SC} , and fill factors often above 80–82%. For example, Panasonic's 25.6% cell had a V_{OC} of $\sim 0.745\ \text{V}$, $J_{\text{SC}} \sim 41\ \text{mA}/\text{cm}^2$, and FF ~ 0.85 [2]. The record 26.7% Kaneka cell (HBC structure) achieved $V_{\text{OC}} \approx 0.750\ \text{V}$ and $J_{\text{SC}} \approx 42.7\ \text{mA}/\text{cm}^2$ with a fill factor ~ 0.89 [4] – incredibly “square” I-V characteristics. These numbers are substantially better than typical PERC cells (which might have $V_{\text{OC}} \sim 0.68\ \text{V}$ and $J_{\text{SC}} \sim 38\ \text{mA}/\text{cm}^2$ at $\sim 22\%$ efficiency). We will quantify efficiency calculation in the next section.

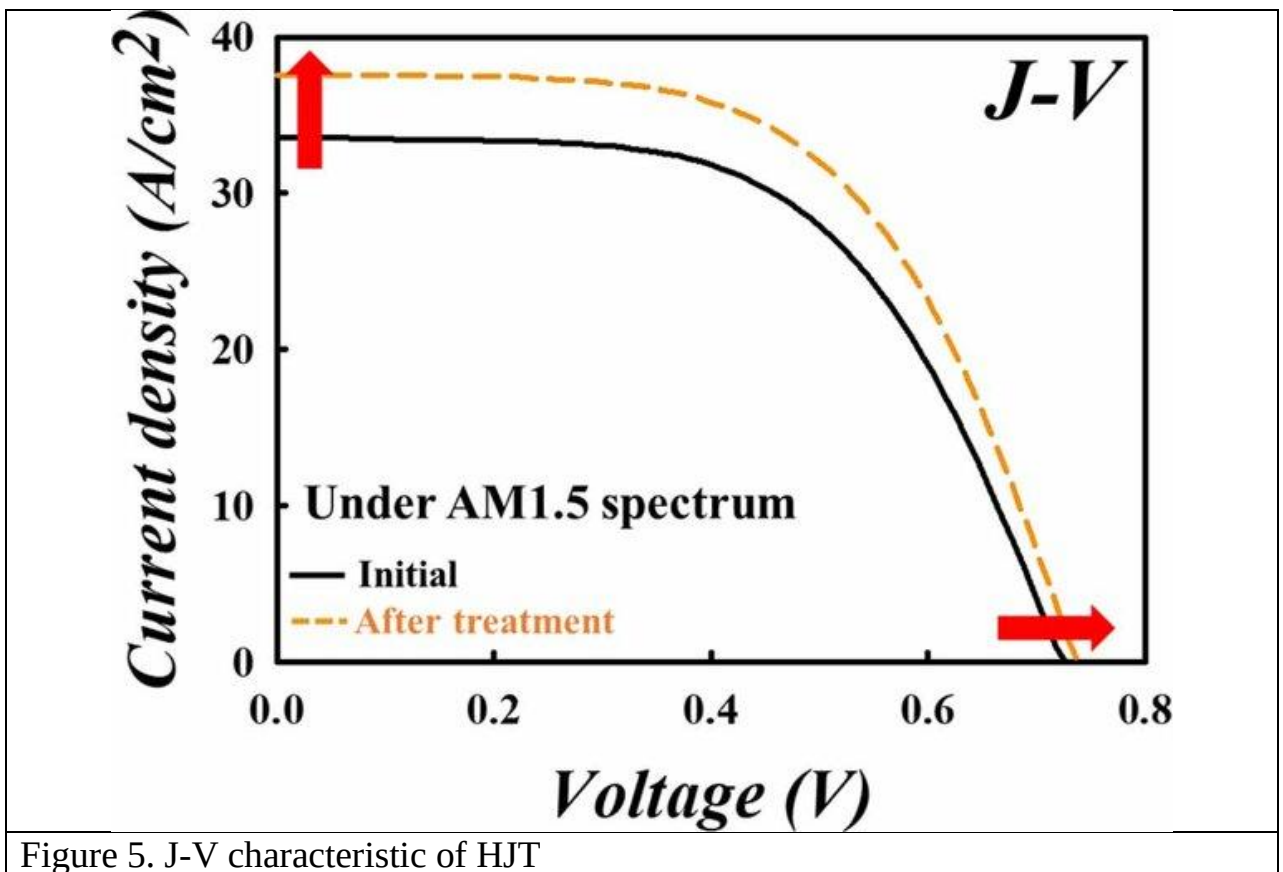


Figure 5. J-V characteristic of HJT

Temperature Coefficient: Solar cells generally produce less power at higher temperatures. The temperature coefficient (% power drop per °C) for HJT cells is remarkably low, around -0.20 to $-0.25\%/^{\circ}\text{C}$ [7]. This is better (less negative) than for standard silicon cells like PERC (around -0.35 to $-0.40\%/^{\circ}\text{C}$) [7]. The reason is partly the higher bandgap of the amorphous layers and excellent surface passivation, which make the V_{OC} less sensitive to temperature. In practical terms, HJT modules maintain a higher fraction of their output on hot days, yielding more energy in climates with high operating temperatures.

I-V Characteristics: The current–voltage curve of an HJT cell has the typical shape of a silicon diode under illumination, but with a high V_{OC} as mentioned. One nuance is that standard HJT cells can exhibit slightly lower short-wavelength response than some other cells – the p -type a-Si:H emitter can absorb a bit of blue light (since a-Si has a higher absorption coefficient in the blue), and the ITO and front surface can also cause some losses[4]. Consequently, the short-circuit current J_{SC} of a conventional bifacial HJT cell on a flat wafer is often a few mA/cm^2 less than a premium diffused-junction cell that has a shallow emitter (which is why Kaneka moved the contacts to the back in their record cell to avoid any front a-Si:H). Nonetheless, HJT cells easily achieve J_{SC} in the high-30s (mA/cm^2) for textured cells, and approaching $40 \text{ mA}/\text{cm}^2$ for advanced designs[4]. The fill factor of HJT cells is

typically very high because the contact resistance can be made low (TCO helps spread current) and recombination is low, yielding ideal diode behavior. Fill factors above 80% are common, and ~85–88% in record cells[4].

Bifacial and Low-Light Performance: Thanks to low recombination losses, HJT cells tend to have good performance at low light intensities (they maintain relatively high voltage and the series resistance is low due to TCO grid). Additionally, as bifacial cells, they can utilize reflected light. The bifacial gain can improve energy yield by 5–20% depending on the installation. A bifacial factor of ~90% for HJT means if the rear side is equally illuminated, it produces about 90% of the front side current, far higher than for PERC bifacial (~70%)[7].

Stability and Degradation: HJT cells show excellent stability. They inherently avoid **light-induced degradation (LID)** associated with the boron-oxygen defect, because they use *n*-type wafers (phosphorus-doped). There is also negligible **potential-induced degradation (PID)** in modern HJT modules due to effective encapsulation and the absence of porous coatings. Some concern exists about long-term stability of a-Si:H passivation (hydrogen could slowly effuse or metastable defects form, akin to Staebler-Wronski effect in a-Si), but in practice HJT modules have demonstrated very low degradation rates (e.g. <0.25% per year power loss), on par with the best silicon technologies[1][4]. Manufacturers often guarantee 90% of initial power even after 25–30 years for HJT modules. This is partly due to the cell design and partly due to using primarily *n*-type silicon which has no B-O LID and better tolerance to impurities[4].

In conclusion, HJT solar cells deliver a combination of high efficiency and robust performance. They excel in V_{OC} and thermal performance, making them particularly effective in real-world conditions (where panels heat up). The only performance area where HJT might lag slightly is initial cost and perhaps slightly lower absolute J_{SC} compared to some new *TopCon* cells (which we discuss next). The following table (Table 1) provides a comparison of key parameters between HJT cells and other mainstream silicon cell technologies, highlighting HJT's strengths:

Table 1: Comparison of Silicon Solar Cell Technologies (lab efficiencies and typical characteristics)[34]

Cell Technology	Best Efficiency PCE)	Lab (%)	Temperature Coefficient (%/°C)	Bifaciality Factor (%)	Market Share (Year)
PERC (Al-BSF p-type)	~24.5% [7]		−0.35 to −0.40	~70%	~75% (2021)
TOPCon (n-type)	~26.1% [7]		~−0.30	~85%	~8% (2020)
HJT (n-type)	~26.5% [7]		~−0.21]	~92%]	~2.5% (2021)

Table 1: PERC = Passivated Emitter Rear Cell (the current industrial standard using p-type silicon); TOPCon = Tunnel Oxide Passivated Contact (a high-efficiency n-type cell with a diffused emitter and polysilicon passivating rear); HJT = Heterojunction with intrinsic thin layer. Data reflect approximate best values reported as of 2020–2021. HJT achieves the highest lab efficiency and best temperature coefficient among these, but in 2021 had a small market share. (Sources: Solar Magazine and industry reports[\[7\]](#).)

It’s worth noting that since 2021–2022, TOPCon and HJT have both advanced; by 2023, both technologies exceeded 26% in production prototype cells, and manufacturers are transitioning from PERC to these next-generation cells. HJT in particular is poised for growth due to its bifacial advantage and simpler process sequence (despite the current higher materials cost). In the next section, we will discuss how to calculate efficiency and interpret the I-V characteristics of a solar cell in more detail, which is important for understanding the performance figures mentioned.

Efficiency and I–V Characteristic Calculations

Solar Cell I–V Curve: The current–voltage (I–V) characteristic of a solar cell under illumination is a crucial tool to evaluate its performance. Figure 6 illustrates a typical I–V curve for a solar cell, showing the key points: the short-circuit current (I_{SC}) at zero voltage, the open-circuit voltage (V_{OC}) at zero current, and the maximum power point (MPP) where the product $I \cdot V$ is maximized. The shape of the curve is governed by the diode equation of the junction with the light-generated current. For an ideal cell, the I–V relation can be written as:

$$I(V) = I_L - I_0(e^{qV/nkT} - 1),$$

where I_L is the light-generated current (which equals I_{SC} at $V=0$), I_0 is the saturation dark current of the diode, q is the electron charge, n is the ideality factor, kT the

thermal voltage. The result is a curve that starts at I_{SC} (maximum current at $V=0$) and ends at V_{OC} (voltage where current drops to zero). The **fill factor (FF)** is a measure of how “square” the I-V curve is – it is defined as the ratio of the maximum power ($V_{mp} \cdot I_{mp}$) to the product $V_{OC} \cdot I_{SC}$. A higher FF means the cell maintains high current until close to V_{OC} (a more rectangular I-V shape). HJT cells often have FF in the 0.80–0.85 range, indicating a very good diode with low resistive losses.

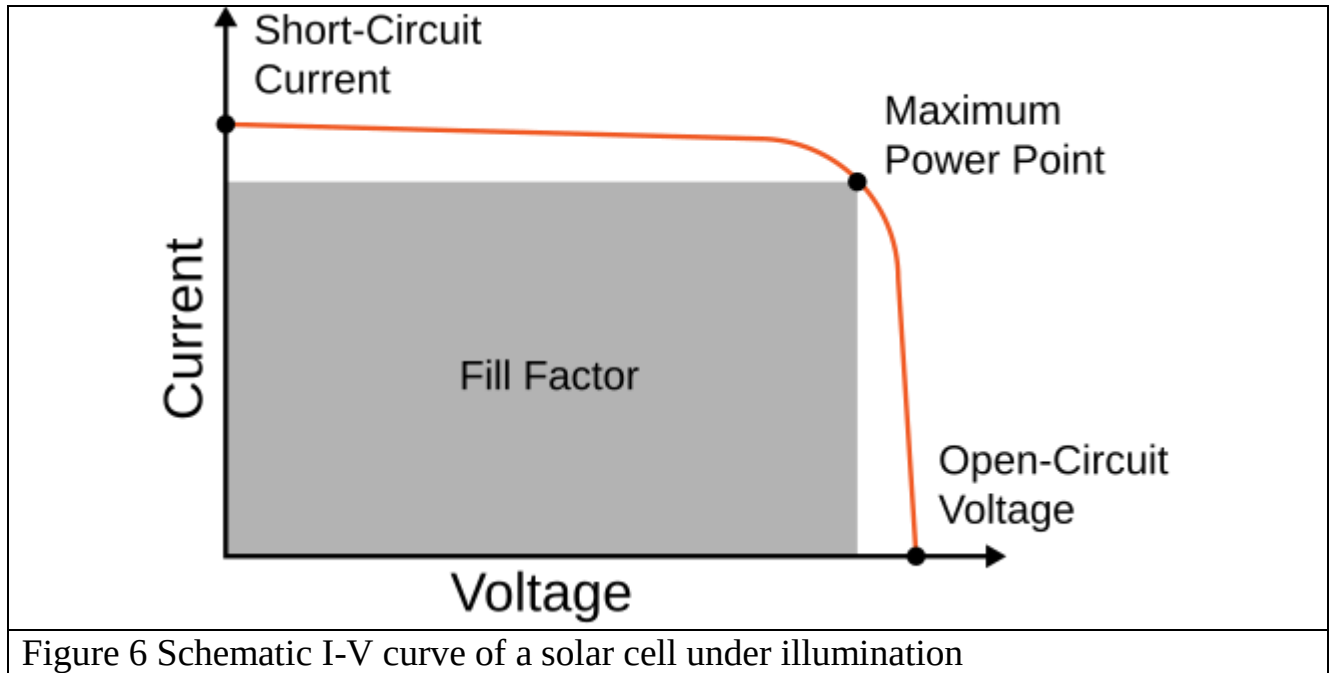


*Figure 6: Schematic I-V curve of a solar cell under illumination. **Key parameters are indicated:** I_{SC} is the short-circuit current (y-intercept, at $V=0$), V_{OC} is the open-circuit voltage (x-intercept, at $I=0$). The shaded gray area represents the maximum rectangular area that fits under the curve, whose height and width correspond to the current (I_{mp}) and voltage (V_{mp}) at the maximum power point (MPP). The fill factor (FF) is the ratio of that area to the product $I_{SC} \cdot V_{OC}$, indicating the “squareness” of the curve. A higher FF (closer to 1) means the cell delivers a high fraction of the theoretical maximum power.[8]*

Using the I-V curve, the **efficiency (η)** of the cell can be calculated. Efficiency is defined as the maximum output power divided by the incident light power input. If P_{in} is the incident light power on the cell (for standard test conditions, $P_{in} = 1000 \text{ W/m}^2$ or 100 mW/cm^2), and the cell’s maximum power point has voltage V_{mp} and current I_{mp} , then:

$$\eta = \frac{V_{mp} \times I_{mp}}{P_{in} \times A} \times 100\%,$$

where A is the cell area (so that $I_{mp} \cdot V_{mp}$ is the power, and dividing by area gives power per unit area). Often, this formula is simplified using V_{OC} , I_{SC} , and FF, since $V_{mp} \cdot I_{mp} = FF \cdot V_{OC} \cdot I_{SC}$. Thus:

$$\eta = \frac{V_{OC} \times I_{SC} \times FF}{P_{in} \times A} \times 100\%.$$

For example, consider a high-performance HJT cell with $V_{OC} = 0.74$ V, $I_{SC} = 38$ mA/cm² (which is 0.038 A/cm²), and FF = 85%. If the cell area is 1 cm² (for simplicity) and $P_{in} = 0.10$ W/cm², then the efficiency would be:

$$\eta = \frac{0.74 \times 0.038 \times 0.85}{0.10} \times 100\% \approx 23.9\%.$$

This rough calculation shows how close the parameters need to be for reaching ~24% efficiency. If I_{SC} is increased to 40 mA/cm² and FF to 88%, we get into the ~26–27% range, which aligns with record HJT cells. The Shockley–Queisser limit for a single junction (33.7%) and the refined Si limit ~29.4%[\[2\]](#) basically set the upper target – HJT cells are now within a few percentage points of this ceiling, so further gains will be challenging and usually require tandem configurations.

The **volt-ampere (V-A) characteristics** of different solar cell types can vary in their V_{OC} , I_{SC} , and FF, which is why one technology outperforms another in efficiency. HJT's high V_{OC} is a major differentiator (due to excellent surface passivation yielding low recombination current I_0). TOPCon cells, for instance, also have high V_{OC} (close to HJT) but might have slightly higher recombination at contacts. PERC cells generally have lower V_{OC} because of more recombination at the metal contacts and in the bulk (especially p -type bulk with boron). The I-V curve of a PERC cell might start at a higher I_{SC} (because no front a-Si:H to absorb blue light), but it will have a lower V_{OC} * (~0.67 V) and slightly lower FF (~80%), ending up with a lower area under the curve (i.e., lower efficiency) compared to HJT.

In practice, to determine a cell's efficiency, one measures the I-V curve under standard test conditions (STC: 1000 W/m², 25 °C cell temperature, AM1.5 spectrum). The I_{SC} is measured directly (current at zero bias), V_{OC} is measured (voltage at open circuit), and the full I-V sweep is recorded. The maximum power point is found either by calculation or by using a tracker circuit. Modern solar simulators and IV testers do this automatically and compute FF and efficiency. For any solar cell including HJT, confirming these parameters under standardized conditions allows fair comparison.

To summarize this section: **the efficiency of a solar cell is calculated from the product of V_{OC} , I_{SC} , and FF divided by the input power**, and heterojunction cells

excel by having superior V_{OC} and high FF, while maintaining competitive I_{SC} . The I-V characteristic of HJT is nearly ideal with a steep drop near V_{OC} , indicating low recombination and resistive losses – a hallmark of a well-passivated, high-quality junction.

Recent Advances and Emerging Trends in HJT Technology

HJT solar cells continue to evolve, with researchers and industry pushing the boundaries in several ways. Below are some of the notable recent advances and trends:

Heterojunction with Back Contact (HBC) Cells(Figure 7): By combining the HJT concept with interdigitated back contacts (IBC), researchers have created HBC cells that eliminate the front grid and front amorphous emitter entirely. All contacts (both n and p) are on the rear in an interdigitated pattern. This approach, as demonstrated by Kaneka's 26.7% cell[4], allows more light to enter (no front metal shading, and in some designs no front a-Si layers absorbing light). The challenge with HBC is more complex patterning on the rear (alternating p and n contact regions), which traditionally required photolithography. However, companies like LONGi have developed laser patterning techniques to simplify manufacturing of HBC HJT cells[6]. The December 2023 LONGi record (27.09%) was indeed an HBC cell made with an *all-laser* process for doping pattern formation[6]. HBC cells also reduced the usage of TCO layers (since only the front needs a full-area TCO for anti-reflection, and rear contacts are local) – LONGi noted using only 1/5th the indium of a bifacial cell in their record device[6]. Going forward, HBC HJT cells might be used in applications demanding highest efficiency or where one side is not exposed (e.g. building-integrated PV with opaque backing).

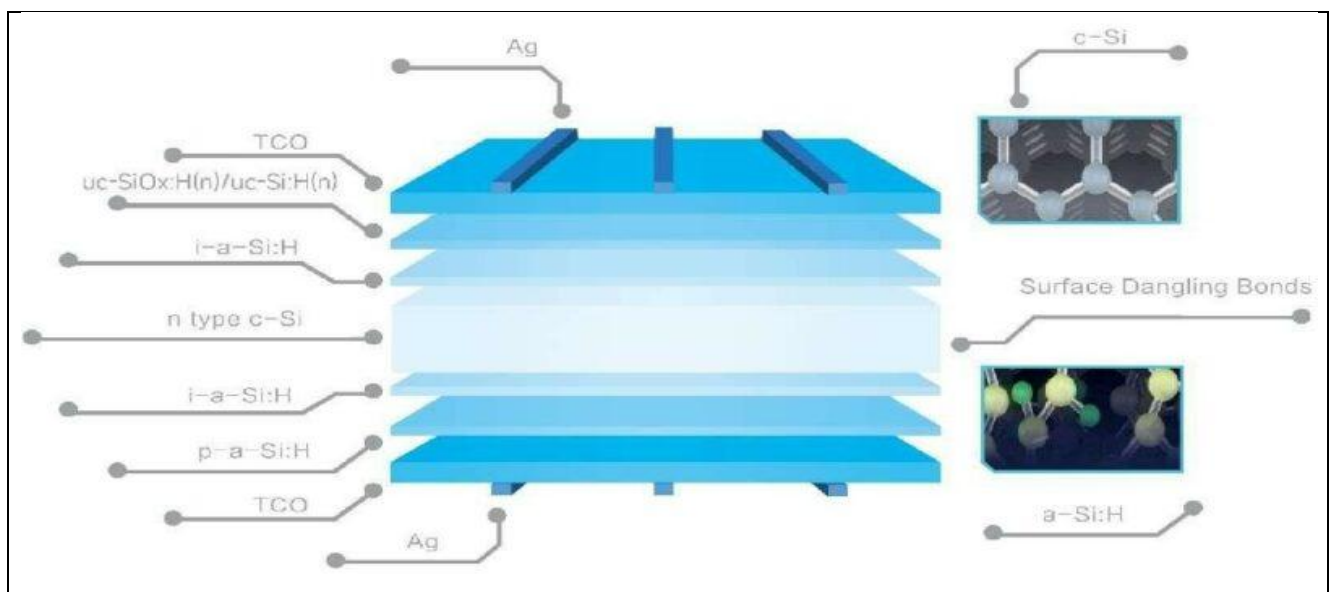


Figure 7. **Heterojunction with Back Contact (HBC) Cells**

Tandem Solar Cells (Perovskite/Si Heterojunction)(Figure 8): Perhaps the most exciting development is integrating HJT cells as the bottom cell in **tandem** architectures to beat the single-junction efficiency limit. Silicon heterojunction is an ideal bottom cell for tandem because of its high V_{OC} and the fact that its top layer (TCO) is already transparent, allowing a top cell to be added. The most common pairing is with a perovskite solar cell as the top cell (perovskites have tunable bandgaps $\sim 1.7\text{--}1.8\text{ eV}$ that complement silicon's 1.12 eV). In a monolithic two-terminal tandem, a perovskite cell is deposited directly on top of a prepared HJT bottom cell. Researchers have demonstrated perovskite/SHJ tandems exceeding **30% efficiency** in the last couple of years[4]. For instance, in 2023 LONGi achieved 33.9% with a monolithic perovskite+HJT tandem[4], and other labs (Oxford PV, HZB Berlin) have also reported $\sim 32\text{--}33\%$ tandem efficiencies. Figure 3 shows a schematic of such a tandem device.

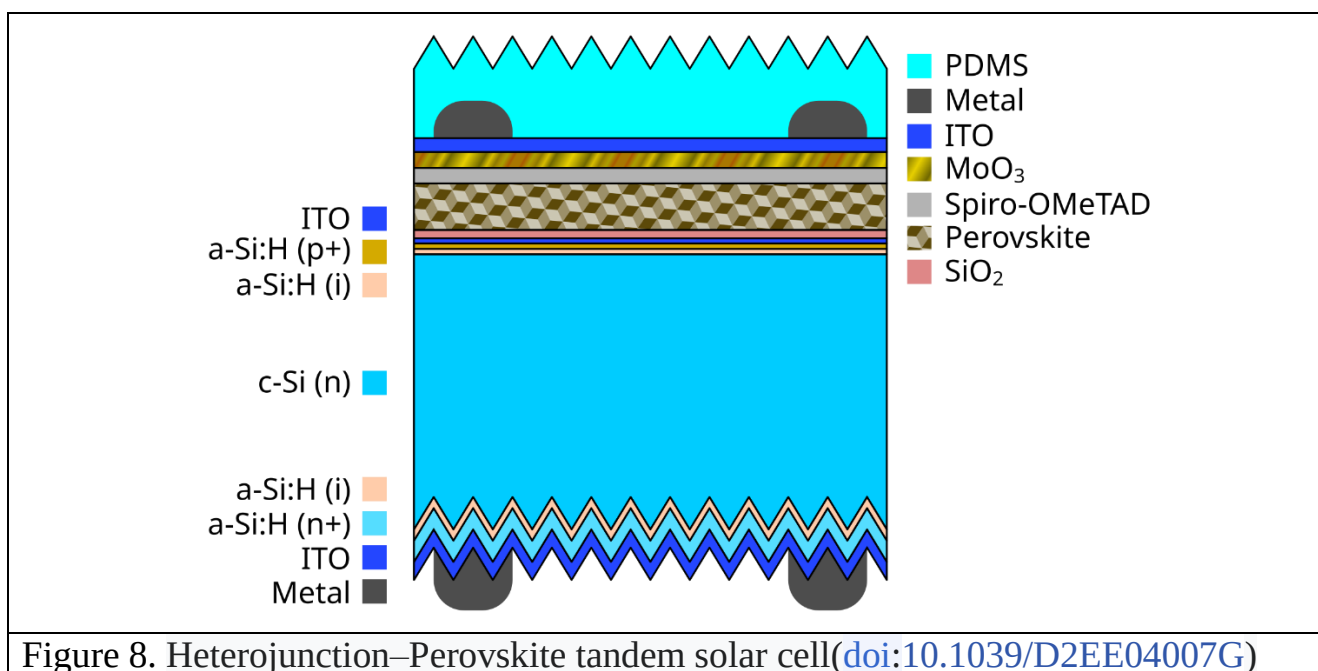


Figure 8: Cross-section of a silicon heterojunction + perovskite tandem solar cell. In this tandem design, a high-bandgap perovskite top cell (upper layers, brown/gold) is stacked on a silicon heterojunction bottom cell (lower layers, blue). The perovskite cell absorbs the higher-energy (short-wavelength) portion of sunlight, while the silicon bottom cell absorbs the lower-energy (longer-wavelength) portion that the perovskite transmits[4]. By splitting the solar spectrum, this dual-junction device can exceed the single-junction efficiency limit. The diagram illustrates one possible configuration: the SHJ bottom cell has its n -cSi absorber (large blue region) with p/i a-Si layers on top and n/i at bottom (blue and pink thin layers), and a transparent front contact that also serves as the bottom contact for the

perovskite cell. The perovskite cell on top consists of layers such as a transparent conducting oxide, electron transport layer, perovskite absorber (gold), hole transport layer, and a top electrode. Light enters from the top, and any photons not absorbed in the perovskite are absorbed by the silicon bottom cell. Such tandem cells have recently achieved ~33–34% efficiency in the lab[4].*

Tandem HJT cells require careful engineering: the interface between the perovskite and the silicon/TCO must be optimized to minimize optical losses and recombination (often a recombination layer or tunnel junction is used to electrically connect the two sub-cells)[9]. There are also challenges with processing – for example, depositing a perovskite layer on top of a finished HJT cell without damaging it (high-temperature processing is off-limits as it would deteriorate the a-Si:H)[9]. Nevertheless, the progress has been rapid, and many expect commercial tandem HJT-perovskite modules in the coming years if stability and scalability of perovskites are resolved. Additionally, research is ongoing with other top-cell materials (III-V semiconductors for multijunctions: e.g. GaInP/GaAs on Si HJT achieving 32–35%[4], though cost is high, or even all-silicon tandems using wide-bandgap silicon compounds).

Organic–Inorganic Hybrid Solar Cells(Figure 9): Organic–inorganic hybrid solar cells are built from a light-absorbing organic donor (typically a conjugated polymer or small molecule) intimately mixed with an inorganic acceptor (such as semiconductor nanoparticles or quantum dots) in a bulk-heterojunction photoactive layer(10). In operation, the organic component absorbs photons to create excitons (bound electron–hole pairs) that diffuse to the organic–inorganic interface. At that junction the exciton dissociates: the electron is transferred into the inorganic phase while the hole remains in the organic phase, and the free charges are then collected at the electrodes

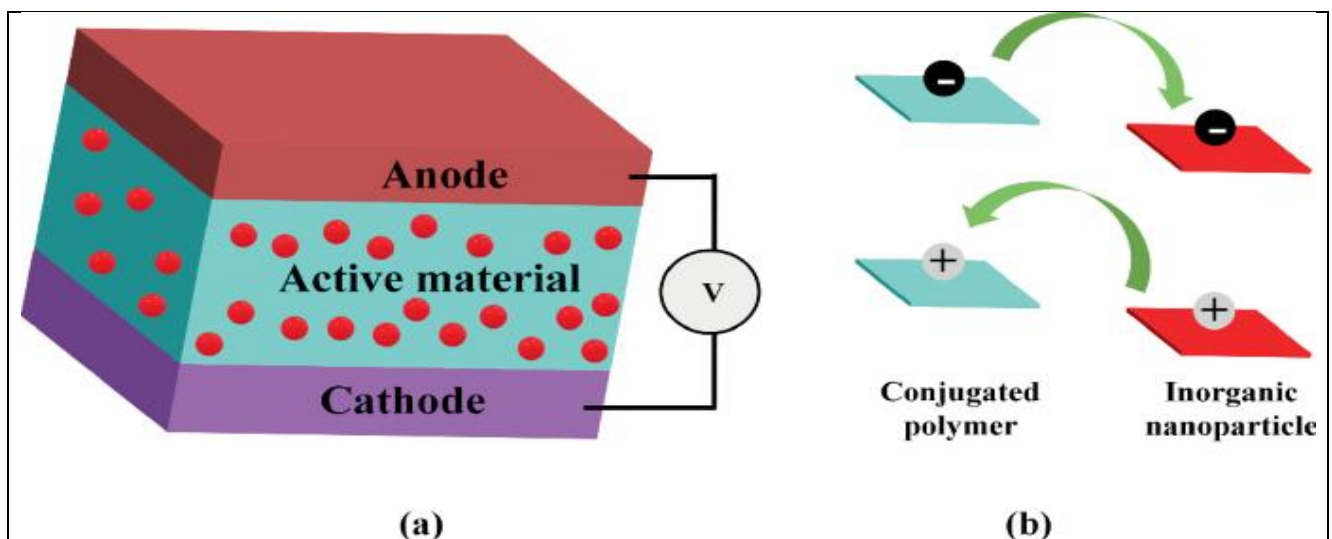


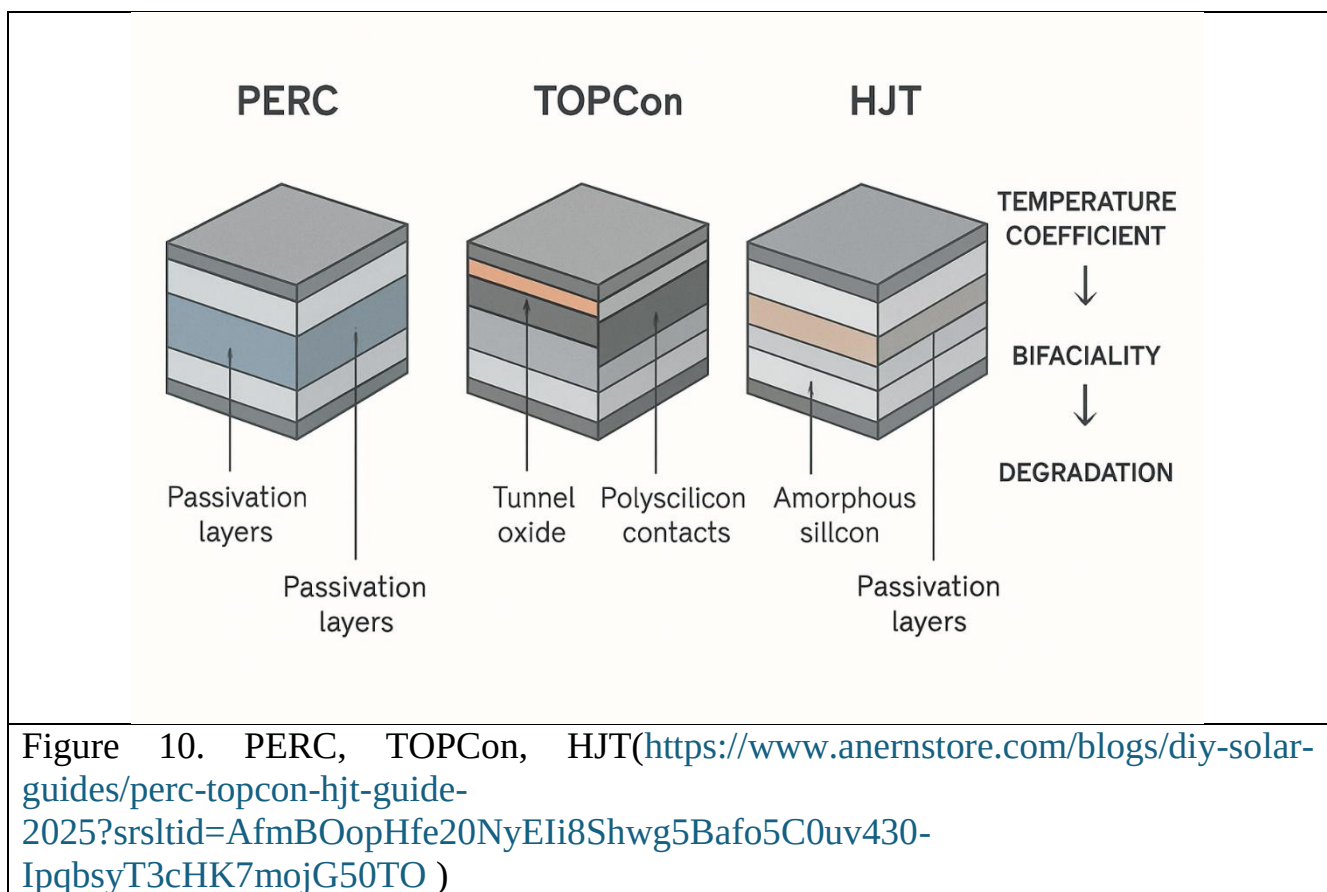
Figure 9. Organic–Inorganic Hybrid Solar Cells (https://doi.org/10.1007/978-981-99-7333-0_6)

This hybrid architecture combines the solution-processability and low fabrication cost of organics with the superior carrier mobility and tunable band-structure of inorganics(11). In practice this means roll-to-roll, large-area manufacturing and the ability to engineer the absorption spectrum (via the inorganic band gap) are possible(12). Inorganic components can also improve device stability and provide high electron mobility, while the organic matrix offers flexibility and low cost(13). Thus, hybrid cells promise low-cost, scalable photovoltaics with adjustable optoelectronic properties, though power conversion efficiencies to date remain modest(14).

Alternative Passivating Contacts: Beyond the classic a-Si:H layers, scientists are exploring other materials to form heterojunction passivated contacts on silicon. Examples include thin films of silicon oxide or molybdenum oxide (MoO_x) for hole-selective contacts, and polycrystalline silicon on thin oxide (as in TOPCon) integrated with HJT. Some hybrid designs use a combination of poly-Si/oxide at one interface and a-Si at the other, aiming to leverage the advantages of both[4]. There have been demonstrations of c-Si/MoO_x heterojunction cells and other novel contacts, though so far the a-Si:H approach still holds the efficiency records when done properly.

Metallization and Module Integration Improvements: Since one of HJT's historical drawbacks was the cost and complexity of metallization, a lot of innovation is happening here. Copper electroplating for grids has been successfully applied, reducing silver usage drastically. Smart Wire Connection Technology (SWCT) uses many fine wires to connect cells, allowing the omission of wide busbars on cells[1]. This not only cuts resistive losses and shading but also can use lower-grade (cheaper) silver paste since the wires provide mechanical support. Moreover, thinner wafers (~100 μm) can be used with HJT to save silicon cost, as long as handling is careful – the good surface passivation means even thin cells can keep high voltages[4]. These incremental improvements collectively aim to make HJT more cost-competitive.

Combining HJT with PERC/TOPCon (Technology Transition)(Figure 10): While not a device structure combination, it's worth noting that many manufacturers are transitioning from PERC to either TOPCon or HJT. Some have explored *hybrid* lines where an existing PERC line is partially converted – e.g. using a diffused emitter like PERC but adding a-Si:H passivating contacts on the rear (a bit like an interim step). However, such combinations (sometimes dubbed HIPER or other acronyms) are not common; generally, HJT is implemented as a full technology replacement because its process flow is distinct. Tandem cells effectively combine HJT bottom with another cell type, as discussed. No significant “tandem PERC” exists because PERC cells are not designed for stacking with another cell (they lack transparency on front). Thus, the combination focus is really HJT with perovskite or HJT with back-contact IBC designs.



Looking ahead, heterojunction technology is poised to play a major role in pushing silicon photovoltaics towards and beyond 30% efficiencies (with tandem) and sustaining high performance in the field. It blends aspects of traditional silicon cells and thin-film technology, giving it a unique position. As manufacturing challenges (like cost of materials and throughput) are being addressed, many expect HJT (and its evolutions like HBC) to gain a much larger market share. In a sense, HJT represents both a **theoretical advancement** – achieving near the limits of single-junction efficiency – and a **practical improvement** – yielding more kWh per kW installed due to better temperature and bifacial performance.

Conclusion

Heterojunction (HJT) solar cells have developed from a novel concept in the early 1990s into one of the leading high-efficiency solar cell technologies today. By marrying crystalline silicon with thin amorphous silicon layers, HJT cells leverage the strengths of both materials: the excellent light absorption and carrier transport of crystalline Si, and the superb surface passivation and carrier-selectivity of a-Si:H heterojunctions. We traced the evolution of HJT cells from the first 12% efficient devices by Sanyo (Tanaka *et al.*, 1992)[2] through successive milestones – 20%+, 25% efficiency – to the latest records around 26–27% in 2023. The key breakthroughs, such as the introduction of intrinsic thin layers and back-contact

architectures, were highlighted. We examined the fabrication of HJT cells, noting the low-temperature PECVD process and specialized metallization required, as well as the implications for manufacturing complexity and cost.

On the performance side, HJT cells stand out for their high open-circuit voltages (approaching 0.75 V) and low recombination losses, translating to superior efficiencies and temperature stability relative to conventional cells. We demonstrated how to calculate efficiency from the IV characteristics and compared HJT with other technologies like PERC and TOPCon, using metrics like fill factor and temperature coefficient to underscore HJT's advantages. Figures were provided to visualize the cell structure, the I-V curve, and even a tandem configuration that pairs an HJT with a perovskite top cell for ultra-high efficiency.

In both theory and application, HJT solar cells represent a fusion of solid-state physics innovation and practical engineering for renewable energy. For undergraduate students and new researchers, HJT cells are a rich topic of study: they involve concepts of semiconductor heterojunction physics, materials science (thin-film deposition, surface passivation), and device engineering (solar cell design and characterization). At the same time, they are directly relevant to real-world solar panel manufacturing and deployment, as evidenced by the growing adoption of HJT in industry and its use in record-setting tandem cells.

As solar energy moves into the terawatt age, technologies like HJT that offer higher efficiency and better energy yield can significantly reduce the cost per watt and the required area for installations. With ongoing improvements in fabrication techniques and tandem integration, it is reasonable to expect HJT-based solar cells (whether single junction or multi-junction) to play a central role in next-generation photovoltaic modules. The journey of HJT from 12% to nearly 30% efficiency in a few decades exemplifies the remarkable progress in solar cell research and gives confidence that further innovations (perhaps beyond silicon) will continue to push the envelope of solar power conversion towards new heights.

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Chapter III

3. MULTIJUNCTION SOLAR CELLS

Introduction. Multijunction (MJ) solar cells stack two or more semiconductor **p–n junctions** with different bandgaps to absorb successive portions of the solar spectrum[1][2]. By capturing high-energy photons in a wide-bandgap top cell and letting lower-energy photons pass to narrower-bandgap bottom cells, MJ devices can surpass the ~33% Shockley–Queisser limit for single-junction cells[1]. Early work in multijunction photovoltaics began in the 1970s: Bedair *et al.* (1979) demonstrated the first monolithic two-junction AlGaAs/GaAs cell[3]. By the mid-1980s a two-junction GaInP/GaAs cell was developed (Olsen *et al.*), and the first space-qualified GaInP/GaAs/Ge triple-junction device was launched around 2000[3][4]. The Japanese company Spectrolab (now part of Boeing) pioneered many advances: e.g. their 2006 III–V MJ cell exceeded 40% efficiency[3]. By 2022 Fraunhofer ISE reported a **4J** GaInP/GaAs//GaInAsP/GaInAs cell reaching 47.6% under 665× concentration[5]. Such lab records illustrate the steep learning curve: from ~21.5% dual-junction space cells in the 1990s[4] to >45% MJ cells today.

History

In 1979 Bedair *et al.* built the first two-junction AlGaAs/GaAs cell[3]. In the 1980s–90s GaInP/GaAs dual cells (21%+) were produced[3] and flown. In 2000 the first GaInP/GaAs/Ge triple-junction (3J) cells were tested in space[4]. In 2006 Spectrolab reported the first MJ cell >40%[3]. By 2022, Fraunhofer reached 47.6% (4J)[5]. In parallel, tandem thin-film tandems emerged: by 2011 a polymer/organic tandem hit 10.6%[6], and by 2025 perovskite–silicon tandems topped 34.9%[7].

What are multi-junction solar cells?

Single-junction solar photovoltaic (PV) cells convert sunlight into electricity by absorbing wavelengths up to a specific limit determined by their bandgap. As a result, only a fraction of the solar spectrum can be efficiently utilized for energy conversion. To maximize the utilization of the solar spectrum, the concept of multijunction solar cells has emerged, as illustrated in Figure 1.

Multi-junction solar cells are capable of absorbing different wavelengths of incoming sunlight by using different layers(Figure 1), making them more efficient at converting sunlight into electricity than single-junction cells. Each layer is optimized to absorb a different range of the light spectrum, allowing the cell to absorb a wider range of light energy and increase the overall efficiency.

- The **top cell** might be made of **Gallium Indium Phosphide (GaInP)**, which captures blue and ultraviolet light.

- The **middle cell** could be composed of **Gallium Arsenide (GaAs)**, which absorbs green light.
 - The **bottom cell** is typically **Germanium (Ge)**, designed to absorb infrared light.
- Each junction operates like an individual solar cell, and the combination of these layers ensures that more photons from different parts of the solar spectrum are captured, which increases the overall energy conversion efficiency.

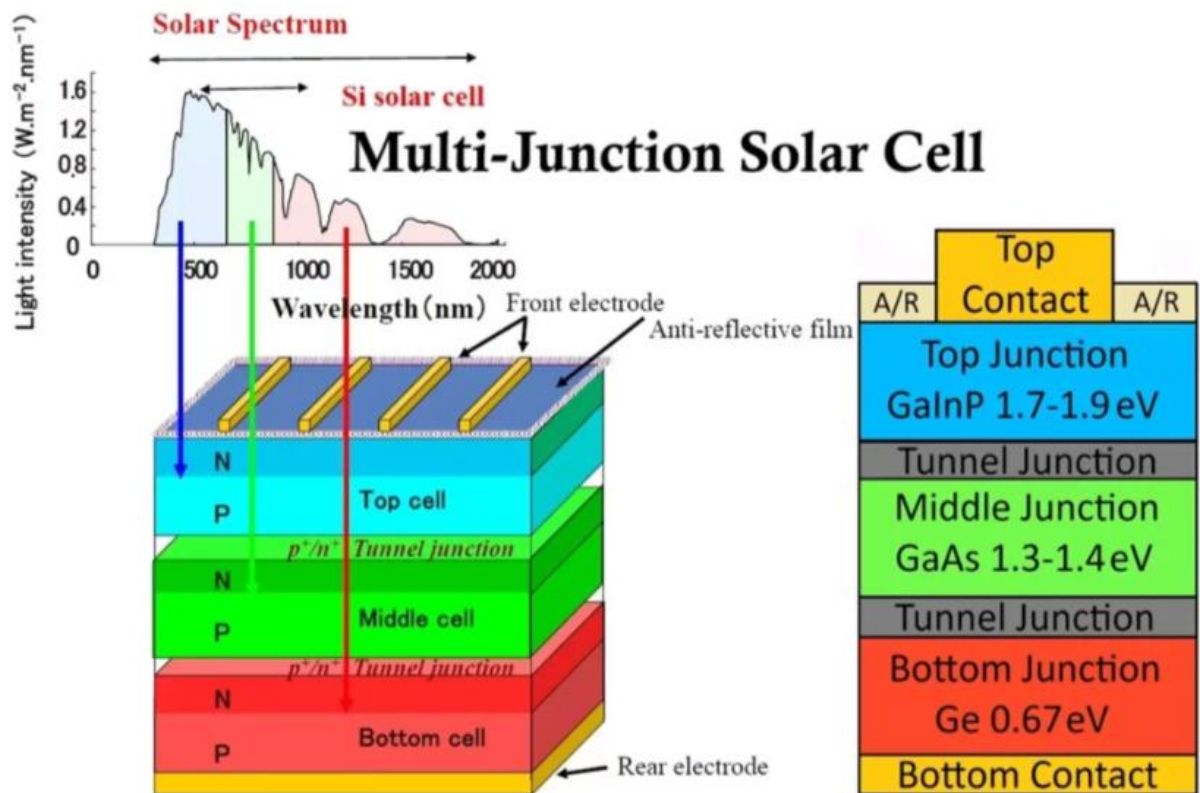


Figure 1. Multi-junction solar cell structure.

<http://large.stanford.edu/courses/2010/ph240/weisse2/>

In contrast, traditional single-junction solar cells only contain one layer of material and are limited to absorbing a narrow range of light. While they have the potential to be many times more efficient than traditional solar cells, high production costs and continuing research and development means that multi-junction cells are not currently commercially available or feasible.

Multi-junction solar cells are a type of **tandem solar cell**, meaning they are made of stacked materials that are optimized to absorb different frequencies of sunlight.

Multi-junction solar cell basics: how do multi-junction solar cells work?

The working principle of multi-junction solar cells is based on the concept of bandgap energy. The bandgap energy is the minimum amount of energy required to free an electron from its orbit and allow it to move freely in the material. Different materials have different bandgap energies, and different light wavelengths correspond to different amounts of energy (Figure 2a).

Multi-junction solar cells have multiple layers of different materials, each with a different bandgap energy. When light enters the cell, it is absorbed by the top layer, which has the highest bandgap energy (Figure 2b). The absorbed energy frees electrons from the material, and they flow freely to the next layer, which has a lower bandgap energy. This process continues until all the electrons have reached the bottom layer, and the electrical energy is collected and converted into usable power.

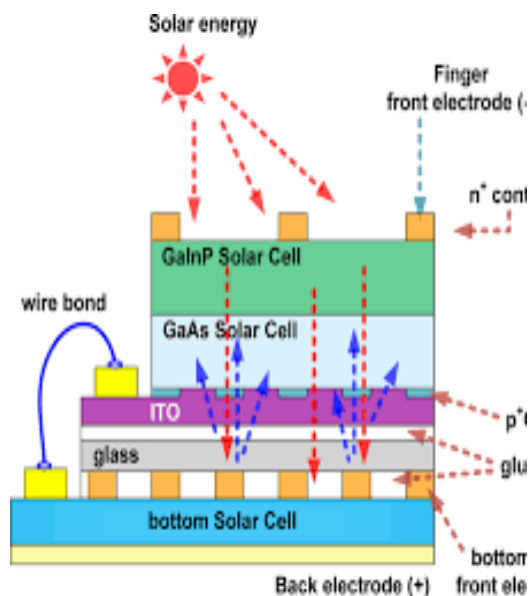


Figure 2a. Operation mechanism of the light reflection path
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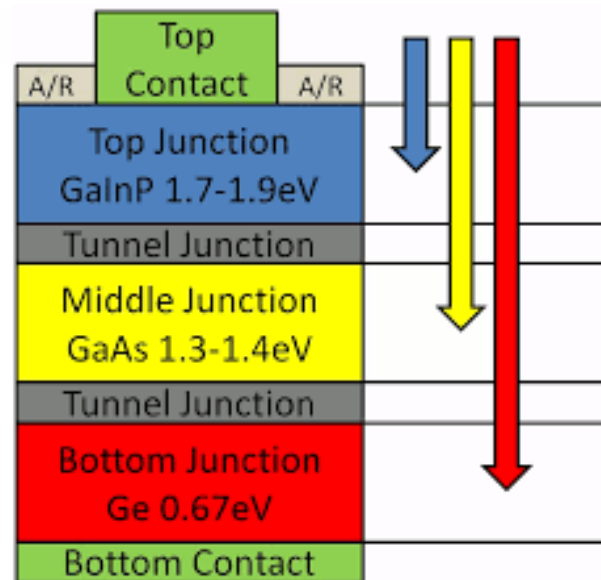


Figure 2b. Schematic of 40% multijunction solar cell.
<http://large.stanford.edu/courses/2010/ph240/weisse2/>

Solar cells are made of semiconductor material, typically silicon in crystalline solar cells. Traditionally, a solar cell has two layers: an *n-type* with a high concentration of electrons and a *p-type* with a relatively low concentration of electrons. When sunlight hits the *n-type* layer, electrons flow from that section to the second and create an electrical current that can be captured and used for power. This

type of solar cell is known as a *single-junction solar cell*, as it has one single boundary/junction between the n-type and p-type layers, known as a *p-n junction*.

Fabrication Methods

Most high-efficiency MJ cells are made by epitaxial growth (MOCVD or MBE) of compound semiconductors. For example, lattice-matched GaInP/GaAs/Ge cells are grown on Ge substrates, then mechanically processed[10]. Advanced methods include inverted metamorphic growth: subcells are grown in an inverted order with subsequent wafer lift-off and flip-chip bonding, allowing bottom cells on lattice-mismatched substrates (InGaAs on GaAs, for instance)[10]. Another approach is direct wafer-bonding: two separately-grown sub-stacks are bonded (via transparent oxide or direct fusion) to form a multi-junction cell[10]. For example, Niemeyer *et al.* bonded a GaAs-based tandem to an InP-based tandem to realize 4-junction devices[10]. Wafer bonding avoids thick metamorphic buffers and can combine dissimilar materials (e.g. GaSb with III–Vs)[10].

Emerging tandem cells use solution or vapor deposition. Perovskite top/bottom cells are often made by spin-coating or evaporation on silicon or glass[7]. Organic tandem cells use roll-to-roll or printing of polymer layers[11].

Table:

Material System	Junctions & Structure	Demonstrated Efficiency (AM1.5, $\approx 25^\circ\text{C}$)	Reference
III–V (GaInP/GaAs on Ge)	3J (GaInP/GaInAs/Ge)	$\sim 28.3\%$ (AM0, space, 2006)[20]; 39–41% (AM1.5 conc.)[7]	NASA (2006)[20] / Spectrolab (2006)[7]
III–V (bonded 4J GaInP/AlGaAs//GaInAsP/GaInAs)	4J inverted-wafer-bonded	47.6% (AM1.5D, 665 $\times$)[8]	Fraunhofer ISE (2022)[8]
IMM multijunction	6J (inverted metamorphic)**	$>50\%$ (theoretical, conc.)[12]	Geisz <i>et al.</i> (2018)[12]
Perovskite/Silicon tandem	2J (perovskite top/Si bottom)	34.9% (cert., 2025)[11]	Huang & Mao (2025)[11]
Perovskite/Perovskite/Si	3J (two perovskites + Si)	27.1% (1 cm^2 , 2025)[2]	Zheng <i>et al.</i> (2025)[2]
Perovskite/Organic tandem	2J (perovskite/organic polymer)	26.4% (1 cm^2 , 2025)[19]	Hou <i>et al.</i> (SERIS, 2025)[19]
All-Organic tandem	2J (polymer/polymer)	21.2% (cert., 2025)[21]	Wang <i>et al.</i> (2025)[21]

Table 1. Representative high-efficiency multijunction/tandem solar cells. IMM = Inverted Metamorphic Multijunction design. (Space AM0 efficiencies are given for III–Vs when available; conc. indicates concentrator results.) Sources: references in the rightmost column.

Dual-Junction (2J) Cells

The simplest MJ is a **2-junction** cell, sometimes called a “tandem”. One example is GaInP/GaAs on Ge, which under AM0 can reach $\sim 21.5\%$ (space BOL, 1997)[4]. Terrestrially, dual-junction cells often pair a high-bandgap top cell with a Si or lower-gap bottom: e.g. perovskite ($\approx 1.7\text{--}1.8\text{ eV}$) on crystalline Si (1.12 eV) has evolved

rapidly. After the first demo in 2015, perovskite/Si tandems now exceed 34%[7]. Similarly, perovskite/CIGS tandems have been studied, though with lower efficiencies. Thin-film tandems (a-Si/a-Si, CuInSe₂/Si, etc.) achieved 20–25% over the 1990s–2000s. Recent notable 2J results include a perovskite/organic polymer tandem at 26.4%[11] and all-polymer tandems reaching ~21%[12]. Organic solar cells still lag III–V, but advanced narrow-gap polymers have enabled polymer/polymer tandems to exceed 10% (2011)[6] and now over 20%[12]. These developments underline that using multiple bandgaps in series can harvest more spectrum: photons above the top bandgap contribute to top-cell current, while sub-bandgap photons are absorbed by the bottom cell.

A low temperature is important for obtaining a considerably higher carrier concentration with MBE. The carrier concentrations in n⁺-InGaP and p⁺-AlGaAs were 1.5×10^{19} and $3 \times 10^{19} \text{ cm}^{-3}$, respectively. During the growth, As₂ and P pressures were 5.0×10^{-6} and 1.2×10^{-5} Torr, respectively. The growth rate of GaAs and In_{0.48}Ga_{0.52}P was 1 $\mu\text{m}/\text{h}$. n⁺-GaAs was grown on the In_{0.48}Ga_{0.52}P window as an electrode contact layer. After the growth, the front electrode was formed using photolithography and a lift-off technique. AuGe=Ni=Au and Ti=Au were used for the front and back electrodes, respectively. The p⁺-GaAs contact layer was removed by chemical etching using the front electrode as an etching mask. The cell size was $5 \times 5 \text{ mm}^2$. TiO₂=SiO₂ antireflection coating (ARC) was employed.

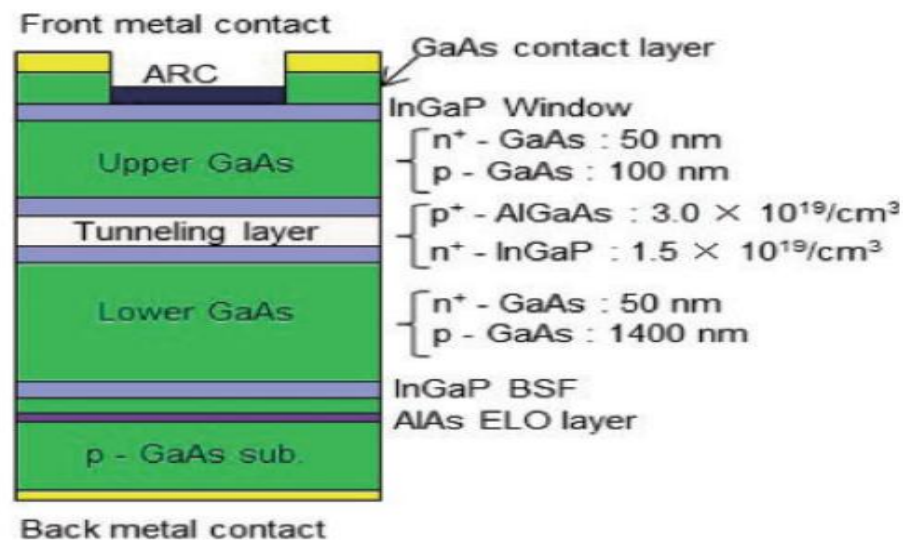


Figure 3. Schematic layer structure of a dual-junction GaAs solar cell. (Takeyoshi Sugaya et al 2018 Appl. Phys. Express 11 052301)

Triple-Junction (3J) Cells

Three-junction cells are the workhorses of space power and CPV. The classic III–V 3J cell stacks GaInP (1.9 eV), GaInAs ($\approx 1.4 \text{ eV}$), and Ge (0.67 eV). Ge serves both as bottom cell and substrate. Under the AM0 spectrum, these have yielded ~28.3%[4] on

orbit. On Earth (AM1.5D) with concentration, 3J GaInP/GaInAs/Ge cells have hit ~41.6%[3]. Figure: the internal layers of a typical GaInP/GaAs/Ge 3J cell, with each subcell tuned to a different spectral band (not shown here), underscore the stacked design[4]. Inverted variants (bottom-up growth) and lattice grading have allowed alternate material choices (e.g. InGaAsP) to tailor bandgaps and boost efficiency. Beyond III–V, 3J combinations include perovskite–perovskite–Si (as in the Sydney work), or silicon–III–V tandems for space (e.g. GaAs/GaInP on Si). The key is current matching: each subcell must generate nearly equal current under illumination. When well-matched, a 3J device shows a single I–V characteristic that saturates at the lowest-generating subcell, while summing the voltages of all three junctions. The open-circuit voltage V_{oc} of a 3J stack can thus be well above 2 V in total (≈ 0.6 – 0.8 V per cell)[8].

In addition, these researchers (Takeyoshi Sugaya et al 2018 Appl. Phys. Express 11 052301) grew an InGaP/GaAs/GaAs triple-junction top cell for smart stacked multijunction solar cells, as shown in Fig. 4. The thicknesses of absorption layers were 150, 200, and 1800 nm. The first InGaP cell contained an InAlP BSF and window layers. The structure of the second and third GaAs cells was the same as that shown in Fig. 3. A p+-AlAs epitaxial lift-off (ELO) layer was grown for a smart stack prior to the growth of a top cell. The InGaP= GaAs=GaAs top cell was separated from the GaAs substrates using a selective etching method referred to as the ELO technique. The top cell was connected to a crystalline Si (c-Si) bottom cell through Pd nanoparticle arrays, as shown in Fig. 4. Here, a classic Al BSF-type c-Si cell[24] was specifically selected as a bottom subcell because its fabrication is simpler than those of other advanced c-Si cells. On a double-side mirror-polished p-type (B-doped, resistivity = 0.5 – $4 \Omega \text{ cm}^2$) Si (100) wafer of $400 \mu\text{m}$ thickness, an n+ front layer and a p+ BSF layer=rear electrode were formed through the thermal diffusion of POCl_3 and the screen printing=firing of an Al paste, respectively.

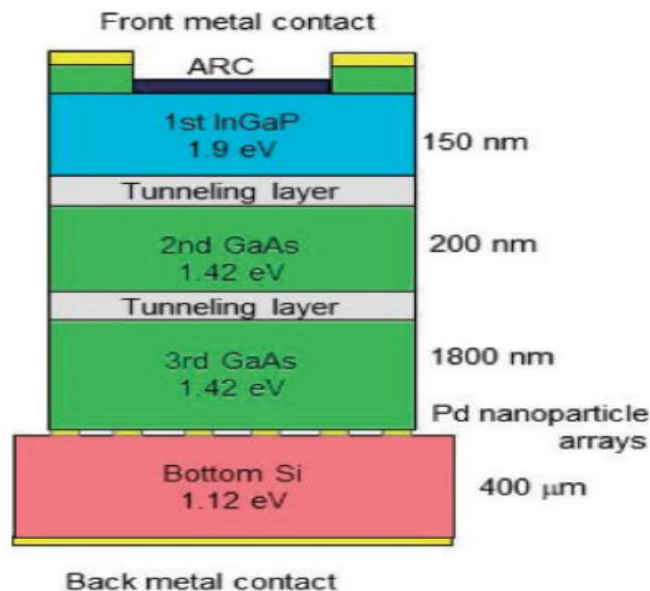


Figure 4. Schematic layer structure of a smart stacked InGaP/GaAs/GaAs//Si triole-junction solar cell. (Takeyoshi Sugaya et al 2018 Appl. Phys. Express 11 052301)

Four- and Five-Junction Cells

Four-junction cells add yet another bandgap splitting. State-of-art 4J devices (often grown via wafer bonding) combine GaInP/AlGaAs with two lower-InGaAs-based junctions. For example, Fraunhofer's 4J is essentially an AlGaInP/AlGaAs top two-junction on a bonded GaInAsP/GaInAs tandem[5]. This design achieved 47.6% at 665×[5], the current world record for any solar cell (as of 2022). Wafer-bond 4J cells often replace costly InP by bonding GaInP/GaAs (on GaAs substrate) to InGaAsP/InGaAs (on InP)[10].



Figure 5. Different cell architectures for wafer-bonded 4-junctional solar cells. The bond is always indicated by the red line. Left: InP-based concept. Center: Ge-based concept. Right: GaSb-based concept. DOI: 10.1109/JPHOTOV.2017.2778567

Five-junction cells have been demonstrated in the lab as well (adding a ~ 0.7 eV GaSb or InGaAsSb bottom junction), with records reaching $\approx 46\%$ [13]. These require complex lattice grading or bonding, and so far only appear in research, not commercial products. These cells contain five semiconductor layers arranged by decreasing bandgap energy from top to bottom. Each sub-cell absorbs a specific slice of the solar spectrum. Electrical connection between layers is maintained via ultrathin tunneling junctions that minimize losses. **Metamorphic (buffered) 5J cells**(Figure 6): Projects like QuintUMM have developed metamorphic 5-junction cells built on germanium. They achieve impressive efficiencies—up to 42.7% under $\sim 800\times$ solar concentration.

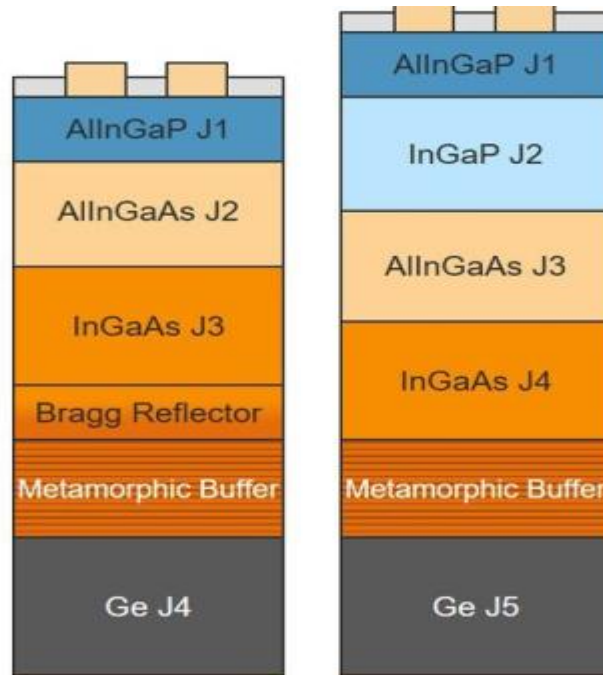


Figure 6. The schematic structure of a five-junction solar cell (b) and a four-junction solar cell, space applications (a). (https://www.energieforschung.de/en/home/project-insights/2020/module-with-five-junction-solar-cell-achieves-efficiency-of-32-per-cent?utm_source=chatgpt.com).

Engineers use a special method, Metal Organic Vapour Phase Epitaxy (MOVPE), to produce the semiconductor stacks of the multi-junction solar cells. In this process, molecules of the various semiconductor materials are successively deposited from the gas phase on a heated substrate, the germanium wafer. The technical term for this process is epitaxial layer growth. This takes place in a production reactor, which simultaneously deposits various semiconductors on several germanium wafers. Within the research project, the scientists developed this method for the new structure of the five partial solar cells, which are stacked on top of each other. Furthermore, the tertiary and quaternary semiconductor materials (InGaAs, AlInGaAs, InGaP and AlInGaP) have a special material composition.

Direct-bonded 5J space cells: Advanced 5J cells using direct semiconductor bonding (SBT) have achieved efficiencies over 35% under one Sun (AM0, space spectrum), with potential to climb to 36–37%.

The fabrication of SBT solar cells contains the following processes, as shown in Fig. 7. Subcells are lattice-matched epitaxial grown on suitable substrates (usually GaAs and InP), while top-cells are inverted and grown with etch layers or a sacrificial layer between the substrate and active layers for further convenience. Wafers are then

direct semiconductor bonded. After the removal of the one-side growth substrate, the mixture is processed following the standard III–V solar cell device art. The advantage of this approach is that all junctions in the stack are grown lattice-matched and therefore have excellent epitaxial quality, which results in higher efficiencies. Also, the bonding process supports the scale-up to 4- inch or larger wafers, which provides the foundation for further industrial applications.

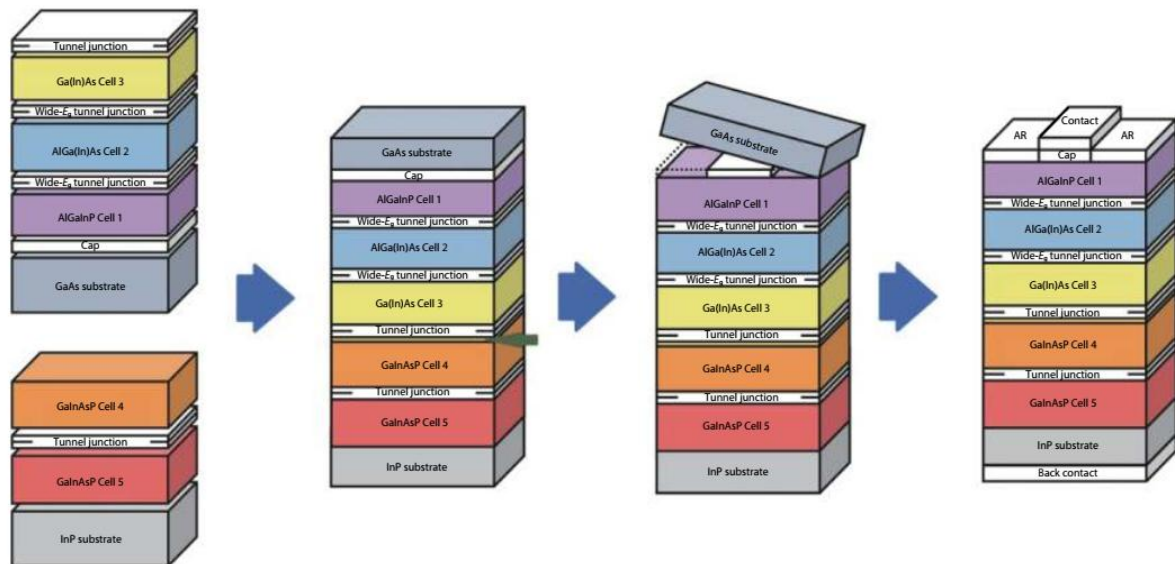


Fig. 7. Fabrication scheme of SBT 5J cells. The arrow indicates the bonding interface. X Y Li, G Li, H B Lu, and W Zhang, >35% 5-junction space solar cells based on the direct bonding technique[J]. *J. Semicond.*, 2021, 42(12).
<https://doi.org/10.1088/1674-4926/42/12/122701>

Six-Junction and Beyond

Research is now exploring **6J and higher**. Geisz *et al.* (2018) proposed a practical 6J design (an **inverted metamorphic** stack of AlGaInP, AlGaAs, GaAs, then three InGaAs junctions) with a pathway to over 50% efficiency under concentration[8]. Their prototype 6J delivered an open-circuit voltage of 5.15 V at one-sun, demonstrating the series integration of six diodes[12]. In principle, adding junctions (7, 8...) approaches the ultimate limit, but practical gains diminish. Still, novel junctions (GaInN for UV, or new low-gap materials) may be inserted.

It was proposed strategies for achieving over 50% efficiency in practical 6J solar cell designs (figure 8). The individual junctions required for these designs have been demonstrated and their quality quantified by the ERE. We have found the design that incorporates three metamorphic grades between the last 4Js to be very promising due to the excellent quality of metamorphic InGaAs junctions. It was demonstrated

integration of the 5J and 6J devices using this strategy. Current balancing to over 8.5 mA/cm² of the 6J structure appears possible using newly developed transparent TJs and metamorphic grades. A single-grade design will require more development for comparable quality junctions.

It was demonstrated excellent performance of an initial 6J IMM device at 1 sun, but achieving low series resistance remains the primary challenge to achieving 50% efficiency. Resistive barriers that develop during the thermal load of subsequent growth must be resolved. In addition, tradeoffs in the design of the top junction and grid must be optimized to provide sufficient photocurrent and sheet resistance with minimal voltage loss at high-concentration operation.

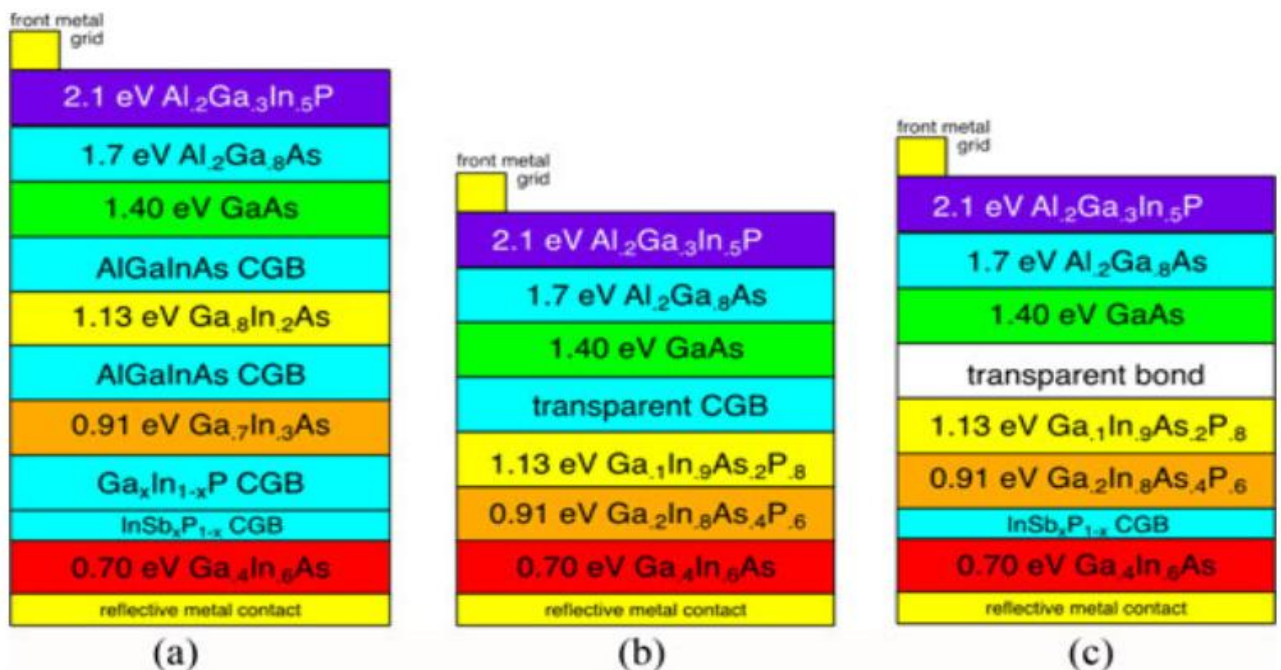


Fig. 8. Schematic for 6J design strategies. The second junction in any of these designs could also be composed of the 1.7-eV quaternary $\text{Ga}_{0.7}\text{In}_{0.3}\text{As}_{0.3}\text{P}_{0.7}$

I–V Characteristics

The I–V characteristic of a series MJ cell behaves qualitatively like a single diode curve but with a higher open-circuit voltage (sum of each cell's V_{oc}) and a current limited by the weakest subcell. Figure:

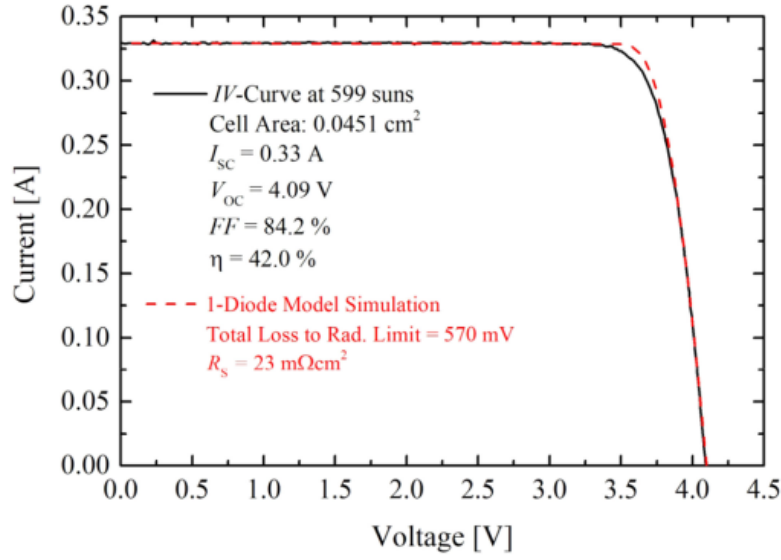


Figure 9. I – V characteristic Sb-based four-junction solar cell at 599 suns, including a modeling based on four 1-diode models in series. DOI: 10.1109/JPHOTOV.2019.2957663

The maximum current I_{sc} of the MJ device equals the smallest subcell current (assuming series wiring). Each junction obeys its own diode equation, so the total current at voltage V must satisfy

$$I = I_{ph,i} - I_{0,i} \left(e^{(V_i/n_i V_T)} - 1 \right)$$

for each subcell i , with $V = \sum V_i$ and $I = I_{ph, \text{rm min}}$ roughly. In practice, one often uses a single-diode equivalent with the total V_{oc} and matched I_{sc} . The fill factor and shape remain high ($FF \sim 0.9$ in GaAs cells) if all subcells have good quality. Parasitic resistances and non-ideal junctions can introduce kinks or multiple-diode behavior, but high-quality MJ designs maintain near-ideal IV curves.

The I – V characterizations under concentration are shown in Fig. 10. The theoretical VOC dependence on the concentration C [last summand of (1) with $n_{id} = 1$] is included in the graph, in which the factor “4” represents the number of junctions. The curve has a constant offset of 570 mV to the radiative limit for a four-junction solar cell at this specific bandgap combination, as discussed below.

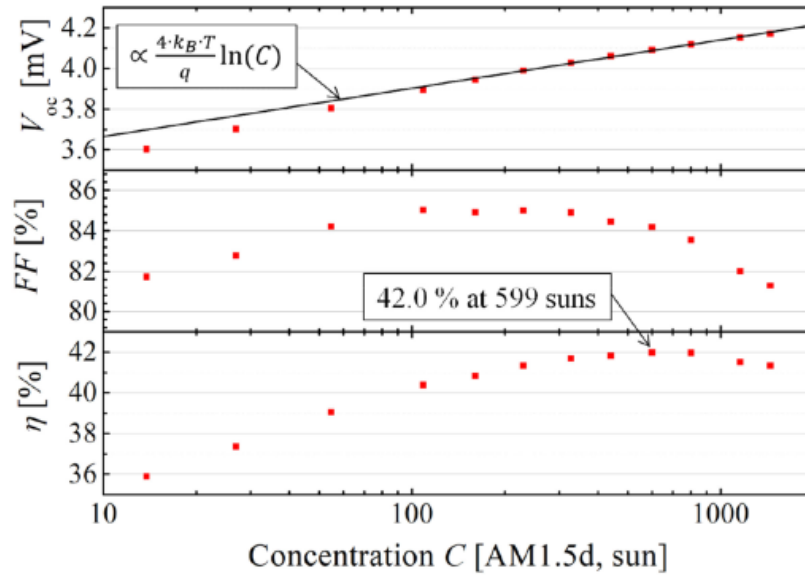


Fig. 10. Summary of the open-circuit voltage V_{OC} , FF, and efficiency η of the Sb-based four-junction cell, determined by concentration-dependent I – V characterization. DOI: 10.1109/JPHOTOV.2019.2957663

Figure 11 shows the measured J – V characteristics of Si, InGaAs, and GaInP/GaAs DJ and TJ solar cells under the one-sun condition in the AM1.5G solar simulator. The TJ solar cells with two structures, including the GaInP/GaAs//Si (Fig. 11(a)) and GaInP/GaAs//InGaAs (Fig. 11(b)) multi-junction solar cells, were fabricated via mechanical stacking.

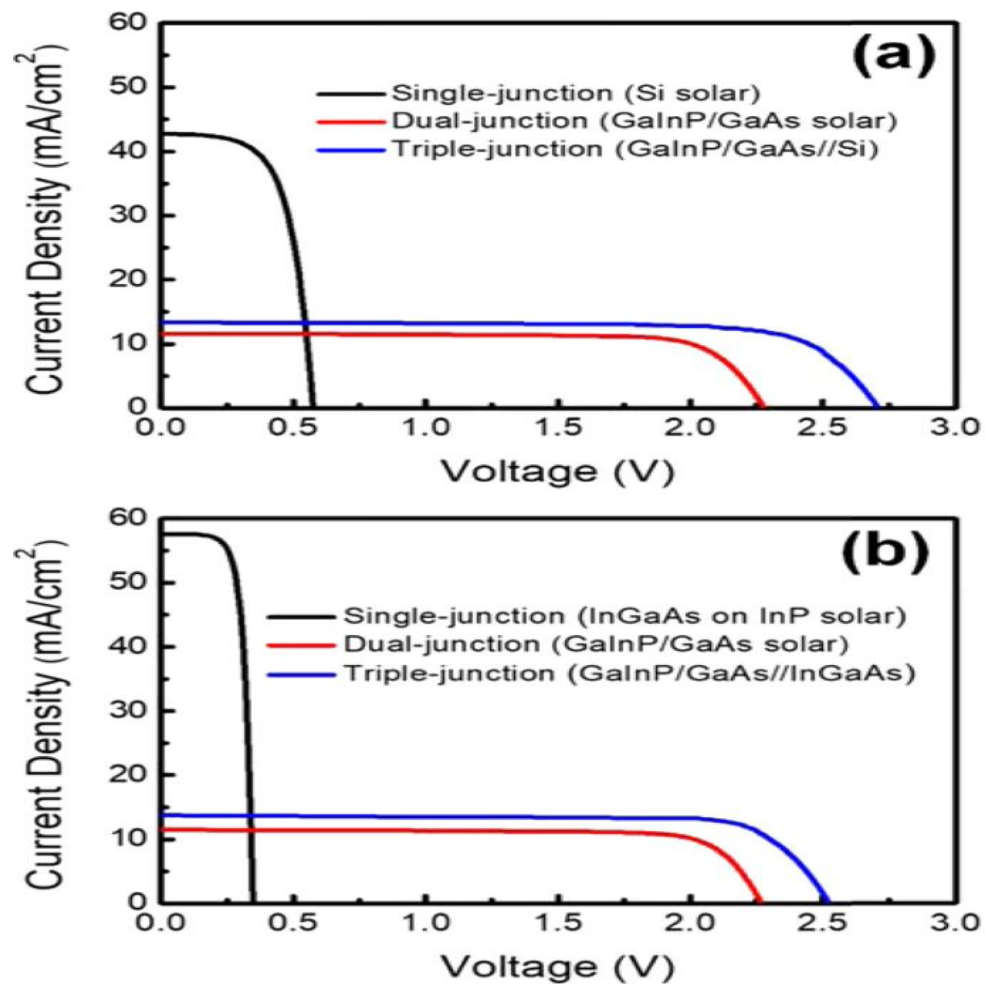


Figure 11. J–V characteristics of (a) GaInP/GaAs//Si and (b) GaInP/GaAs// InGaAs TJ solar cells measured using a one-sun AM1.5G light source. They were measured under the individually fabricated dual-, single-, and stacked junctions.

<https://doi.org/10.1038/s41598-019-40727-y>

Si type	V _{oc} (V)	J _{sc} (mA/cm ²)	FF (%)	η (%)
Single-junction Si solar cell	0.57	42.78	63.63	15.50
Dual-junction solar cell	2.28	11.59	77.98	20.60
Triple-junction solar cell	2.71	13.37	75.40	27.31

TABLE I

OPTIMAL BANDGAP COMBINATION AND EFFICIENCY FOR FOUR-, FIVE-, AND SIX-JUNCTION SOLAR CELLS FOR THE “EMPIRIC POTENTIAL” CASE AND REAL-WORLD EFFICIENCY TARGET FOR THE SB-BASED FOUR-JUNCTION CELL.

DOI: 10.1109/JPHOTOV.2019.2957663

Device Concept & bandgap combination [eV]	J_{SC} [mA/cm ²]	V_{OC} [V]	FF [%]	η [%]
4-Junction, Empiric Potential 1.92/1.43/1.03/0.69	15.54	4.27	88.8	58.9
5-Junction, Empiric Potential 2.06/1.60/1.25/0.98/0.69	12.43	5.53	89.2	61.2
6-Junction, Empiric Potential 2.17/1.73/1.43/1.17/0.94/0.69	10.34	6.84	89.4	63.2
Sb-based 4-Junction Real-world Efficiency Target 1.89/1.42/1.05/0.68	14.03	4.21	86.1	50.8

Note: The values are calculated for a concentration of 500x (AM1.5d spectrum, 1000 W/m²) at 25 °C.

Materials and Junction Examples

III–V semiconductors (GaAs, GaInP, InGaAs, GaSb, etc.) dominate high-efficiency MJ cells[1][10]. These materials are lattice-engineered to achieve desired bandgaps: e.g. GaInP ($E_g \approx 1.85$ eV), GaAs (1.42 eV), InGaAsP (~ 1.2 – 1.0 eV), GaInAs (0.7–1.1 eV), GaSb (0.67 eV)[14][12]. Bandgap engineering (via alloy composition) and low-defect metamorphic buffers permit stacking these layers on single substrates (GaAs or Ge)[14].

Perovskites (e.g. lead-halide materials) offer tunable bandgaps and low-cost fabrication. Perovskite top cells (>1.7 eV) paired with silicon bottom cells (1.12 eV) reach 34–35%[7]. Perovskites are solution-processable (spin-coating, evaporation) and have already matched MJ GaAs record for a single junction (25.7% single-junction PSC)[12].

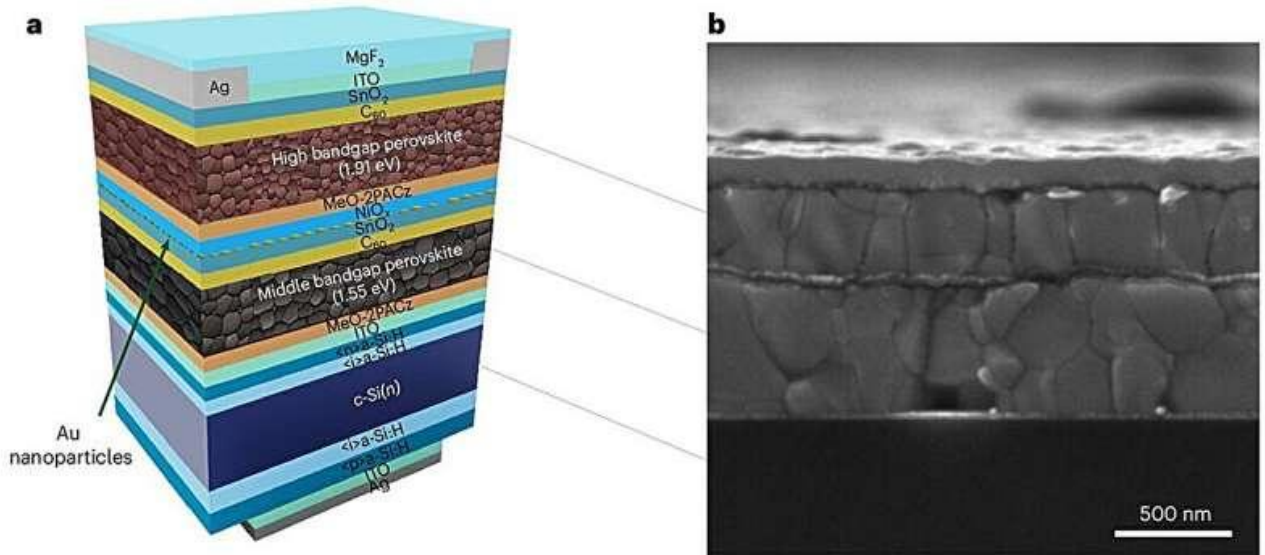


Figure 12. Photovoltaic performance and stability of the triple-junction perovskite–perovskite–silicon tandem. Device structure schematic (a), cross-sectional SEM image (b) Credit: *Nature Nanotechnology* (2025). DOI: 10.1038/s41565-025-02015-x

Figure 12: (a) Schematic and (b) cross-sectional SEM of a triple-junction perovskite–perovskite–silicon solar cell[2]. Three stacked absorbers of different bandgaps are connected by recombination layers. The certified cell (1 cm²) reached 27.06% efficiency[2]. (Image: Zheng et al., Nat. Nanotech.* 2025) *

Organic (polymer) PV materials can be tuned from ~1.3–1.8 eV. Their best single-junction OPV is ≈19–20%. Tandems stacking a high-gap front polymer and a low-gap rear polymer have achieved 21.5%[21]. These are usually made via roll-to-roll solution processing or vapor deposition.

Hybrid tandems (perovskite/organic, perovskite/CIGS, etc.) leverage complimentary absorption. For example, a recent perovskite/organic tandem (wide-gap perovskite + narrow-gap organic) hit 26.4%[19], rivaling pure III–V tandems in lab scale.

Space vs. Terrestrial Applications

Space-based PV has long used MJ cells because efficiency and low weight trump cost. Space MJ cells are typically optimized for AM0 (extraterrestrial solar spectrum) and radiation tolerance. The GaInP/GaAs/Ge triple junction (28% AM0) is standard on satellites[4]. Recently, quadruple and quintuple cells are being pursued for next-gen missions. Space MJ cells are manufactured by suppliers like Spectrolab, Azur, and Emcore using epitaxial processes. The high power-to-weight ratio is critical; for example, GaAs-based MJs have ~10× the specific power of Si modules.

Terrestrial PV uses MJs mainly in concentrated photovoltaics (CPV) and specialty tandems. The high cost of substrates and complexity requires concentration (lenses/trackers) to reduce area. With 500–1000× suns, MJ CPV systems reach overall

system efficiencies >40%. The Fraunhofer 47.6% record was under 665×[8]. Dual-axis trackers and Fresnel lenses are used. Bifacial architectures can be combined with MJs: for instance, a tandem module might be built on a transparent substrate to collect albedo on the rear side, potentially boosting current, though this is mainly theoretical. Emerging terrestrial uses include building-integrated or portable PV: lightweight, flexible perovskite and organic tandems can power IoT devices and vehicles.

Efficiency Calculation and Performance

Calculating MJ efficiency follows the same basic formula as single cells, but with each subcell's bandgap accounted for in the absorbed spectrum. A common approach is to compute detailed balance efficiency for each layer, then optimize bandgaps for maximum total output[1]. The actual I – V curve is found by solving the series circuit:

$$I = I_{ph,i} - I_{0,i} \left(e^{(V_i/n_i V_T)} - 1 \right)$$

where I_{sc} is the matched photocurrent (limiting current of the stack) and I_0 a combined dark saturation current. In practice one ensures each layer is current-matched under the illumination (e.g. by adjusting thickness or optical filters), so $I_{sc} \approx I_{sc}$ of each cell. The output power $P=IV$ is maximized at (I_{mp}, V_{mp}) , giving efficiency $=I_{mp}V_{mp}/P_{in}$. Experimentally, MJ cells exhibit excellent fill factors (typically >0.85) when well-fabricated, so efficiency differences mainly come from V_{oc} (sum of bandgaps) and I_{sc} (limited by spectrum coverage).

As an example, consider the triple-perovskite/silicon cell in Fig. (Zheng *et al.*, 2025)[2]. Each of the three subcells is connected by a transparent tunnel junction. The current through the stack was 13 mA/cm² (limited by the smallest photo-generated current) and the total V_{oc} was about 2.0 V. The product $I_{mp}V_{mp}$ yields the 27.06% power conversion efficiency on 1 cm²[2].

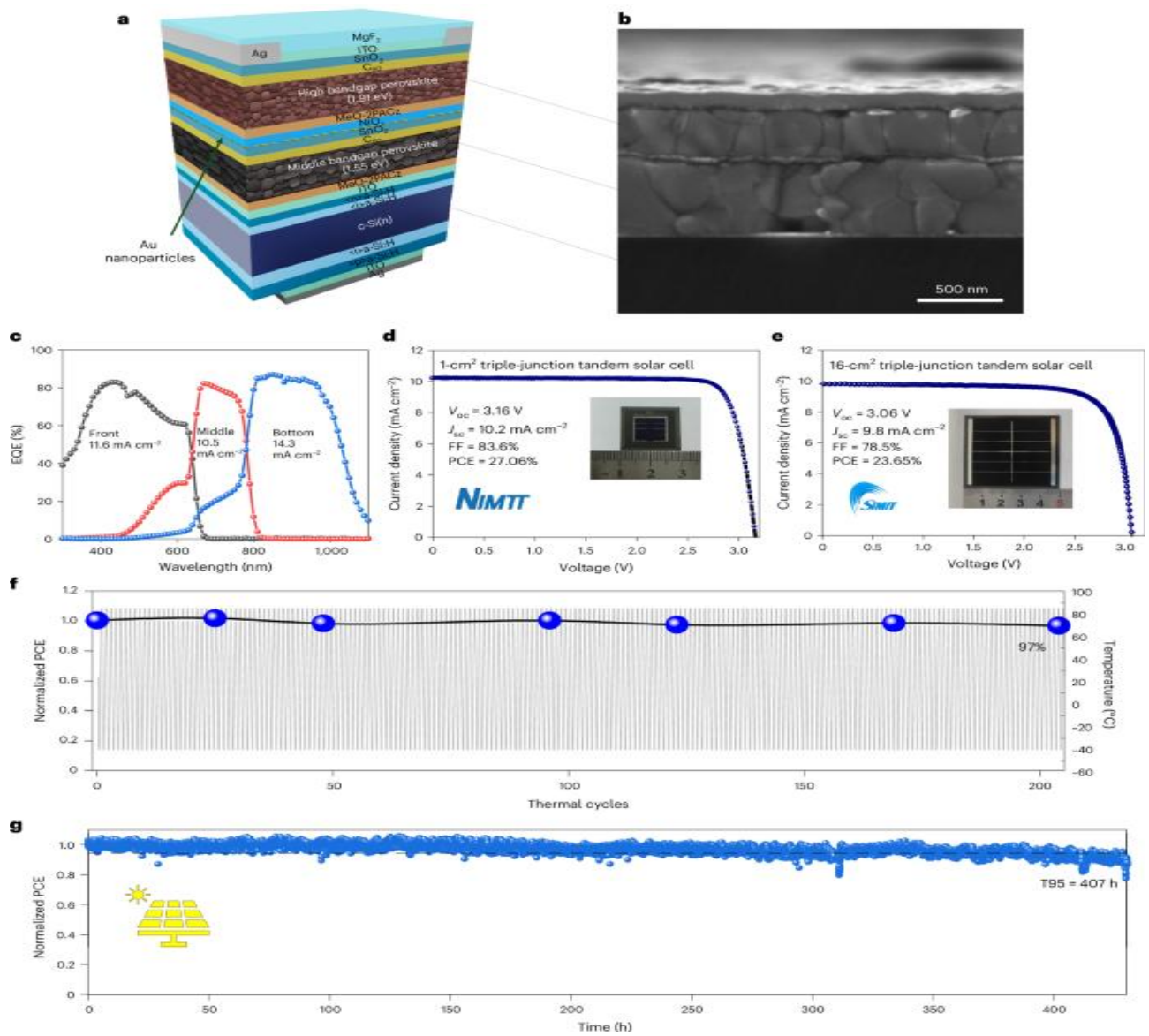


Fig. 13: Photovoltaic performance and stability of the triple-junction perovskite-perovskite-silicon tandem.

Figure 13: **a–c**, Device structure schematic (**a**), cross-sectional SEM image (**b**) and EQE (**c**) curves (black for wide-bandgap perovskite; red for mid-bandgap perovskite; and blue for low-bandgap silicon) of a representative triple-junction tandem. **d,e**, Third party-measured reverse-scan J – V curves of champion triple junctions: 1 cm² (**d**) and 16 cm² (**e**). **f,g**, Encapsulated 1-cm² triple-junction solar cells under thermal cycling (between –40 °C and ~85 °C) (**f**) and MPPT (**g**) at 25 °C in ambient. T95, time for the power output to decrease to 95% of its initial value. [2]

Each subcell in an MJ stack has its own **current–voltage (I–V) behavior**. In series-connected MJ cells, the same photocurrent flows through all junctions, so the device current is limited by the subcell generating the lowest short-circuit current, while the total open-circuit voltage is the sum of each subcell’s voltage[2][8]. In practice, designers choose materials so that subcells produce matched current under the target spectrum. The **efficiency** is

$$\eta = P_{\max}/P_{\text{in}}$$

where I_{mp} and V_{mp} are the current and voltage at the maximum-power point. Typically one reports I_{mp} I_{sc} for well-designed stacks. Each subcell's I–V can be modeled by the diode equation $I=I_0 \exp V_i/n_i V_T-1$, but in series the total voltage $V=iV_i$. Because the device is composed of multiple diodes, the MJ I–V curve still has a single-knee shape but with higher voltage and the current determined by the weakest layer. Figure:

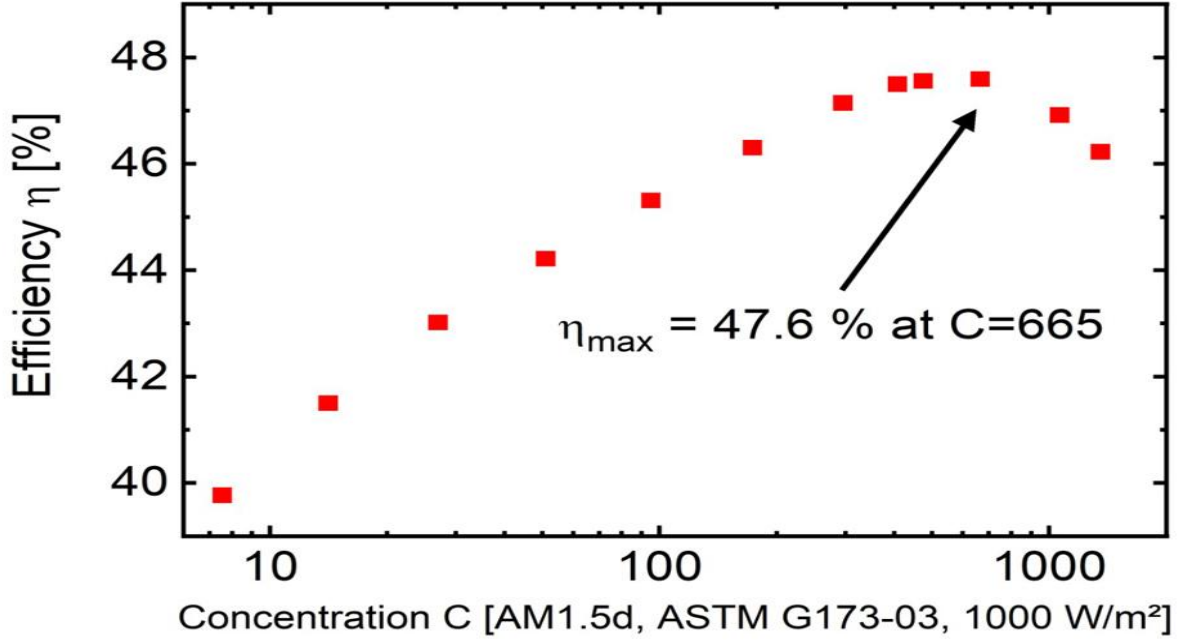


Figure 14. *Efficiency of a high-efficiency 4J* concentrator solar cell vs. light concentration (AM1.5D spectrum)*

Figure 14: *Efficiency of a high-efficiency 4J* concentrator solar cell vs. light concentration (AM1.5D spectrum)*[8]. The GaInP/AlGaAs//GaInAsP/GaInAs device reaches 47.6% at ~665× sunlight (indicative of Fraunhofer ISE's record[5]). Efficiency is plotted, showing the benefit of concentration.

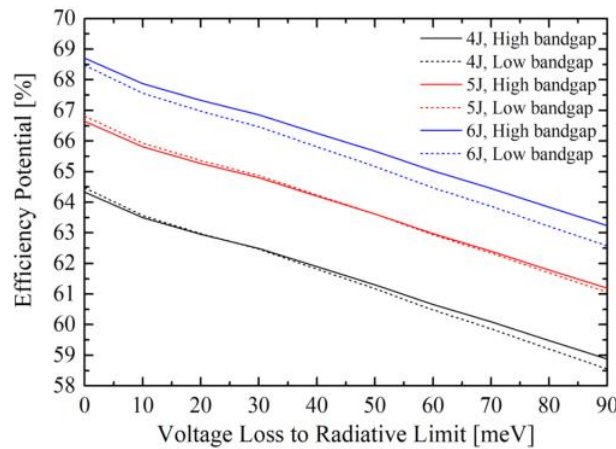


Figure 15. Efficiency potentials for four-, five-, and six-junction (J) solar cells at 500x AM1.5d, plotted as a function of the assumed voltage loss to the radiative limit for each junction. “Low bandgap” stands for the efficiency maximum at a bottom cell bandgap between ~ 0.51 and ~ 0.56 eV and “high bandgap” for the maximum at 0.69 eV. DOI: 10.1109/JPHOTOV.2019.2957663

The theoretical efficiency of a single-junction under one-sun is about 33.5% (Shockley–Queisser limit)[1]. Adding junctions in series raises the multi-junction limit: two junctions can theoretically reach ~ 42 – 45% , three ~ 51 – 55% , and an infinite-junction ideal approaches $\sim 86\%$ (under high concentration)[9][1]. In practice, >3 junctions give diminishing returns for terrestrial one-sun use, but under strong concentration or broad-spectrum illumination (e.g. AM0, UV-rich space light) extra junctions are justified[9][1].

Tandem and Bifacial Combinations

Multijunctions can be combined with other advanced module concepts. **Tandem** generally means stacking two different complete cells, which is exactly what MJ is. However, in practice “tandem” often refers to combining disparate technologies (e.g. perovskite/silicon, perovskite/CIGS, organic/silicon). For example, a perovskite–silicon tandem (2J) is just a bi-facial “integrated tandem”: the perovskite is semi-transparent and sits on top of a Si cell. Likewise, a **bifacial MJ** is possible: one could fabricate a transparent-back MJ cell to capture light from both sides (useful with ground albedo). Recently, bifacial perovskite/perovskite tandems have been demonstrated, achieving up to $\sim 29\%$ equivalent efficiency under 30% back illumination[14]. Mechanical stacking allows combining a standard MJ cell with a Si wafer as a rear cell, effectively making a 4-terminal tandem (GaAs MJ + Si bottom). In CPV, dual-axis trackers naturally allow partial bifacial gain.

In general, any high-efficiency single or tandem cell could be made bifacial by using transparent contacts and mounting on clear substrates. The efficiency gain depends on

rear irradiance (albedo) and cell design. Research (e.g. Shaner *et al.*) suggests bifacial tandems can mitigate uncollected light losses between panels[15]. Commercial bifacial tandems are still nascent, but the combination of MJ with bifacial modules remains an active area of study for maximizing total solar harvest.

Cost, Deployment, and Future Trends

MJ cells remain expensive compared to silicon due to costly III–V materials and complex fabrication[1]. To date they are niche: satellites, space probes, concentrated PV in sun-rich regions, or special terrestrial installations. However, emerging low-cost tandems may broaden use. Perovskite/silicon tandems are nearing pilot production (e.g. Oxford PV aims for commercial 30%-plus tandem panels). Seris/NUS’s flexible perovskite–organic modules (26.4% in 2025) are envisioned for wearables and IoT[11]. Future trends include:

- **Higher efficiencies:** Pushing MJ efficiency further (50%+ is theoretically possible with 6–8 junctions under concentration[8]).
- **New materials:** GaInN could open UV region; GaSb and dilute nitrides for infrared; stable lead-free perovskites for longevity.
- **Cost reduction:** Developments in epitaxial lift-off, bulk III–V manufacturing, and alternative substrates (like Ge-on-Si) aim to cut costs[10][5].
- **Integration:** Monolithic tandem cells (2T devices) are favored for simplicity; however multi-terminal (3T, 4T) tandems can decouple subcells and reduce current-matching losses at the expense of complexity.
- **Commercialization:** Some 2J tandem PV (perovskite/Si, CIGS/Si) may reach market soon. Concentrated MJ (CPV) saw a resurgence in projects for utility-scale generation.
- **Space missions:** New deep-space and lunar missions will use MJ for high-efficiency power (e.g. NASA’s Space Solar Cell program).
- **Energy payback:** As MJ modules become more efficient and lighter, their energy payback time improves, justifying higher upfront cost in specialized applications.

In summary, multijunction solar cells represent the “state of the art” in PV efficiency, blending semiconductor physics with advanced manufacturing. From the first lab 2J devices of the late 20th century to modern III–V and perovskite tandems, the field has matured dramatically[3][7]. Both theory (detailed-balance modeling, thermodynamics) and practice (epitaxial growth, bonding, novel materials) continue to advance. For space and concentrated terrestrial power, III–V MJs will remain essential. For mass-market PV, the trickle-down of MJ concepts into cost-effective tandems (silicon-perovskite, organic-perovskite, etc.) is a key trend[7][12]. This

chapter has outlined the evolution, fabrication, and performance of multijunction cells, with examples up to the latest records and ongoing research frontiers.

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Chapter IV

4. BIFACIAL SOLAR CELLS

Bifacial solar cells are photovoltaic devices designed to collect light on *both* their front and rear surfaces, allowing them to convert reflected (“albedo”) or diffused light into additional electricity. In contrast, monofacial solar cells produce electrical energy only when photons impinge on their front side bifacial solar cells can make use of [albedo](#) radiation, which is useful for applications where a lot of light is reflected on surfaces such as roofs. The concept was introduced as a means of increasing the energy output in solar cells. This concept, first patented by Hiroshi Mori in Japan in 1960, was realized experimentally in the 1970s. Early space-based experiments (e.g. by Bordina et al. in the USSR) showed substantial gains: bifacial cells exposed to ground- or Earth-reflected light produced **17–45%** more power than standard (monofacial) cells[1][2]. In practical terms, modern bifacial modules on earth can boost energy yield by roughly **10–30%** (even up to ~34% in high-albedo environments such as snow-covered ground) compared to identical monofacial modules[1][2]. As a result, bifacial modules have become increasingly popular; today they comprise an estimated ~20% of new PV capacity, with forecasts suggesting up to 70–85% of utility-scale modules will be bifacial by the early 2030s[1][2]. Major manufacturers (e.g. Jinko, LONGi, Trina) now offer bifacial versions of advanced cell types (PERC, PERT, PERL, HJT, IBC, etc.)[2], reflecting the broad adoption of bifacial architectures in high-efficiency PV. Figure shows the layer structure of a typical *silicon heterojunction (HJT)* cell, an inherently dual-sided design that exemplifies modern bifacial technology.

Historical Evolution

- **1960s–1970s:** The idea of collecting light on both faces was first articulated in the 1960 patent by Hiroshi Mori. Experimental **bifacial cells** were built in the mid-1970s (e.g. by Soviets such as Bordina et al.), demonstrating that rear illumination from ground reflection could substantially increase output. For instance, tests on Soviet Salyut space stations achieved ~34% more power with bifacial arrays than monofacial ones[2].
- **1980s–2000s:** Work continued at a research level (e.g. in Japan and Spain). However, commercial deployment was limited by cost and lack of demand. Only in the late 2000s–2010s, when PV demand exploded, did bifacial modules see rapid scaling. In 2012, for example, Panasonic licensed bifacial Hitachi solar cells (n-type heterojunction) to Yingli[7]. By 2020 the bifacial market share had surged to ~15–20%.
- **2010s–2020s:** A major industry shift occurred as “n-type” cell technologies (which naturally lend themselves to bifacial design) moved into mass production. Today, nearly all leading manufacturers produce bifacial versions

of PERC, PERT, PERL, heterojunction (HJT/HIT), TOPCon, and IBC cells. Analysts predict that by 2030 bifacial modules will account for the majority of installations[2].

In summary, bifacial PV started as a niche idea but has become mainstream, driven by improvements in cell design, optics (e.g. anti-reflective coatings on both sides), and deployment in high-albedo settings. Early enthusiasm about 30–40% energy gains[2] has translated into typical field gains of 10–30%, depending on site conditions (snow, sand, bright roof surfaces, etc.)[1]. Modern bifacial modules also often use glass–glass framing to further enhance long-term reliability[8].

Structure of Bifacial solar cells

An additional advantage of bifacial solar cells results from the decrease in cell working temperature and corresponding increase in maximum power output due to the reduced infrared absorption in the absence of the aluminum back metallization [16–18] although an increase in thermal insulation on the back side of the bifacial module is produced when a back glass is included instead, rather than the traditional backsheet laminate. Due to the decrease in working temperature, bifacial PV modules are able to operate at lower temperature than monofacial ones, resulting in an increase in maximum power output.

Fig. 1 shows a cross-section of the most common produced bifacial solar cells: the standard bifacial crystalline silicon solar cells. An open metallization grid is printed on both sides to absorb illumination from either side or both simultaneously. For the n-type cells, the emitter is the p^+ diffused layer, whereas the n^+ layer serves as a back surface field (BSF), and vice versa for the p-type solar cells. To achieve the open metallization grid at industrial production scales, texturized wafers and passivating anti-reflective coatings (ARC) are partially covered by screen printed metallic contacts [16].

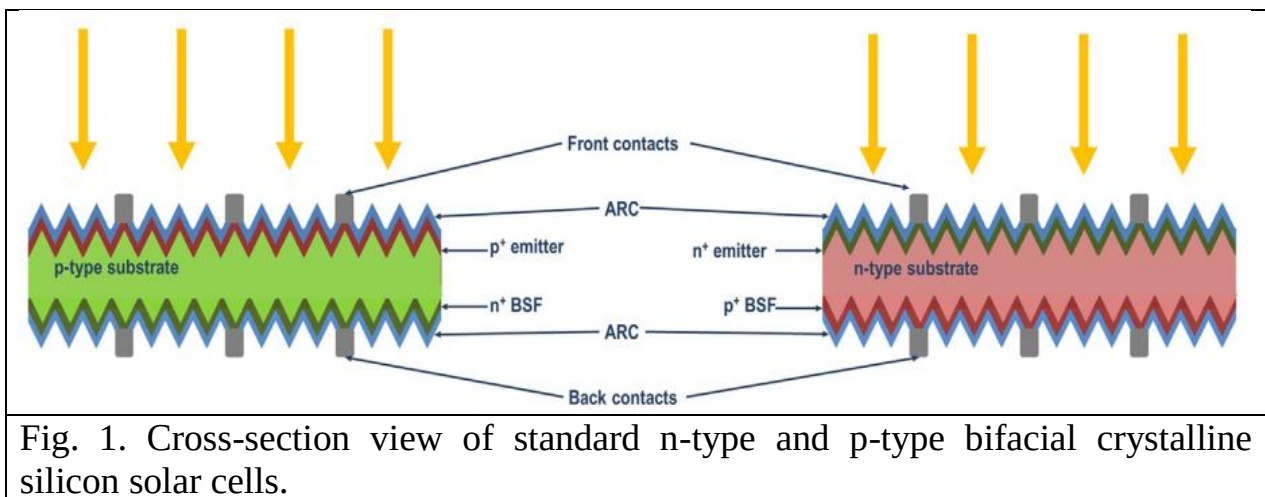


Fig. 1. Cross-section view of standard n-type and p-type bifacial crystalline silicon solar cells.

How it works

Bifacial solar cells work by generating electricity from both direct sunlight on the front and reflected light (albedo) on the back. The front of the panel functions like a traditional solar panel, converting direct sunlight into electricity. The back of the panel then collects light that has bounced off the ground or other surfaces below, and converts this reflected light into additional electricity, increasing the total energy output.

Front-side absorption: The front of the panel works identically to a standard solar panel, absorbing direct sunlight to generate electricity.

Back-side absorption: Light that isn't absorbed on the front can pass through the panel to the back. It can also be reflected off surfaces like snow, sand, light-colored roofs, or water and bounce back up to the panel's backside.

"Bifacial gain": The back-side solar cells capture this reflected light and convert it into electricity, providing an additional and independent power source.

Increased efficiency: By collecting light from both sides, bifacial panels can produce significantly more power than conventional panels, especially when mounted with space underneath to allow for light reflection.

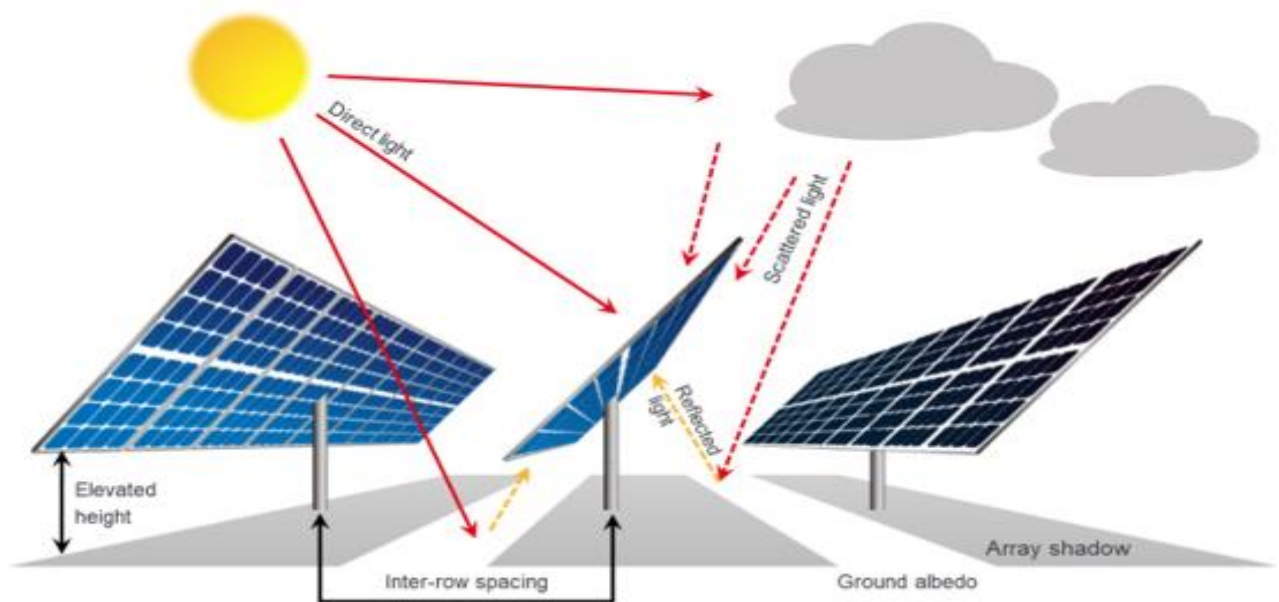


Figure 2

Why substrate choice matters for bifacial cells

Substrate determines mechanical support, optical behavior (transparency/reflectance), electrical boundary conditions (rear contact type), thermal expansion match,

manufacturability, and—critically—how the cell collects light from the rear side. For bifacial operation the substrate must often be at least partially transparent (optical or electrically) or paired with a transparent backsheet / glass + TCO stack so that albedo or reflected light reaches the absorber.

Key substrate design drivers for bifacial cells:

- **Optical transparency** (or use of transparent backsheet/glass + TCO)
- **Electrical conduction** (TCO sheet resistance vs metal grid)
- **Mechanical thickness & strength** (handling during manufacture, wind/snow load in modules)
- **Thermal and chemical stability** (encapsulation, soldering, humidity)
- **Cost and availability** (silicon dominant today)

Different substrates used for bifacial solar cells:

The first substrates for bifacial solar cells were produced from monocrystalline silicon more than 40 years ago [19]. Also substrates of multicrystalline silicon are common in this technology [20]. Moreover, glass and transparent conductive oxides (TCO) or alternative metallic contacts are usually considered as substrates for silicon thin film [21], GaAs thin film [22], CdTe [23,24], CIGS [25], and dye-sensitized solar cells [26]. However, the amount of papers devoted to bifacial technology using silicon substrates considerably exceed the other alternative material substrates (Fig. 3) [27]. This fact combined with the dominant role in the PV market gives silicon the upfront position as substrate for bifacial technology in the short and medium term. (Bifacial solar photovoltaics – A technology review).

The most important substrate parameter to be defined is the thickness because it is directly related to material and cost savings.

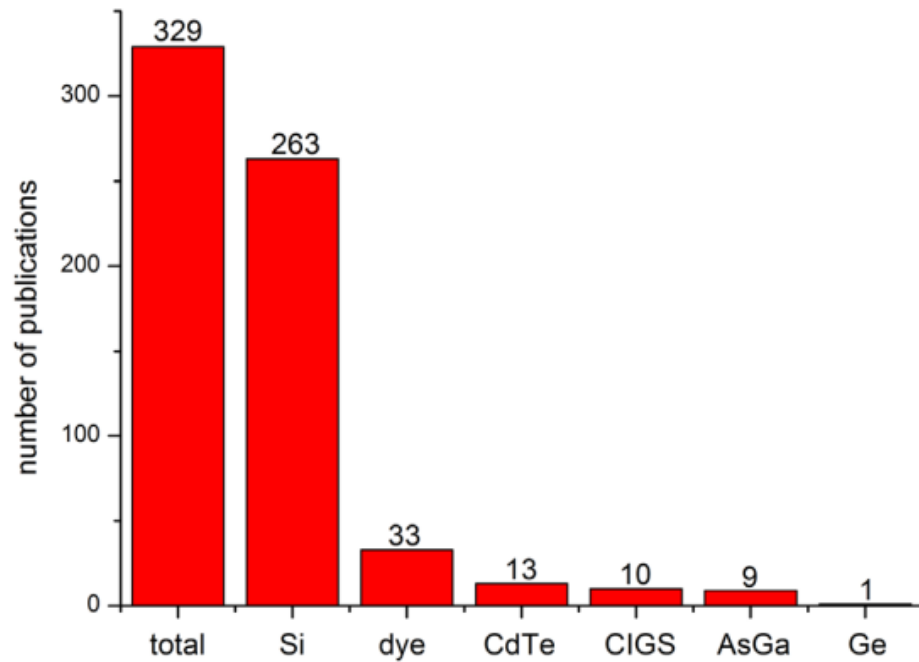


Fig. 3. Number of scientific publications devoted to different bifacial PV cell substrates from 1979 to May 2015 [27].

Assessments of different Si substrate thickness values on the conversion efficiency for each type of bifacial solar cell have been studied using direct testing [28] or modeling and simulation [29]. The experimental results with a Si substrate thickness of 140 mm compared to 240 mm show an improvement in efficiency attributed to the reduction of the impact of bulk and rear recombination, and better light trapping compared to monofacial [28] but further experiments are needed. Simulations indicate minimal decrease in conversion efficiency (0.6 percentage points) from decreasing the Si substrate thickness from 200 mm to 58 mm as well as possible manufacturing cost savings, but also indicate increasing handling difficulties [29]. Other alternatives to planar structures have been considered to reduce the amount of silicon used in the manufacturing process for bifacial cells; for example the Slivers concept, where the micro-machined 60 mm-thick solar cells decreases silicon usage by a factor of 12 (including kerf losses) [30]. (Bifacial solar photovoltaics – A technology review).

Monocrystalline silicon (c-Si)

Common uses: wafer-based bifacial PERC, TOPCon, heterojunction, n-type and p-type architectures.

Material & structure: single-crystal Si wafer produced by Czochralski (CZ) or float-zone (FZ) methods. Typical commercial wafer thickness historically ~180–200 μm ; mainstream modules today often use 140–160 μm wafers; research/ultra-thin

demonstrations go down to $<100\text{ }\mu\text{m}$ (handling and fracture risk increase as thickness decreases).

Bifacial specifics:

- Rear-side can be passivated (BPR — bifacial passivated rear) with local contacts or full-area transparent passivation + metal grid. Rear illumination increases energy yield (bifacial gain) depending on albedo and layout.
- For wafer thinning, mechanical support during processing uses temporary carriers, glass handling, or wafer-to-wafer bonding steps.

Advantages: very high material quality $\rightarrow$ high open-circuit voltage and efficiency; mature manufacturing and large supply chain; many process choices for rear passivation and contact schemes.

Limitations: cost per wafer higher than multicrystalline; extreme thinning raises fragility & handling cost.

Typical thickness ranges (practical): 80–220 μm (production commonly 120–180 μm).

Manufacturing notes: wafering kerf loss can be 100–200 μm of material per wafer in slurry sawing; kerfless techniques (epitaxial growth, wire saw, or plasma-sawn thin wafers) reduce waste but increase process complexity.

Diagram — cross-section (monocrystalline wafer bifacial cell):

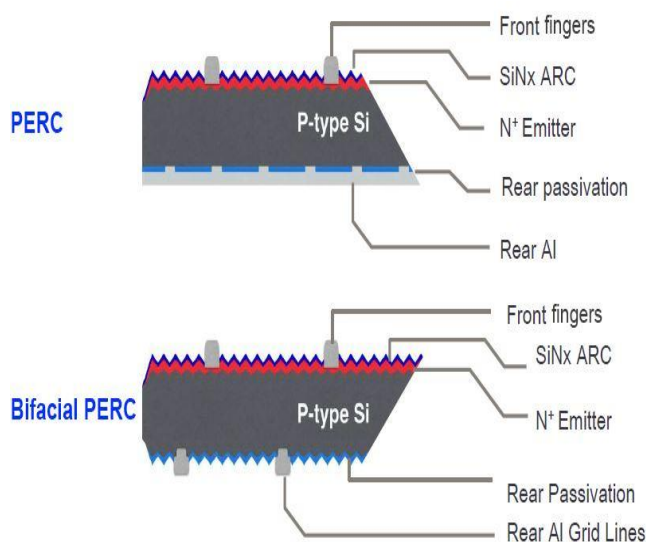


Figure 4a. Mono PERC solar cells and Bifacial PERC Solar Cell

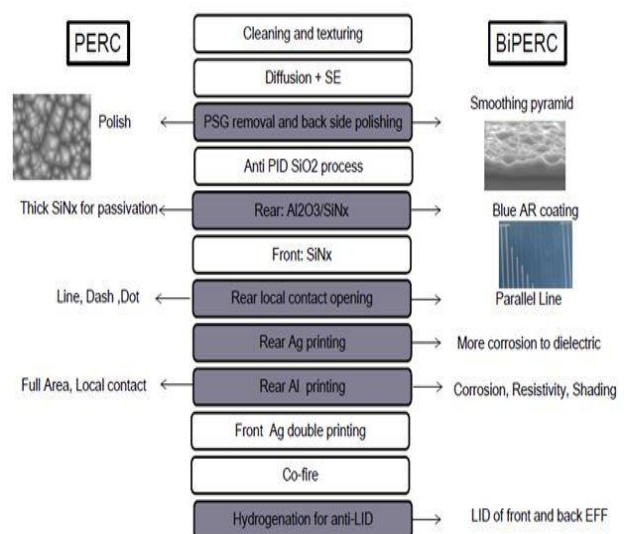


Figure 4b. Fabrication of monocrystalline wafer bifacial cell

Function of Each Layer of Bifacial Monocrystalline Solar Cell

Layer	Function / Purpose
Front glass / encapsulant	Protects from environment; must allow good light transmission with minimal loss.
Anti-reflection coating (ARC) + front passivation	Reduces reflection of incident light; passivation reduces surface recombination.
Front metal grid / busbars	Collects current; design trade-off between shading loss and resistance.
Emitter (n- or p-type front layer)	Creates the p–n junction; defines which type of doping is front side.
Si wafer substrate (monocrystalline)	Main absorber; its thickness balances cost, optical absorption, and mechanical strength.
Rear passivation dielectric	Helps avoid carrier recombination on rear surface; can be dielectric like SiO _x , AlO _x , etc.
Rear transparent contact	Let albedo or reflected light pass in and supply the rear side of the absorber; also collects current.
Rear glass / encapsulant / backsheet	Mechanical protection; when transparent, allows rear illumination.

In the solar-cell industry, “polysilicon” often refers to two related concepts:

1. **Polycrystalline silicon material** (i.e., multi-crystalline silicon substrate) — silicon made up of many crystalline grains.
2. **Polysilicon layer** as a **passivating contact layer** (e.g., deposited poly-Si on silicon oxide (SiO_x) used in TOPCon-type cells) rather than the substrate itself.

Polycrystalline (Multicrystalline) silicon (mc-Si)

A polycrystalline (multicrystalline) silicon (mc-Si) bifacial solar cell is a type of solar cell that can generate electricity from both the front and the back sides, using a material made of multiple silicon crystals. These cells are known for their ability to capture reflected and scattered light, which increases overall power output, especially when installed on reflective surfaces. While they typically have lower efficiencies than monocrystalline bifacial cells due to the grain boundaries impeding electron movement, their production cost is lower.

Material & structure: many crystalline grains; produced by directional solidification into ingots and wafering. Grain boundaries create recombination sites.
Bifacial specifics:

Bifacial mc-Si cells use the same rear-side passivation/contact options as c-Si, but overall cell efficiency is lower due to grain boundary recombination.

Bifacial gain similar in relative percent to c-Si but absolute power is lower because of reduced front efficiency.

Multicrystalline silicon (mc-Si): The cells are made from this material, which has a grainy, blueish appearance due to its multiple silicon crystals with varying orientations.

Enhanced efficiency in specific conditions: Bifacial cells can be installed over highly reflective surfaces (like white ground) to capture reflected light and potentially surpass the power output of a standard monofacial cell.

Manufacturing process: Mc-Si is produced through a directional solidification process, where molten silicon is cooled to form multiple crystals.

Lower efficiency compared to monocrystalline: The multiple crystal grains in mc-Si impede the movement of electrons, resulting in lower efficiency compared to monocrystalline cells, which have a single, uniform crystal structure. However, the bifacial design can compensate for this

Diagram — mc-Si cross-section (same stack as c-Si):

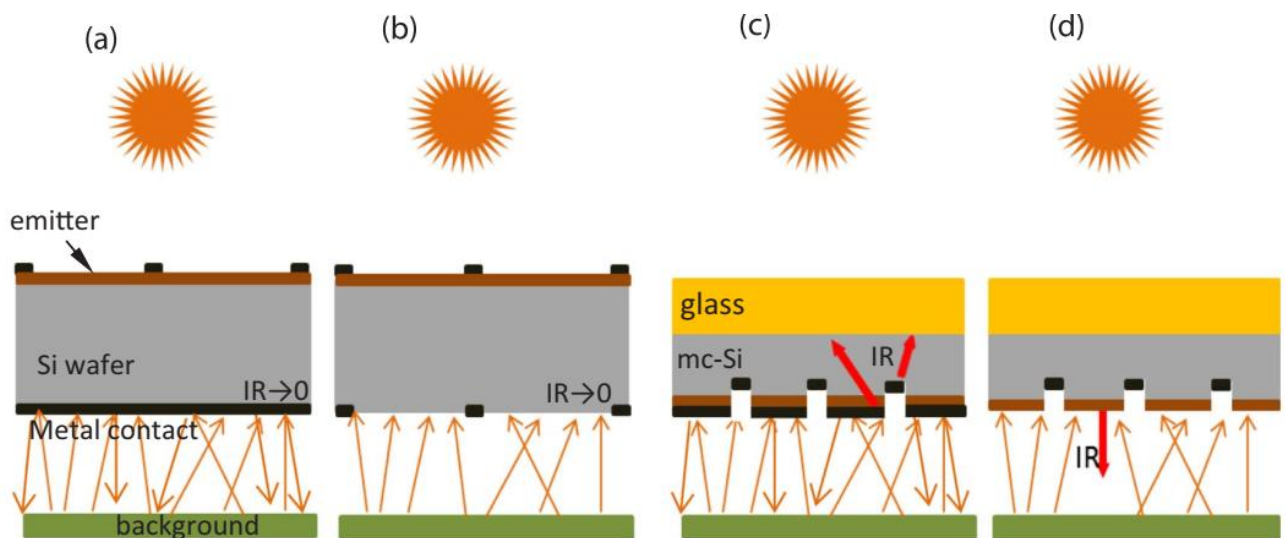


Figure 5. Sketches of monofacial wafer cell (a), bifacial wafer cell (b), monofacial mc-Si thin film solar cell (c), and bifacial mc-Si thin film solar cell (d).

(<https://doi.org/10.1016/j.solmat.2017.04.004>)

Advantages: lower material cost; well-established manufacturing.

Limitations: reduced carrier lifetime and open-circuit voltage; slightly more variation in mechanical properties; thinning limited by wafer strength.

Typical thickness ranges (practical): 120–220 μm (production commonly 150–200 μm).

Polysilicon layer

A poly-Si substrate is a semiconductor material made of many silicon crystals, used in some bifacial solar cells, particularly for the passivating contact layer or as the base material for tandem cells. For bifacial cells, it's important to use high-quality polysilicon and apply specialized fabrication techniques like passivating contacts to optimize performance and efficiency by improving passivation and reducing recombination losses on both the front and rear surfaces.

- In the bifacial silicon cell literature, the term more often refers to the latter: a thin poly-Si layer used for selective or full-area contacts on the wafer (substrate). For example, a “poly-Si/SiO_x passivating contact” on the rear of a wafer. ([osti.gov+2tib-op.org+2](https://www.osti.gov/2tib-op.org+2))
- Thus, when we speak of “poly-Si substrate” for bifacial cells, what is typically meant is a silicon wafer (mono or multi) with a poly-Si layer forming the rear or front contact/passivation, rather than the substrate being entirely polycrystalline silicon.

Glass + Transparent Conductive Oxide (TCO) or metallic transparent contacts (thin-film stacks)

Common uses: substrates for silicon thin-film (a-Si or μ c-Si), CdTe, CIGS, GaAs thin film (when grown on glass + buffer/evap layers), and DSSC. Glass is the mechanical support while TCO provides front/back electrical contact and optical transparency.

In bifacial silicon thin-film solar cells, glass substrates coated with transparent conductive oxides (TCOs) such as indium tin oxide (ITO) or fluorine-doped tin oxide (FTO), or alternative metallic contacts, are commonly used to enable light transmission and collection from both sides. These substrates support the deposition of thin silicon layers (typically 1-5 μ m thick) while minimizing material costs and allowing for rear-side illumination. The research [13] focuses on enhancing light trapping using self-assembled silver nanoparticles on the rear surface to improve absorption in the thin active layer, which is particularly beneficial for bifacial designs where light enters from both front and back. This approach increases short-circuit current density (J_{sc}) by up to 20% compared to flat references, with optimal nanoparticle coverage around 20-30% for wavelengths >600 nm. The structure typically involves a glass/TCO front contact, p-i-n silicon absorber, and nanoparticle-enhanced rear reflector on a similar TCO or metallic back contact. Challenges include balancing transparency for bifacial operation with reflectivity for light trapping, and the paper notes that silicon thin-film bifacial cells dominate research due to scalability and cost-effectiveness.

Diagram from the Research Paper (Ouyang et al., 2011): Figure 3 in the paper illustrates the cross-sectional structure of the thin-film silicon solar cell, showing the glass/TCO substrate at the front, a 2 μ m amorphous silicon i-layer sandwiched

between p- and n-doped layers, and Ag nanoparticles (average 100 nm diameter) embedded in the rear ZnO:Al contact layer for plasmonic scattering. The diagram includes ray-tracing simulations demonstrating light paths, with incoming rays from the front refracting through the glass substrate and rear rays bouncing off nanoparticles to trap within the absorber, highlighted in red for enhanced paths.

Typical materials: Soda-lime glass (2–3 mm) or borosilicate for high-temperature processes. TCO examples: ITO (indium tin oxide), AZO (Al-doped ZnO), FTO (fluorine-doped tin oxide), and doped SnO₂. **Diagram(Figure 6) — thin-film on glass (bifacial transparent back contact):**

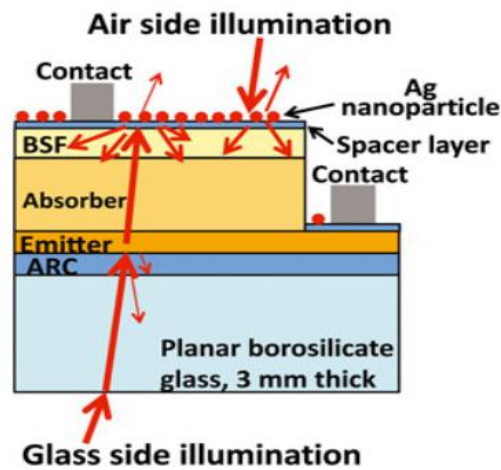


Figure 6. Cross-sectional schematic of an evaporated solar cell (not to scale). Ag nanoparticles are applied on the Si surface or on the dielectric spacer layer on top of the Si surface. Note the light scattered into Si by the nanoparticles. The incident light can enter either from the glass or the air side because of the bifacial configuration. BSF, back-surface field (DOI: 10.1002/pip.1135)

Key parameters:

- **TCO sheet resistance (Rsh)** — tradeoff between optical transparency and conductivity; typical Rsh values 5–50 Ω/sq depending on thickness and material.
- **TCO thickness:** usually 100–500 nm (tuned for optical/electrical tradeoff).

Bifacial specifics:

- Using glass + TCO on both sides gives inherently bifacial thin films because light can reach the absorber from the rear through the glass/TCO stack.
- For metal substrates (flexible steel or polymer), a transparent top TCO and a rear TCO or thin metal mesh are used to enable bifaciality.

Advantages: robust mechanical support, low marginal cost per area (glass), compatibility with large-area processing (roll-to-roll for flexible substrates).

Limitations: TCOs are less conductive than metal contacts (so rely on metal grids); TCOs can degrade under harsh chemical/back-contact processing; mismatch in thermal expansion can cause stress.

Typical thickness ranges: glass plate 1.8–3.2 mm, TCO 0.1–0.5 μm .

GaAs thin-film

Common uses: high-efficiency cells (space and concentrator PV); GaAs thin films are often grown on lattice-matched substrates (GaAs, Ge) by MOCVD or MBE.

Bifacial specifics:

- GaAs absorbers are very thin (a few micrometers), so a transparent back contact (TCO) or epitaxial lift-off onto glass can create bifacial cells.
- Epitaxial lift-off (ELO) enables reuse of expensive growth substrates and placement on transparent carriers for bifacial operation.

Advantages: high efficiency at small thickness; excellent material quality and radiation hardness (space applications).

Limitations: cost of epitaxy and substrates; complex manufacturing; limited large-area economical route today.

Typical thickness ranges: active GaAs absorber < 5 μm ; buffer + contact layers add a few μm .

Diagram(Figure 7) — GaAs thin film on glass (bifacial):

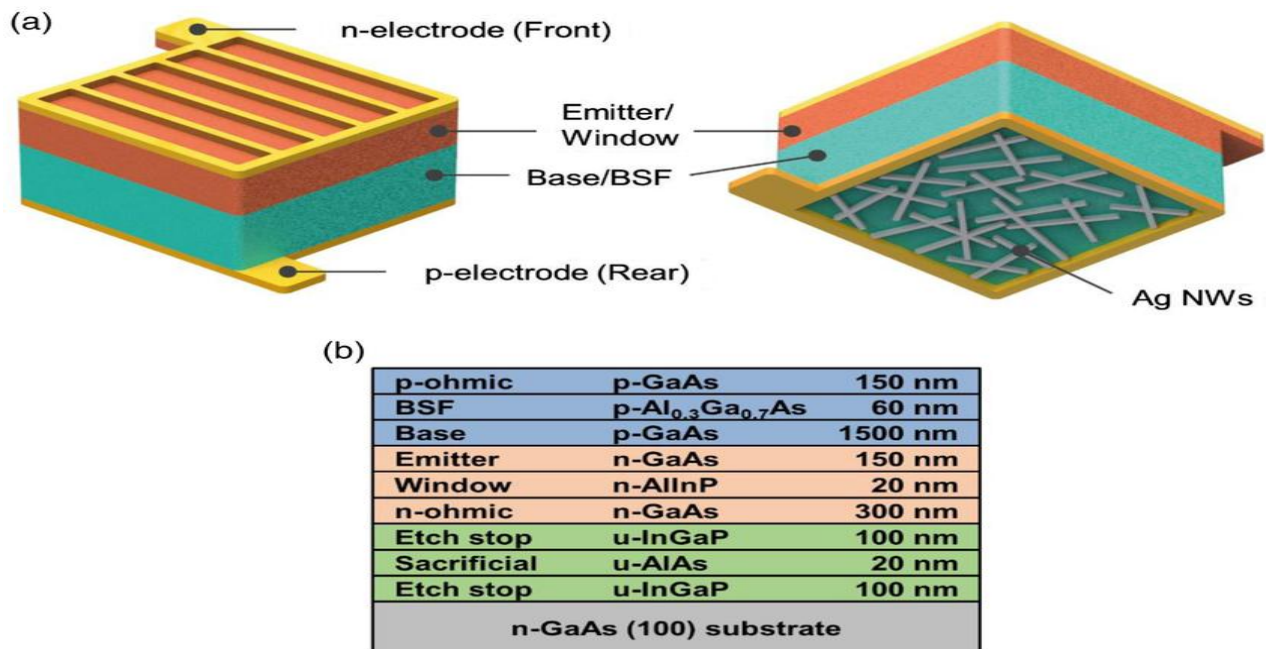


Figure 7. a) Schematic of the GaAs bifacial thin-film solar cell. Randomly dispersed Ag nanowires and metal bus bar form the p-electrode on the backside. A regular grid pattern is used for the front electrode. b) Detailed heterostructure grown by metal–organic chemical vapor deposition (MOCVD). The asymmetric p–n junction with n-GaAs emitter and p-GaAs base was designed and the inverted structure was grown

considering that the structure is flipped over after the transfer to the colorless polyimide sheet.(DOI: [10.1002/adpr.202100297](https://doi.org/10.1002/adpr.202100297))

CIGS (Cu(In,Ga)Se₂)

Common uses: thin-film flexible and rigid modules (glass, metal foils, polymer).

Bifacial CIGS on glass refers to copper indium gallium selenide (CIGS) solar cells fabricated on a glass substrate that can absorb sunlight from both the front and rear sides. This technology is attractive because it can increase overall energy production by capturing direct light, reflected light (albedo), and diffused light. Key challenges include developing a transparent rear contact and minimizing performance-degrading GaOx formation at the interface between the CIGS layer and the transparent back contact.

Bifacial specifics:

- CIGS can be grown on transparent glass + front TCO so that rear illumination (through rear glass/TCO or through transparent polymer backsheets) contributes. For flexible metal foils, designers add rear TCO + metal grid to permit bifacial operation.

Advantages: tunable bandgap, high absorption coefficient, compatible with flexible substrates.

Limitations: elemental scarcity (indium, gallium), reproducibility and scale challenges vs CdTe and Si.

Typical thickness ranges: CIGS absorber 1–2 μm ; buffer (CdS) ~ 50 nm; glass 1.8–3.2 mm.

Diagram — bifacial CIGS on glass:

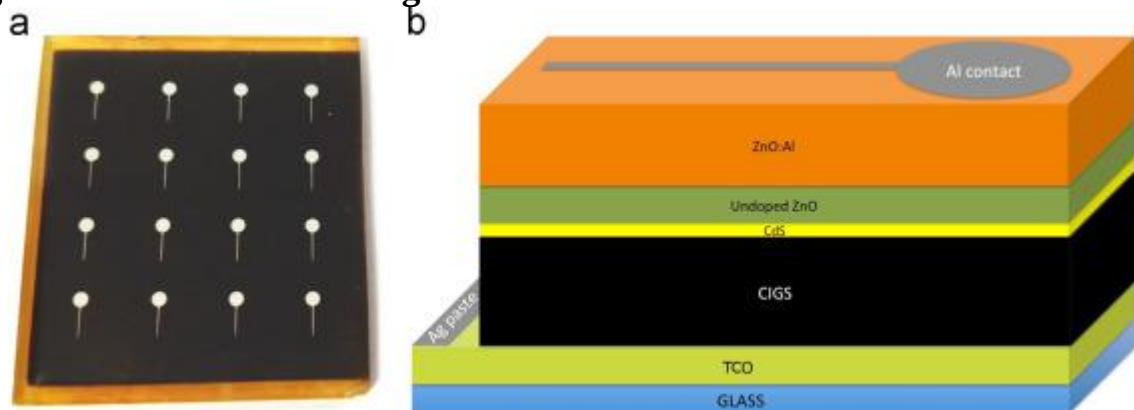


Fig. 8. a) Standard test sample processed into $16 \times 0.05 \text{ cm}^2$ devices by mechanical scribing, b) Schematic representation of the architecture of the solar cells.

<https://doi.org/10.1016/j.solmat.2016.10.048>

Dye-sensitized solar cells (DSSC)

Common uses: semitransparent building-integrated PV, agrivoltaics, low-light environments.

Bifacial Dye-Sensitized Solar Cells (DSSCs) are designed to absorb light from both the front and rear, increasing overall energy conversion efficiency by leveraging reflected light. Key developments include using transparent counter electrodes, optimizing photoanode structures with scattering layers, and improving electrolytes and dyes to enhance performance under both front and rear illumination. These cells are promising for applications like Building-Integrated Photovoltaics (BIPV) and indoor environments

Structure & materials: glass substrates coated with TCO (e.g., FTO), TiO_2 nanoparticle film (10–20 μm) sensitized by dye molecules, electrolyte (liquid, quasi-solid), and a counter electrode (Pt/graphite on TCO glass).

Bifacial specifics:

- DSSCs are inherently well-suited to bifacial operation because both sides can be transparent and the cell can collect light from either direction.
- Backside illumination yields comparable performance to front side if the counter electrode and back TCO are transparent.
- **Transparent counter electrodes (CEs):** Research focuses on creating transparent or semi-transparent CEs using materials like polyaniline, carbon nanotubes, or metal selenide alloys to allow light to pass through to the photoanode from the rear.
- **Optimized photoanodes:** Structuring the photoanode with both a main and a scattering layer of titanium dioxide (TiO_2) improves light harvesting. The scattering layer traps more light, increasing the path length for photons and enhancing absorption, especially from the rear.
- **Improved electrolytes:** Research is ongoing to find electrolytes that are stable and efficient for both front and rear illumination. Cobalt-based electrolytes are being investigated, and work is being done to minimize light absorption by the electrolyte itself to improve rear-side performance.

Advantages: good low-light performance, aesthetic transparency control, low-temperature processing.

Limitations: long-term stability (liquid electrolytes), lower peak efficiency (typically <15% in practical cells), sealing difficulties.

Typical dimensions: TiO_2 film thickness 5–20 μm ; electrolyte thickness ~25–100 μm ; glass thick

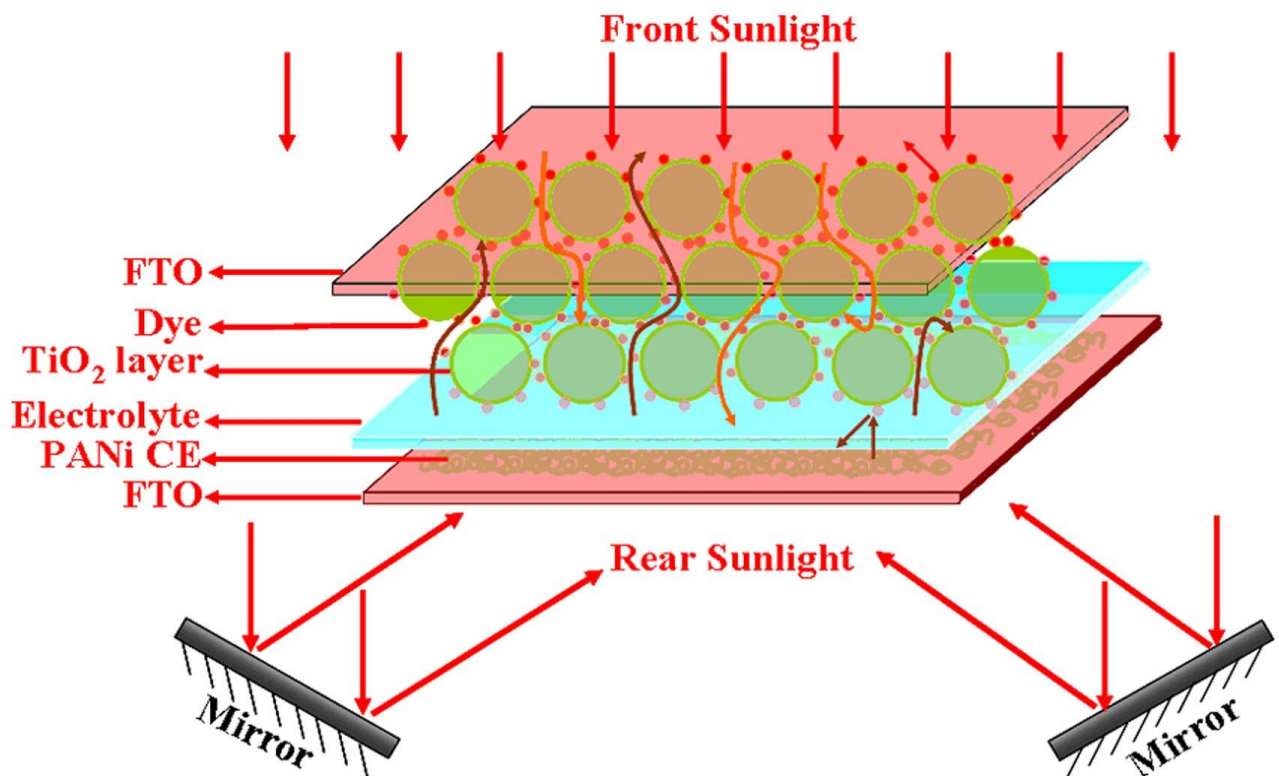


Figure 9. A bifacial DSSC by combining transparent PANi counter electrode with traditional TiO₂ photoanode(DOI: 10.1038/srep04028)

Quick summary table (substrate → bifacial considerations)

Substrate	Typical absorber thickness	Bifacial enabling element	Advantages	Disadvantages
Monocrystalline Si	80–220 μm (wafer)	Rear passivation + selective contacts	High efficiency, mature	Cost, fragility when very thin
Multicrystalline Si	120–220 μm	Same as c-Si	Lower cost	Lower efficiency, grain recomb.
Glass + TCO (thin films)	glass 1.8–3.2 mm; TCO 0.1–0.5 μm	Transparent contacts on both sides	Large area processing, transparent	TCO conductivity, degradation
GaAs thin film	<5 μm	Epitaxial lift-off to transparent support	Very high eff., thin	Very costly, complex

Substrate	Typical absorber thickness	Bifacial enabling element	Advantages	Disadvantages
CdTe	$\sim 2\ \mu\text{m}$	Transparent rear contact / glass	Low absorber thickness, low cost	Cd toxicity, Te scarcity
CIGS	$1\text{--}2\ \mu\text{m}$	Transparent rear contact / glass or foil	Flexible, tunable bandgap	Indium/Ga scarcity, scale challenges
DSSC	TiO ₂ $5\text{--}20\ \mu\text{m}$; electrolyte $\sim 25\text{--}100\ \mu\text{m}$	Transparent TCO both sides	Intrinsically bifacial, good low-light	Lower efficiency, stability issues

Silicon Cell Architectures in Bifacial Form

All major silicon cell architectures have bifacial variants. The key technologies include:

Heterojunction (HJT/HIT) cells: These combine a crystalline silicon wafer with very thin amorphous-Si layers on both sides, plus transparent conductive oxides (TCO). HJT cells naturally allow light in from the back side (through the rear TCO), giving very high bifacial factors (often $>90\%$). HJT holds the record for highest lab and commercial efficiency among silicon cells, thanks to exceptional surface passivation. For example, in 2023 the average commercial HJT cell efficiency was $\sim 25.0\%$ [\[3\]](#) (compared with $\sim 23.3\%$ for p-type PERC). HJT cells also achieve very high open-circuit voltages (typically $>700\ \text{mV}$) and fill factors due to low recombination[\[3\]](#). Critically for bifacial use, HJT's symmetric structure (amorphous-Si on both faces) yields **bifaciality** factors above $\sim 90\text{--}95\%$ [\[10\]](#), meaning nearly equal efficiency from the rear as from the front. In practice, dual-glass HJT modules with front and rear glass can exceed 30% efficiency in the lab for tandem/perovskite stacking[\[3\]\[4\]](#).

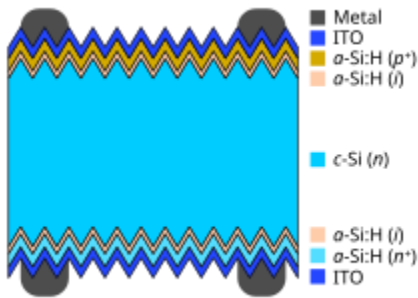


Figure 10. A cross-sectional schematic of the layers of a bifacial silicon heterojunction solar cell[3]

Figure 10: Schematic of a silicon heterojunction (SHJ) solar cell. An n-type crystalline Si wafer is coated front and rear with amorphous-Si passivation layers, TCO, and gridlines. This symmetric design enables very high bifaciality (often >90%)[3].

Passivated Emitter Rear Cell (PERC): PERC is a widely used high-efficiency p-type cell that adds a dielectric passivation layer and partial aluminum back-surface field on the rear. The standard PERC cell has a continuous Al layer on the back, making it monofacial by default. However, converting PERC to bifacial form is relatively straightforward: the continuous rear Al is **patterned or removed** so that light can penetrate to the silicon (often by leaving local Al “dots” or grids and exposing the rest). In other words, bifacial PERC uses the same processing as monofacial PERC up to the point of metallization, but changes the rear electrode pattern so that the rear side can absorb light[5]. As a result, bifacial PERC cells typically have front efficiencies in the low 20% range (e.g. 19.4–21.2%[2]) and rear efficiencies of ~17–19%. The **bifaciality factor** is around 70–80%[2] (since the rear collects somewhat less light due to less incident irradiance and residual metallization). Despite this, bifacial PERC modules (e.g. 5-to-10 busbar designs by Trina, LONGi, JA Solar) are extremely common and cost-effective. They benefit from PERC’s mature process (low cost, high throughput) with only minor changes for bifaciality[5]. Modern bifacial PERC modules often still achieve 22–23% module efficiency. Figure 4a illustrates a cross-section of a bifacial PERC cell, where the rear metal is locally patterned.

Tunnel Oxide Passivated Contact (TOPCon): TOPCon is an advanced n-type cell architecture that adds an ultra-thin silicon dioxide layer plus a doped polycrystalline Si film on the rear, forming a “tunnel oxide passivated” back contact. The structure (with a selective boron front emitter and n-type (phosphorus) TOPCon rear) greatly reduces recombination at the contacts. TOPCon cells routinely exceed 25% efficiency in the lab[6] (and p-type TOPCon production cells average ~24.9%[3]). The n-type

base avoids light-induced degradation, and the device offers a better temperature coefficient than p-type cells. Importantly for bifacial use, TOPCon can be made bifacial by applying TCO and metal grids to the rear **in addition** to the front. The result is higher rear-side sensitivity than PERC: field measurements show TOPCon bifacial cells with bifaciality ~75–76% (versus ~64% for PERC)[7]. In real-world tests, bifacial TOPCon modules have outperformed PERC: one field study found TOPCon yield ~5.6% higher than PERC (and ~2% lower than HJT) in identical conditions[7]. TOPCon’s combination of high efficiency and decent bifacial gain makes it a leading choice in new high-end bifacial panels.

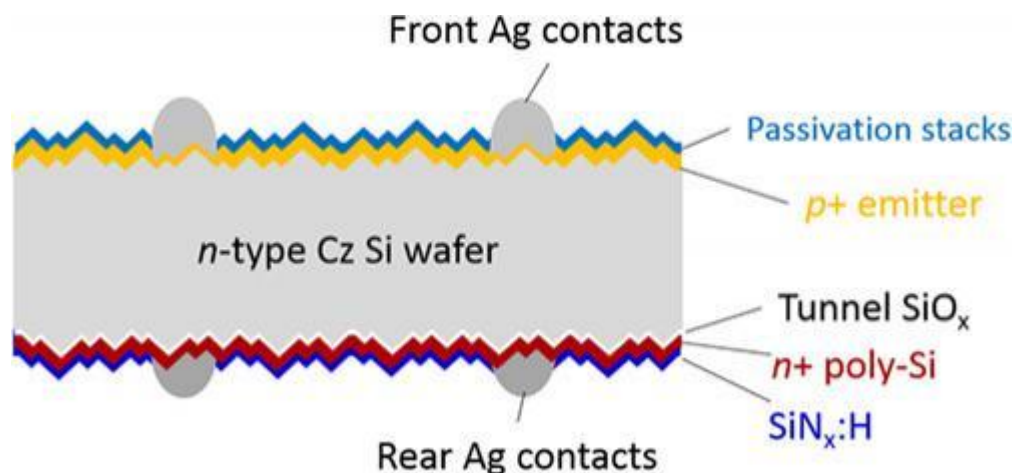


Figure 11. A bifacial solar cell concept, typical for an industrial n-type TOPCon solar cell.

Figure 11: Schematic of a TOPCon solar cell. An n-type Si wafer has a thin tunnel oxide (+poly-Si) passivation layer on the rear. Both front and rear surfaces have textured junctions and metal contacts, allowing bifacial collection.

Other Silicon Variants: Several niche or emerging designs also appear in bifacial modules. These include PERT (Passivated Emitter, Rear Totally-diffused, a variant of PERC), PERL (with local boron diffusions), and IBC (Interdigitated Back Contact) cells. For example, PERT cells can reach 19.5–22% front efficiency (17–19% rear) and ~80–90% bifaciality[2]. PERL can reach ~19.8% (front) and ~80–90% bifaciality[19]. IBC cells avoid front shading entirely, giving high theoretical bifaciality (~70–80%), and lab IBC cells have 23%+ efficiency[2]. However, complexity and cost limit their market share. These alternatives show that virtually any modern cell architecture can be adapted to bifacial use by providing transparent/rearside contacts and passivation on both faces.

Cell Type	Front Efficiency (%)	Rear Efficiency (%)	Bifaciality (%)
PERC (p-type)	19.4–21.2[14]	16.7–18.1[14]	70–80[14]

Cell Type	Front Efficiency (%)	Rear Efficiency (%)	Bifaciality (%)
PERT/PERL (p-type)	19.5–22.0[18]	17–19[18]	80–90[18][19]
IBC (n-type)	~23.2[20]	– (back contacts)	70–80[20]
HJT/HIT (n-type)	~24.7[9]	~24.7 (similar)	95–100[10]
TOPCon (n-type)	>25 (lab)	~22–24 (typical)	75–85[16]

Table 1: Typical efficiency and bifaciality figures for different silicon cell technologies in bifacial form (sources in brackets). “Bifaciality” is the rear-side efficiency relative to the front.

Fabrication Methods

General Bifacial Cell Fabrication: Turning a conventional solar cell process into a bifacial one typically involves additional or modified steps to enable light capture on both sides. Key changes include doping both surfaces and adjusting metallization:

- **Dual-sided junctions:** Whereas a standard (monofacial) p–n cell only requires forming a junction on one face (e.g. phosphorus diffusion on one side and full-Al on the back), a bifacial cell may require doping or diffusing **both** sides differently. For instance, one approach is **co-diffusion**: simultaneously diffusing boron (for a front p+ emitter) and phosphorus (for a rear n+ emitter) on opposite sides of a wafer[2]. Another method is **ion implantation**, allowing precise doping on both faces with minimal thermal budget. In any case, bifacial cells often have asymmetric doping: typically a highly doped thin emitter on one side and a more lightly doped layer on the other, to optimize performance from both directions.
- **Surface passivation and ARC:** Both faces need high-quality passivation (to minimize surface recombination) and anti-reflection coatings (ARC) for efficient light in-coupling. Materials such as silicon nitride (SiN_x) or ultra-thin silicon dioxide are applied symmetrically. For example, TOPCon cells use a stack like $\text{SiO}_2/\text{Al}_2\text{O}_3/\text{SiN}_x$ on the front and $\text{SiO}_2/\text{poly-Si}/\text{SiN}_x$ on the back[8]. HJT uses intrinsic a-Si:H films on both faces. Advanced AR coatings (double-layer or textured surfaces) are applied to both sides to maximize transparency. In sum, the fabrication steps up to front metallization are largely the same as monofacial cells; the differences are in rear processing and the addition of back-side transparent structures.
- **Back contacts:** The metalization pattern on the rear is critical. For bifacial PERC, the rear Al is no longer a solid foil; instead, a **patterned rear contact** is used. Typically, a local Al grid is printed (using pastes and low-temperature firing) or plated on the rear with exposed silicon between contacts to admit

light[5]. This requires precise screen-printing or photolithography to ensure uniform grids that balance conductivity and transparency. HJT and TOPCon bifacial cells use thin conductive oxides (TCO) on the rear, followed by fine metal fingers; here copper plating techniques (electroplated copper onto etched seed layers) are becoming common to reduce silver paste usage while maintaining good conduction.

- **Temperatures and Equipment:** Notably, n-type HJT and TOPCon lines avoid very high-temperature steps (no high-temp diffusions or metallization firing). HJT uses low-temperature PECVD and sputtering (typically $<250^{\circ}\text{C}$)[4], which reduces thermal stress and energy use. TOPCon requires a thin oxide growth (e.g. $\sim 10\text{ nm SiO}_2$) followed by polycrystalline Si deposition, but both are done at relatively moderate temperatures ($\sim 800^{\circ}\text{C}$ for oxide growth, compared to 900°C for PERC diffusions). By contrast, p-type PERC cells use a high-temperature phosphorus diffusion and aluminum alloying furnace. In summary, bifacial variants typically add only one or two extra masks/processes compared to their monofacial counterparts, meaning factories can often retrofit lines to bifacial production with minimal new investment.

Performance Metrics and I–V Characteristics

The performance of any solar cell (bifacial or not) is quantified by its **current–voltage (I–V) characteristic** under illumination. Figure 12 (below) illustrates a typical I–V curve of a silicon cell.

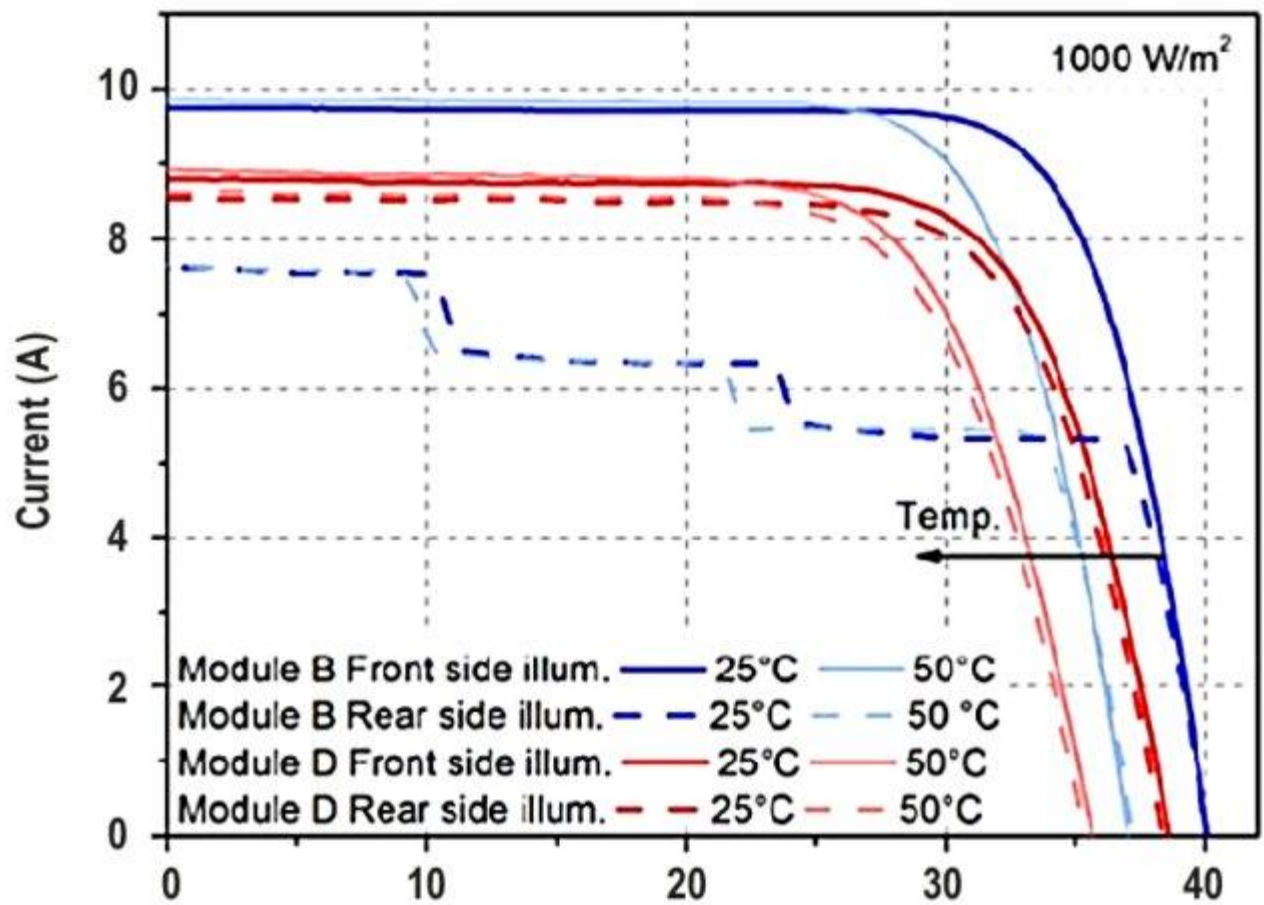


Figure 12. IV curve for bifacial solar cell (doi: <https://doi.org/10.1109/jphotov.2018.2834625>)

Key parameters defined from this curve are:

- **Short-Circuit Current (I_{sc}):** The current when the output is shorted ($V=0$). This is proportional to the light absorbed. Bifacial cells will have a higher I_{sc} under rear illumination or combined illumination than under front-only.
- **Open-Circuit Voltage (V_{oc}):** The voltage at zero current (open circuit). This depends logarithmically on I_{sc} and the diode saturation current; higher I_{sc} typically yields slightly higher V_{oc} .
- **Maximum Power Point ($P_{max} = V_{mp} \times I_{mp}$):** The point on the curve (V_{mp} , I_{mp}) giving maximum power.
- **Fill Factor (FF):** The ratio of P_{max} to ($V_{oc} \cdot I_{sc}$). It measures how “square” the I–V curve is and indicates losses; FF is typically 0.7–0.8 for good silicon cells[24].
- **Conversion Efficiency (η or PCE):** The ratio of P_{max} to incident power (P_{in} , typically 1000 W/m² for “one sun”). Equivalently, the **power conversion efficiency (PCE)** is:

$$\eta = (V_{oc} \cdot I_{sc} \cdot FF) / P_{in}$$

convention η is given as a percentage.

A tutorial on solar cell characterization notes that V_{oc} , I_{sc} and FF are all extracted from the I–V curve[9][10]. For bifacial cells, one may measure separate I–V curves for front-side illumination and rear-side illumination. Often an “equivalent” or “combined” efficiency is defined by weighting the two by their relative irradiances[2]. (In practice, for ground-mounted bifacial panels, one might measure the sum of the currents or perform indoor tests with simultaneous dual-illumination.) One subtlety is the **bifacial separation rate**: the current under combined illumination can slightly exceed (or sometimes fall short of) the sum of currents measured separately, due to device series resistances and V_{oc} changes[27].

Typical I–V and P–V curves for a silicon solar cell. The open-circuit point (V_{oc} , $I=0$), short-circuit (I_{sc} , $V=0$), and maximum-power point (V_{mp} , I_{mp}) are indicated. Efficiency is P_{max}/P_{in} and fill factor FF is $(V_{mp} \cdot I_{mp}) / (V_{oc} \cdot I_{sc})$.

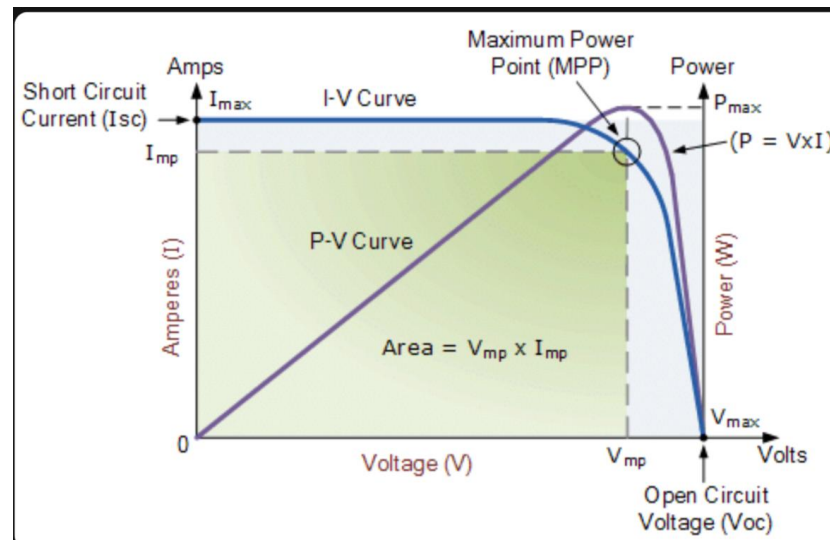


Figure 13. A typical silicon cell I–V curve and corresponding P–V curve

Figure 13: A typical silicon cell I–V curve and corresponding P–V curve, illustrating I_{sc} , V_{oc} , maximum-power point, and fill factor[24]. (Parallel-connected cells or modules simply scale these values.)

In summary, efficiency is computed from the I–V parameters. For example, a bifacial PERC cell might have $I_{sc} \approx 9.8$ A at $V=0$ and $V_{oc} \approx 0.685$ V; if $V_{mp} \approx 0.55$ V and $I_{mp} \approx 9.0$ A (as in the DS New data[5]), its $P_{max} \approx 4.95$ W (for a 156 mm cell), yielding an efficiency ($P_{max}/\text{area}/1000$ W/m²) around 22.3%.

Performance Comparisons and Bifacial Gains

Field and lab comparisons show clear differences among PERC, HJT, and TOPCon bifacial modules:

- **Efficiency:** HJT cells have the highest intrinsic efficiency. As noted, commercial HJT cells average ~25%[\[3\]](#), versus ~24.9% for n-type TOPCon and ~23.3% for p-type PERC in 2023[\[3\]](#). Laboratory records even higher: e.g. HJT was on track for 26.7% single-junction. In addition, HJT stacks under bifacial/tandem schemes can exceed 30%. PERC cells are simpler but top out around ~22–23% in production. TOPCon (n-type) cells are bridging the gap, with recent TOPCon cells certified above 25%.
- **Bifaciality Factor:** HJT stands out with **extremely high bifacial factors**. The excellent passivation and transparent back emitter mean its rear-side efficiency can approach 95–100% of the front side[\[3\]](#). By contrast, PERC’s rear side, with residual metal shading and only partial irradiance, is ~70–80% of front[\[3\]](#). TOPCon is intermediate: in one field test, measured bifaciality was ~83% for SHJ (HJT), ~76% for TOPCon, and ~64% for PERC[\[7\]](#), closely matching their efficiency gains.
- **Field Energy Yield:** Real-world performance is best judged by energy yield over time. One 2022 outdoor study in Hainan, China directly compared bifacial TOPCon, HJT, and PERC modules under identical conditions. It found that **HJT modules produced ~8.8% more energy than PERC, and TOPCon ~5.6% more than PERC** over the test period[\[7\]](#). These gains arise mainly from the higher bifaciality and better temperature response of HJT/TOPCon. For example, HJT has a lower temperature coefficient ($\approx -0.23\%/^{\circ}\text{C}$) than PERC ($\approx -0.29\%/^{\circ}\text{C}$), meaning HJT loses less efficiency on hot days[\[3\]](#). The study’s authors attributed the superior performance primarily to HJT’s high rear-side collection and stability, with TOPCon’s advantage over PERC due to improved low-light behavior (back surface passivation)[\[7\]](#).
- **Operating Conditions:** In diffuse or shaded light, bifacial modules can still generate power. Even on an overcast day or at dawn/dusk, the rear side (especially if reflective ground is present) contributes extra current. The I–V curves of bifacial modules under combined illumination show higher I_{sc} (and slightly higher V_{oc}) than monofacial under the same front illumination. However, partially shaded conditions can reduce the effective gain; system designers often use bypass diodes judiciously.
- **Environmental Effects:** High-albedo settings amplify bifacial benefits. In snowy conditions or on bright rooftops, bifacial gains of 30%+ have been observed[\[3\]](#). Conversely, on dark soil the gains are modest (maybe 5–10%). Agrivoltaic installations often use bifacial panels to harness reflected light from vegetation/ground. Overall, bifacial modules tend to outperform similarly sized monofacial modules in energy per footprint, improving project economics (higher return on investment for the same rack area).

Calculation of Efficiency and I–V Characteristics

The **efficiency (η)** of a solar cell is defined as the ratio of its maximum electrical power output to the incident light power. Mathematically:

$$\eta = (V_{oc} \cdot I_{sc} \cdot FF) / P_{in}$$

where V_{oc} is open-circuit voltage, I_{sc} is short-circuit current, FF is the fill factor, and P_{in} is the incident irradiance (e.g. 1000 W/m²). In practice, I_{sc} , V_{oc} , and FF are extracted from the measured I–V curve. The fill factor is defined as

$$FF = (V_{mp} \cdot I_{mp}) / (V_{oc} \cdot I_{sc})$$

where V_{mp} and I_{mp} are the voltage and current at maximum power (the “knee” of the I–V curve)[9]. Typical fill factors for good crystalline silicon cells are 0.7–0.8[9]. Thus one can calculate efficiency directly from measured I–V data.

For **bifacial modules**, one often defines an “equivalent efficiency” combining front and rear illumination. One approach is to weight the front and rear I–V contributions by their respective irradiances. If $I_{sc,(front)}$ and $I_{sc,(rear)}$ are the short-circuit currents under front and rear illumination (with corresponding $V_{oc,f}$, $V_{oc,r}$), the total (bifacial) current at maximum power is not strictly $I_{mp,f} + I_{mp,r}$ due to resistive and voltage effects. The *separation rate* formula notes that combined current can be slightly higher than the sum of separate measurements[2]. In system terms, designers will often simulate or measure the module under realistic albedo conditions to get the true PCE.

In summary, the **voltage–current (V–I) curve** and derived parameters (V_{oc} , I_{sc} , V_{mp} , I_{mp} , FF) fully characterize a cell. Bifacial cells follow the same physics: two illuminated PN junctions contribute additional photocurrent. The maximum power from both sides is easily computed: if front and rear illumination are independent, one might use $V_{mp} \approx 0.9 \cdot V_{oc}$ and $I_{mp} \approx 0.9 \cdot I_{sc}$ as rough estimates (0.8–0.95 factors depending on material)[35]. For example, if a bifacial PERC cell has $I_{sc(front)}=10$ A and $I_{sc(rear)}=7$ A under given light, and $V_{oc} \approx 0.69$ V, then $V_{mp} \approx 0.6$ V, $I_{mp} \approx (0.9 \times 10 + 0.9 \times 7) = 15.3$ A (assuming linear sum), giving $P_{max} \approx 9.18$ W for that cell. At 1000 W/m², this corresponds to $\eta \approx (9.18 \text{ W}) / (156 \text{ mm} \times 156 \text{ mm} \times 10 \text{ W}) \sim 22\%$, comparable to measured values. (Actual measurements must account for series resistance, spectral differences, etc.)

Organic and Other Non-Silicon Bifacial Cells

While most bifacial modules use silicon, there is growing research in **organic and perovskite** bifacial cells:

- **Organic Solar Cells (OSC):** Traditional organic PV cells (based on polymer or small-molecule semiconductors) are inherently thin and can be made semi-

transparent. Researchers have built bifacial organic cells using transparent electrodes on both sides. For example, a recent study by Çokduygular *et al.* (2024) used a PtB7 polymer absorber with a transparent MoO₃/Ag/WO₃ contact, achieving a **bifacial factor** ~ 0.94 (i.e. rear efficiency $\approx 94\%$ of front)[11]. Their cells had an AVT (visible transmittance) of $\sim 47\%$, and front/back efficiencies of $\sim 3.9\%$. In essence, organic materials can be arranged symmetrically to yield nearly equal performance from both faces[31]. More impressively, Ren *et al.* (2024) reported an **organic bifacial cell with 20.4% PCE** under a rear albedo of 0.2[12]. They used ultra-thin Ag electrodes and special antireflective nanostructures to minimize optical losses. Under 0.2 albedo, the combined output reached 20.4% efficiency[12], demonstrating that high-performance organic cells can exploit reflected light. These advances suggest that flexible or lightweight bifacial organic modules (for window-integrated PV, IoT devices, etc.) may be feasible.

- **Perovskite and Tandems:** Metal-halide perovskite solar cells are often semi-transparent and are currently the fastest-advancing PV technology. Researchers have begun exploring **bifacial tandem cells** combining perovskite with silicon or other perovskite layers. For example, four-terminal bifacial perovskite/silicon tandems can capture both top-spectrum light (in the perovskite) and bottom-spectrum plus albedo (in silicon). One modelling study found that adding a ~ 1.44 eV perovskite as a top cell yielded $\sim 13.4\%$ extra power at 30% albedo compared to a monofacial tandem[13]. In extreme albedo cases (80%), a four-terminal tandem could exceed 495 W/m² power density[13]. All-perovskite tandem cells have also been demonstrated in bifacial form; a recent report achieved an equivalent $\sim 29.3\%$ efficiency with bifacial illumination[14]. These tandem concepts show that bifaciality combined with multi-junction design may push efficiencies well beyond single-junction limits, especially in snowy or reflective environments.
- **Other Materials:** Research is also exploring thin-film bifacial cells (CIGS, CdTe, etc.) by depositing transparent back contacts, and hybrid designs (organic/silicon, etc.). Any PV cell architecture that can be made semi-transparent on the rear can, in principle, be used bifacially. The trend toward tandem and building-integrated PV is driving interest in bifacial flexible cells (as for hybrid PV facades).

In summary, bifacial design principles are extensible beyond silicon. New materials like organics and perovskites are now being engineered with double-sided structures to harvest ambient light. These emerging bifacial cells currently have lower absolute efficiencies than silicon, but they open applications (e.g. transparent windows, curved surfaces) where rear-side light can be significant.

Tandem and Combined Bifacial Architectures

Because bifacial modules capture extra light, they pair naturally with multi-junction (tandem) cells to push efficiency further. In a tandem, the top cell can use the extra rear irradiation as well. Some examples:

- **Perovskite/Silicon Tandem:** A perovskite top cell is typically semi-transparent. In a monofacial tandem, the bottom silicon only sees sunlight filtered through the top cell. In a bifacial tandem, the bottom cell *also* sees reflected light. Studies have modeled that a 2-terminal perovskite/Si tandem with a ~ 1.44 eV perovskite can achieve a **13.4% higher power output** at 30% albedo than the same tandem facing only front light[33]. Four-terminal tandems (with separate outputs) can be even better; simulations show power densities exceeding **495 W/m²** when the albedo is 80%[13]. This means bifacial tandem modules (especially in snowy or highly reflective settings) could approach or exceed 35–40% effective module efficiency.
- **All-Perovskite Tandem:** Recent experiments have built fully perovskite tandems that are bifacial. For instance, a four-terminal “all-perovskite” stack achieved an equivalent $\sim 29.3\%$ efficiency under bifacial illumination[14]. These devices leverage the broad spectral capture of perovskite and use the rear absorber to capture longer-wavelength and diffuse light. The ability to make perovskite layers semi-transparent simplifies bifacial design (just use transparent electrodes on both sides).
- **Organic/Silicon Tandem:** Preliminary research is exploring organic top cells over silicon with bifacial backing, though commercial examples are still far off.
- **Emerging Stacks:** In principle, any tandem that uses thin top layers can exploit bifacial illumination on the bottom layer(s). For example, combining thin-film CIGS or organic cells on top of silicon, all integrated into a bifacial module, could enhance yield. The rapidly evolving field of tandem PV frequently considers bifacial modes as part of system optimization.

Overall, bifaciality acts as a “performance multiplier” for tandem cells in real sites, capturing what would otherwise be wasted rear-side light. While monofacial tandems already have record efficiencies, bifacial tandem modules offer a path to even greater generation in practical installations. However, real-world optimization requires accounting for the installation geometry (tilt, height, ground reflectivity) and the fact that rear-illumination spectra differ from direct sun.

Summary

Bifacial solar cells have evolved from a laboratory curiosity in the 1960s–1970s to a mainstream commercial technology by the 2020s. Virtually all high-efficiency silicon cell designs today (HJT, TOPCon, PERC variants, IBC) can be—and often are—manufactured in bifacial versions. The key benefits of bifacial modules are higher energy yield (especially in reflective environments) and better temperature

performance, at modest additional manufacturing cost. We have seen that Heterojunction (HJT) cells, with their symmetric amorphous-Si contacts, achieve the highest bifacial factor ($\approx 95\%$); PERC cells can be made bifacial by rear-metal patterning; and TOPCon cells marry the advantages of both with rear-side TCO contacts[7][3]. Calculating efficiency and I–V characteristics follows the same principles as for monofacial cells, with efficiency determined from I_{sc} , V_{oc} , and fill factor[9][10].

In practical terms, field trials confirm that HJT modules outperform PERC by roughly 8–9% in yield, with TOPCon $\sim 5\%$ above PERC[7]. Organic and perovskite bifacial cells, while lower in efficiency now, demonstrate that the bifacial concept extends beyond silicon. With PV installations moving to bifacial in growing numbers, it is likely that by 2030 most new utility projects will use bifacial panels to maximize the energy output per unit area[1][2].

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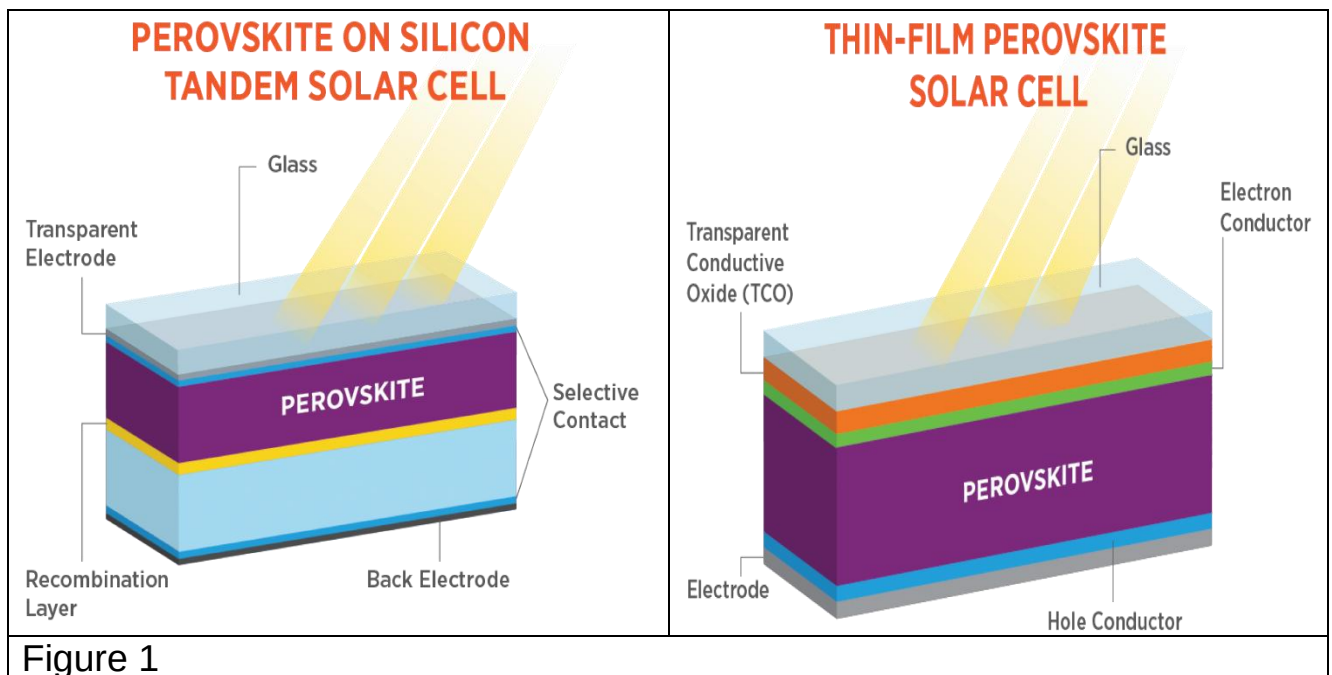
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Chapter V

5. Perovskite Solar Cells

Introduction

Perovskite solar cells (PSCs) are a rapidly emerging photovoltaic technology that uses a class of materials with the perovskite crystal structure as the light-absorbing layer. These materials, generally metal-halide perovskites, have the chemical form ABX_3 (where A is a cation like methylammonium or cesium, B is a metal such as lead or tin, and X is a halogen such as iodine or bromine)[1]. The name “perovskite” comes from a calcium titanate mineral first discovered in the 19th century, but its application in solar cells is very recent. Perovskite absorbers exhibit exceptional optoelectronic properties – strong absorption across the visible spectrum, long charge-carrier diffusion lengths, and tunable bandgaps – all achieved with low-cost solution processability[1]. This combination of high performance and low production cost potential makes PSCs one of the most exciting developments in solar energy.



In a perovskite solar cell, a thin polycrystalline film of perovskite semiconductor is sandwiched between charge-selective contact layers to form a photovoltaic device(Figure 1). When sunlight strikes the perovskite layer, it generates electron-hole pairs that are efficiently separated and collected as electrical current by the adjacent electron and hole transport layers[1]. Unlike conventional silicon solar cells, which require expensive high-temperature processing of crystalline wafers, PSCs can be fabricated at relatively low temperatures on various substrates (even

flexible plastic) using coating or printing techniques. This gives perovskites the status of a “third-generation” solar technology with the promise of combining high efficiency with low manufacturing cost. Indeed, since the first report in 2009, the power conversion efficiency of PSCs has skyrocketed from about 3% to over 26% for single-junction cells, and tandem cells that combine perovskites with silicon (Figure 1) have exceeded 33% – rivaling the best silicon cells and even breaking through the theoretical single-junction efficiency limit[2][1]. Researchers are also attracted by the versatility of perovskite chemistry; by compositional engineering, the material’s bandgap and stability can be tuned, enabling applications from colored or transparent solar cells to tandem architectures.

However, challenges remain before PSCs can see wide commercial use. Stability is the foremost issue – early perovskite cells would degrade within minutes or hours due to moisture, heat, or UV light, whereas a commercial solar panel must last 20–25 years[3][4]. Significant progress has been made in improving perovskite stability (for instance, using 2D/3D hybrid perovskites or interface engineering), with some recent devices retaining ~80% of performance after 5 years of equivalent aging[8][7]. Efforts are also underway to scale up lab-sized (~0.1 cm²) high-efficiency cells to larger modules while maintaining performance[3][9]. Despite these hurdles, the pace of innovation in PSCs is remarkable, and there is strong optimism that perovskite solar cells will become a viable technology for cost-effective, high-efficiency solar power in the near future.

Historical Development and Efficiency Progress

Research into perovskite-based solar cells is only a little over a decade old, yet the efficiency progress has been unprecedented in the history of photovoltaics. Below we trace the development from the first prototype cells to the latest record-breakers, highlighting key milestones and how efficiencies have improved step by step.

- 2009 – First Perovskite Solar Cell: The concept of using a perovskite material in a solar cell was first demonstrated by Miyasaka and coworkers in 2009. They used an organometal halide perovskite ($\text{CH}_3\text{NH}_3\text{PbI}_3$) as a sensitizer in a dye-sensitized solar cell (DSSC) architecture, achieving a power conversion efficiency (PCE) of ~3.8%[10]. In this design, perovskite nanoparticles coated a mesoporous TiO_2 scaffold and worked in conjunction with a liquid electrolyte, similar to DSSCs. While the efficiency was modest (only a few percent), this result was “*an exciting finding at the time*” (Kojima *et al.*, 2009)[5], as it proved that perovskites could effectively convert visible light to electricity. A major drawback was the device stability – the liquid electrolyte caused the perovskite to dissolve, so the cell lasted only minutes[3]. Nevertheless, this 2009 report is regarded as the birth of perovskite photovoltaics.
- 2011 – Efficiency Rises to 6–7%: In 2011, Park and colleagues improved the perovskite cell efficiency to 6.5% by refining the DSSC-style architecture (Nam-Gyu

Park *et al.*)[3]. They used a similar methylammonium lead iodide perovskite on mesoporous TiO₂ but achieved higher photovoltage and current through interface improvements (Im *et al.*, 2011). This showed the 2009 result was not a fluke and that rapid efficiency gains were possible, although stability was still poor due to the liquid electrolyte.

- 2012 – Solid-State Perovskite Cells (~10% PCE): A *breakthrough* came in 2012 when researchers in Oxford (Lee, Snaith *et al.*) replaced the liquid electrolyte with a solid hole-transport material (HTM), spiro-OMeTAD[13]. They also found that the mesoporous TiO₂ layer was not strictly necessary – an inert scaffold or even a flat layer could work if a proper electron transport layer was present[3]. Using a solid-state mesoscopic configuration, they achieved about 9–10% efficiency, marking the first solid-state perovskite solar cells[3]. By late 2012, perovskite cells exceeding 10% efficiency were reported, and the photovoltaics community began paying serious attention. Importantly, solid-state cells showed improved stability (no liquid to dissolve the perovskite), although stability was still far from commercial requirements.
- 2013 – Exceeding 15% Efficiency: In 2013, multiple groups pushed efficiencies higher by improving fabrication methods and device architectures. A notable advance by Burschka *et al.* (EPFL) used a two-step sequential deposition process to form the perovskite, achieving 15% efficiency with a mesoporous TiO₂ scaffold[3]. Meanwhile, Malinkiewicz *et al.* demonstrated evaporation techniques for a planar device in an inverted (p–i–n) configuration (~12% PCE)[3], and Liu *et al.* (Oxford) showed a planar n–i–p device with co-evaporated perovskite at 15% PCE[3]. These results proved that *planar thin-film perovskite cells* (with no mesoporous TiO₂) could be highly efficient. By the end of 2013, both mesoporous (sensitized) and planar architectures had crossed the 15% efficiency mark.
- 2014 – Reaching ~20%: Innovations in 2014 continued at breakneck speed. Researchers explored interface engineering and compositional tweaks to boost performance. For example, a planar cell from Yang Yang’s group at UCLA achieved ~19% PCE (reverse-scan) by optimizing interfaces (Zhou *et al.*, 2014)[3]. Around the same time, a Korean group (KRICT, led by Seok) set a certified record of 20.1% (non-stabilized) in late 2014[3]. Perovskite solar cells had thus reached the level of multicrystalline silicon in just a few years. Researchers also discovered that using mixed halides (iodide/bromide) and different cations (formamidinium (FA) in place of methylammonium, or adding cesium) could improve the bandgap and stability, further improving efficiency in subsequent years.
- 2015–2016 – Rapid Records and Exceeding 20%: By 2015, the floodgates of perovskite research were fully open, and efficiency records were being broken every few months. Multiple teams pushed single-junction PSC efficiency above 20%. A

notable strategy was compositional engineering: Jeon *et al.* (2015) introduced mixed cation/halide perovskites (e.g. $\text{FA}_{0.85}\text{MA}_{0.15}\text{Pb}(\text{I}_{0.85}\text{Br}_{0.15})_3$), achieving ~20–22% with improved thermal stability[3]. By the end of 2016, certified efficiencies around 22% were reported, with incremental improvements in film quality and charge-carrier management.

- 2017–2019 – Approaching 25%: Efficiencies climbed into the mid-20s (%). Researchers focused on reducing non-radiative recombination and improving the fill factor. For instance, in 2018–2019, cells with 23–24% PCE were demonstrated by incorporating passivation molecules to reduce defects. Notably, a triple-cation mixed-halide perovskite ($\text{Cs}^+/\text{FA}^+/\text{MA}^+$) with mixed I/Br) became a “champion” composition due to its high phase stability and efficiency – this was used by Yang *et al.* (2017) and others to reach ~22–23%. In 2019, a landmark Science paper by Jeong *et al.* (Seok’s group) reported a stable 25.2% cell by managing the interface and suppressing iodide ion migration (Jeong *et al.*, 2019). By 2020, several groups (UNIST, Oxford, etc.) had independently certified 25%+ efficiencies on small-area cells, firmly establishing PSCs as efficiency leaders among thin-film solar technologies.

- 2020–2021 – Reaching 26% and Tandem Breakthroughs: In the early 2020s, single-junction PSCs inched up to ~26% PCE. For example, researchers at UNIST in Korea set a new record of 25.7% (certified) in 2021[21] using enhanced interface engineering (Min *et al.*, 2021)[3]. Around the same time, perovskite/silicon tandem cells were grabbing headlines by exceeding the efficiency limit of single-junction silicon. Since about 2016, the record tandem (perovskite on silicon) efficiency had *always* stayed ahead of the single-junction PSC record[3]. Oxford PV and the Helmholtz-Zentrum Berlin (HZB) led this tandem race, each pushing past 25%, 28%, and then 29%. In late 2020, HZB announced a certified 29.15% tandem (two-terminal perovskite-on-silicon) – the first solar device to clearly beat silicon’s ~29% theoretical limit[3]. By 2021, HZB achieved 29.8% in a tandem device[3], and Oxford PV was close behind. Thus, by 2021, we had ~26% in single cells and ~30% in tandem cells.

- 2022–2023 – Exceeding 30% (Tandems) and 26% (Singles): The tandem cell efficiency saw dramatic jumps in 2022 and 2023. In late 2022, researchers at Helmholtz Berlin achieved 32.5% with a perovskite-silicon tandem (certified by European and US labs)[5]. This was quickly surpassed: in early 2023, a KAUST-led team (Alamri *et al.*) reported 33.2%, and shortly after 33.7% (certified) – a tandem incorporating a high-bandgap perovskite with improved reliability[5]. Chinese manufacturer LONGi also joined the race, achieving 33.5% in mid-2023[5]. Meanwhile, single-junction perovskite cells continued incremental improvements: scientists demonstrated devices around 26%–26.5% (for instance, ~26.1% certified as of 2022[6]).

- 2024–2025 – Latest Records: By 2025, perovskite solar cells have reached new milestones. The certified record for a single-junction lab cell now stands at 26.7% (University of Science and Technology of China, 2025)[7]. The tandem record (perovskite on silicon, two-terminal) is an impressive 34.85%, achieved by LONGi and certified by NREL in 2025[3][8]. This result, reported in April 2025, is the first to surpass 34% and even beats the classic Shockley-Queisser limit for single junctions (around 33% for silicon bandgap)[8]. In addition, all-perovskite tandem cells (stacking two perovskite absorbers with different bandgaps) have exceeded 30% efficiency by 2023[7], showing promise for entirely thin-film multi-junction devices. *Figure 1* below summarizes the astonishing efficiency rise of perovskite solar cells over time, outpacing other emerging PV technologies[9].

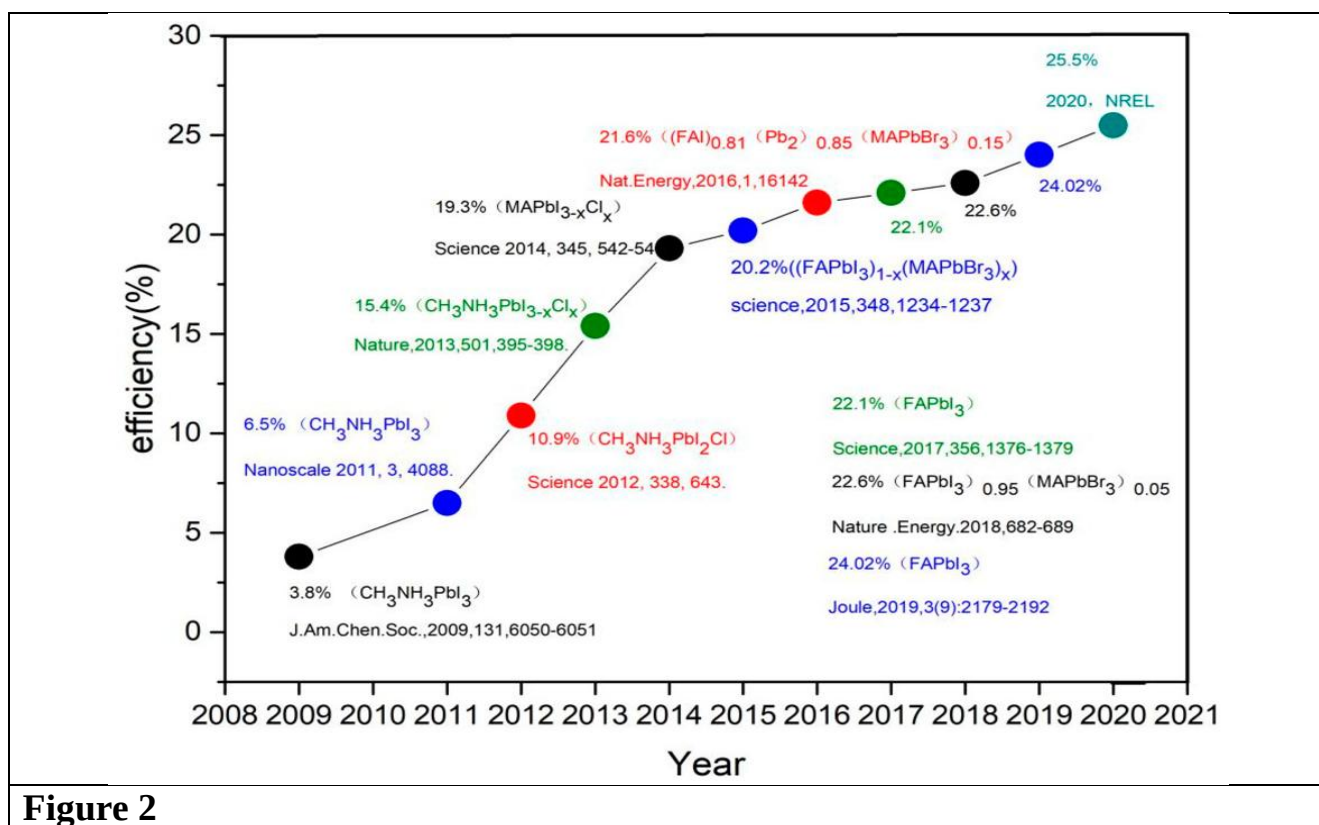


Figure 2: Historic improvement in the champion efficiencies of single-junction perovskite solar cells from 2009 to 2020, based on reported research cell data[3][4]. The first perovskite cells in 2009 used liquid electrolytes and $\text{CH}_3\text{NH}_3\text{PbI}_3$ sensitizers on mesoporous TiO_2 , achieving only ~3–4% PCE[4]. By 2013, solid-state devices with organic hole conductors and mixed-halide perovskites had pushed efficiencies above 15%[8]. Continued advances – including compositional engineering (e.g. formamidinium or cesium incorporation) and interface optimizations – led to rapid gains, with certified efficiencies exceeding 20% by 2015 and reaching about 25–25.5% by 2020[3][5]. Sources: NREL and literature records compiled in[3][4].

Key factors behind efficiency improvements: Several scientific and engineering innovations underlie this dramatic progress. These include: (1) *Materials chemistry*: moving from the original MAPbI₃ to mixed cation formulations (e.g. adding formamidinium and cesium) reduced phase instabilities and improved bandgap alignment, yielding higher voltages. (2) *Film deposition techniques*: improved methods (sequential deposition, antisolvent quenching, vapor deposition) produced perovskite films with larger grain sizes, fewer pinholes, and reduced defects, which raised the photocurrent and fill factor. (3) *Interface engineering*: using better charge transport layers (for example, TiO₂ surface treatments, SnO₂ electron transport layers, interface passivation molecules) helped increase the open-circuit voltage (V_{OC}) by reducing recombination at interfaces[3]. (4) *Tandem architectures*: pairing a wide-bandgap perovskite top cell with a silicon or low-bandgap perovskite bottom cell enabled more complete use of the solar spectrum, raising the theoretical efficiency limit into the 40+% range[5]. Thanks to these developments, perovskite solar cells have advanced faster than any prior solar technology – for comparison, it took decades for silicon cells to move from single digits to ~25%, but PSCs achieved a similar leap in just 10–12 years.

Structure and Working Principle of Perovskite Solar Cells

Device Architecture: A typical perovskite solar cell is built in a thin-film, layered structure. *Figure 2* shows a representative planar PSC architecture in the so-called n–i–p configuration (electron-selective contact first). In this design, a transparent glass substrate coated with a conductive oxide (ITO or FTO) serves as the front electrode. On this, an electron transport layer (ETL) is deposited, which assists extraction of electrons from the perovskite and blocks holes. Next comes the active perovskite layer (the light-absorbing semiconducting film). Above the perovskite, a hole transport layer (HTL) is added to extract holes and block electrons. Finally, a metal back electrode (e.g. gold or silver) is evaporated on top to collect the charge and complete the circuit[10]. When sunlight enters through the glass/ITO side, the perovskite layer generates electron-hole pairs which are separated and collected by the ETL and HTL, respectively, creating a current flow out to the electrodes.

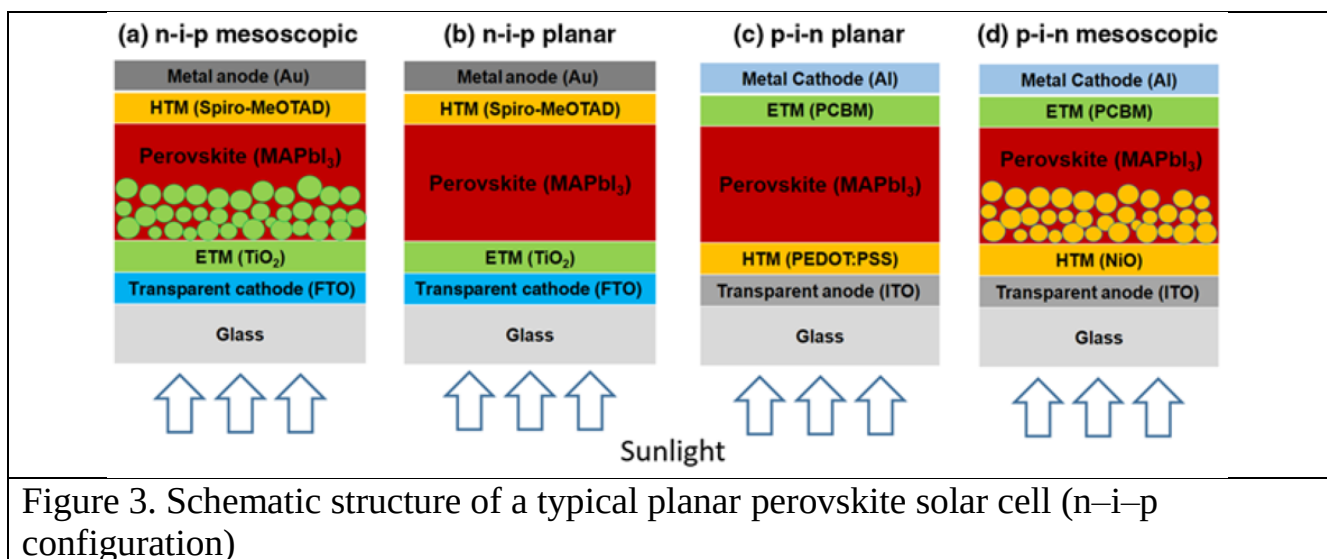


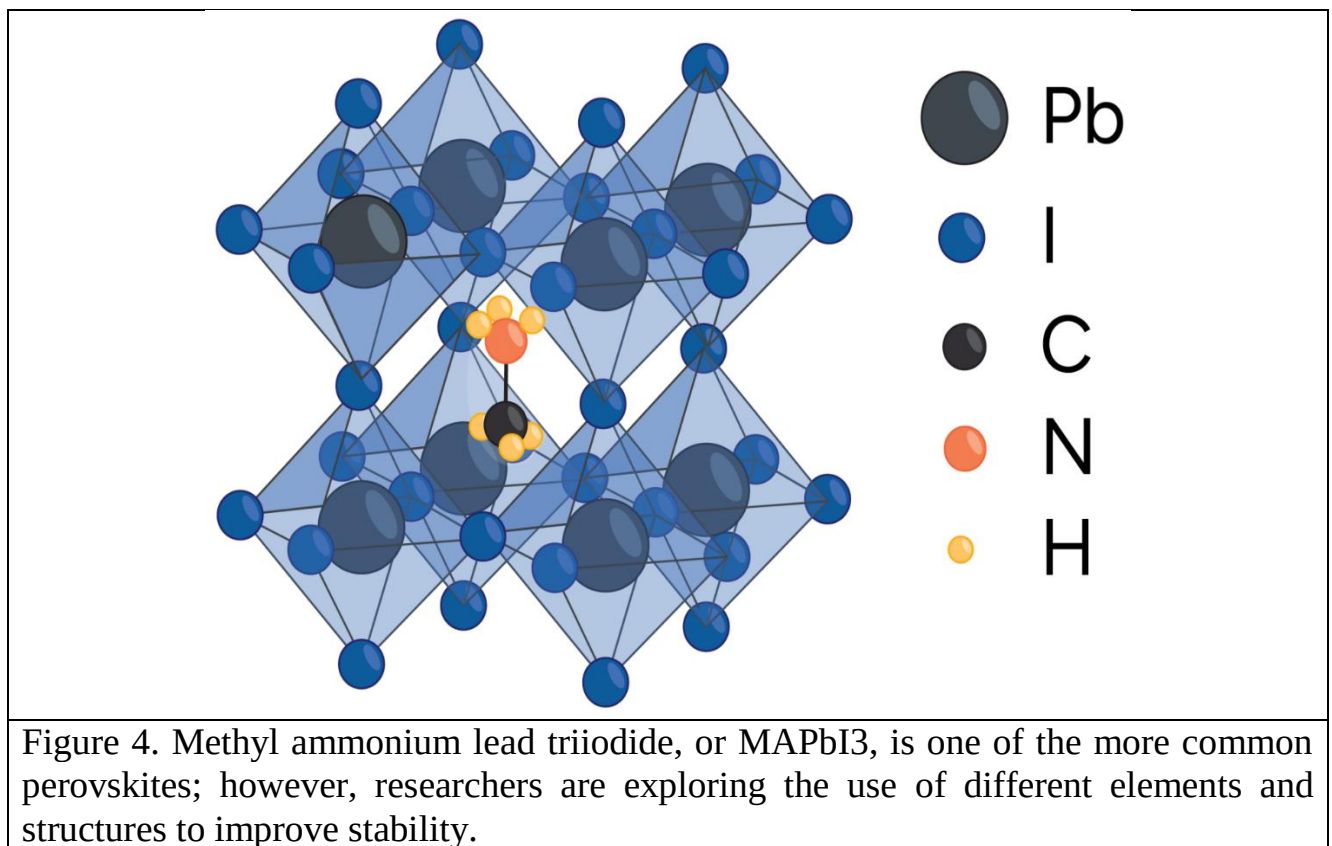
Figure 3: Schematic structure of a typical planar perovskite solar cell (n-i-p configuration). The layers (from bottom/front to top/back) are: a glass substrate, a transparent conducting oxide (TCO) front electrode (such as ITO), an electron transport layer (ETL, e.g. TiO_2 or SnO_2), the perovskite light-absorbing layer (MAPbI_3 or a variant), a hole transport layer (HTL, e.g. Spiro-OMeTAD), and a metal back electrode[10]. This stack constitutes a thin-film device usually only a few hundred nanometers thick. (Illustration credit: U.S. DOE)

Two main layout variants exist: the “normal” or n-i-p structure as described above, and the inverted or p-i-n structure. The inverted configuration flips the order of contacts – a hole-transport layer is placed next to the transparent electrode (collecting holes first), and an electron-transport layer is on top under the metal back contact[3]. The inverted design often uses materials like PEDOT:PSS (conducting polymer) as the bottom hole contact and fullerene-based electron contacts on top. Both architectures can achieve high efficiencies (~25%); the choice often comes down to processing preferences and stability considerations. Inverted cells (p-i-n) tend to have less hysteresis in their current-voltage curves and can be processed at lower temperatures (since they may use oxide contacts that can be deposited at the end)[3]. The mesoscopic architecture is another subtype: it includes a mesoporous scaffold (typically TiO_2 or Al_2O_3) infiltrated with perovskite. This was used in early cells and is still sometimes employed to improve stability or interface contact, but many of today’s record cells are planar (no mesoporous layer).

Perovskite material properties

The active layer in PSCs is a metal-halide perovskite semiconductor, most commonly a lead halide perovskite. The prototypical compound is methylammonium lead iodide, $\text{CH}_3\text{NH}_3\text{PbI}_3$ (abbreviated MAPbI_3)(Figure 4). This material has a direct bandgap

around 1.55–1.6 eV (optimal for single-junction solar cells) and strongly absorbs visible light (absorption coefficient $>10^5 \text{ cm}^{-1}$), allowing it to harvest sunlight effectively with a film only 300–600 nm thick. The perovskite crystal structure (ABX_3) can accommodate a wide variety of substitutions: for example, formamidinium (FA, $\text{HC}(\text{NH}_2)_2^+$) or cesium (Cs^+) can occupy the A-site instead of methylammonium; tin (Sn^{2+}) can replace lead (though with lower efficiency so far); and bromide or chloride can partially substitute for iodide to widen the bandgap. This tunability is a huge advantage – by mixing halides, one can adjust the bandgap from $\sim 1.2 \text{ eV}$ up to $\sim 2.3 \text{ eV}$, useful for tandem cells (e.g. a 1.7–1.8 eV perovskite paired with a 1.1 eV silicon). By mixing cations (FA, MA, Cs, Rb, etc.), one can enhance the structural and thermal stability of the perovskite, reducing the tendency to form light-inactive phases[3]. Researchers have also developed 2D perovskites (layered Ruddlesden-Popper phases) and quasi-2D/3D blends to improve moisture stability; these use bulky organic cations that form protective layers, greatly increasing resistance to humidity at some cost to efficiency[4]. Overall, the “defect tolerance” of lead halide perovskites (their ability to still perform well even with solution-processed polycrystalline films) is a key to why high efficiencies are possible without expensive fabrication.



Operating principle

When light enters a PSC, photons with energy above the bandgap are absorbed in the perovskite layer, generating electron-hole pairs (often free carriers, as the exciton binding energy in perovskites is low). Under the built-in electric field and the band alignment of the device, electrons move toward the ETL/TCO side and holes move toward the HTL/metal side (Figure 5). The ETL (n-type layer such as compact TiO_2 , SnO_2 , or PCBM in inverted cells) facilitates electron collection and prevents holes from reaching the contact, while the HTL (p-type layer such as Spiro-OMeTAD, PTAA, or NiO in inverted cells) does the converse for holes [10]. This selective contact structure “forces” the current to flow in one direction through an external circuit [1]. The result is a photovoltaic effect: a voltage builds up (V_{OC}) between the contacts, and a photocurrent (I_{SC}) flows when the circuit is closed. Notably, perovskites are capable of generating high voltages relative to their bandgap – a 1.6 eV bandgap perovskite can produce ~ 1.1 – 1.2 V open-circuit voltage in the best cases, indicating relatively low non-radiative recombination losses. This is a strength of the material; for comparison, silicon (bandgap 1.12 eV) gives ~ 0.7 V in standard cells. The high V_{OC} of perovskites, combined with decent currents (~ 20 – 25 mA/cm^2 in single junction) and fill factors of 0.8+, yields the high efficiencies reported.

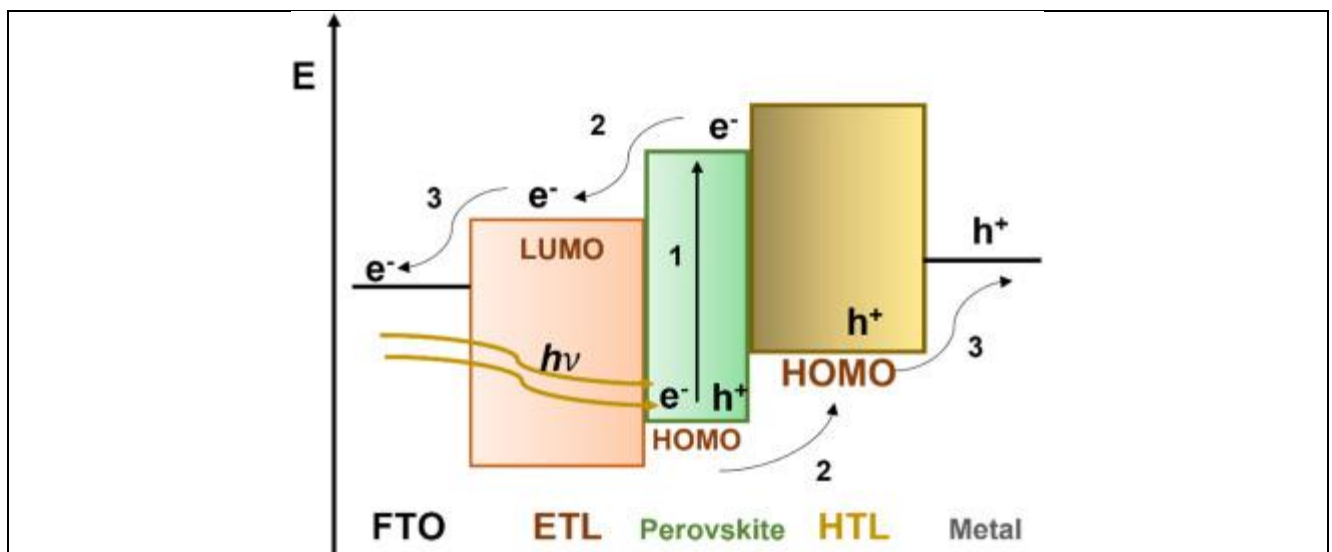


Figure 5. Operating principle of PSC. <https://www.sciencedirect.com/topics/medicine-and-dentistry/perovskite>

It is worth mentioning that perovskite solar cells often exhibit a phenomenon called current-voltage hysteresis – the I–V curve can differ depending on scan direction or rate [3]. This is attributed to mobile ionic charge in the perovskite and interfacial capacitive effects. By improving compositions and contacts (and measuring under stable conditions), hysteresis can be minimized, and certified measurements typically employ techniques to obtain stabilized efficiency readings.

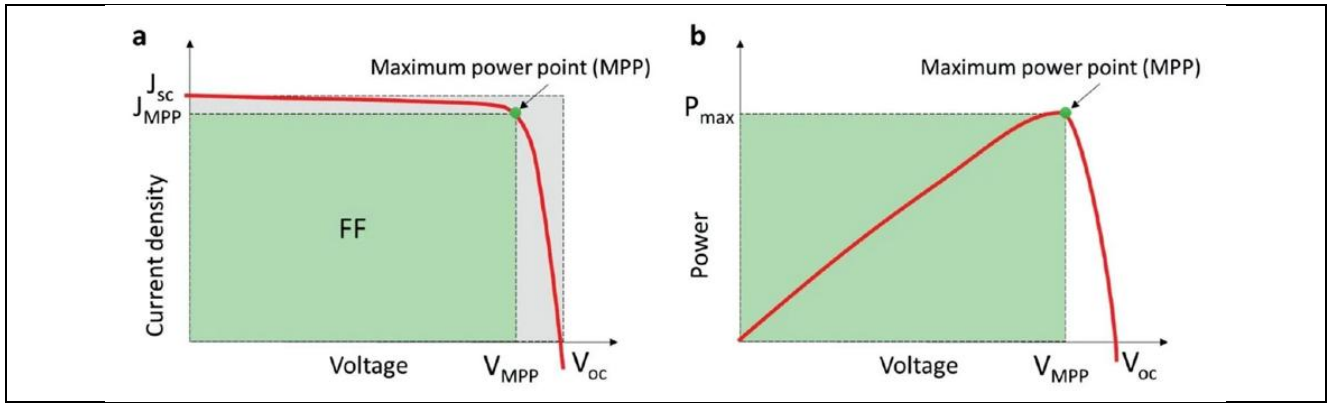


Figure 6. A typical current density–voltage (J–V) curve of a perovskite solar cell under 1-sun illumination

Figure 6: A typical current density–voltage (J–V) curve of a perovskite solar cell under 1-sun illumination, illustrating key performance parameters[2]. The short-circuit current density (J_{sc}) is the current at zero applied voltage, and the open-circuit voltage (V_{oc}) is the voltage at zero current[3]. The maximum power point (MPP) is indicated by the knee of the J–V curve where the product $J \cdot V$ is maximized (green point), and the fill factor (FF) quantifies the “squareness” of the curve – defined as the ratio of the maximum obtainable power to the product $J_{sc} \cdot V_{oc}$ [1][2]. Using J_{sc} , V_{oc} and FF, one can calculate the power conversion efficiency (PCE), which represents the fraction of incident solar power that is converted into electric power by the cell[5].

$$PCE = \frac{P_{max}}{P_{in}} = \frac{V_{MPP} \times J_{MPP}}{P_{in}} = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}$$

Tandem architectures

One of the most exciting applications of perovskites is to use them in tandem (multi-junction) solar cells to surpass the single-junction efficiency limit (~33% for 1 sun). The most common tandem is a perovskite/silicon tandem, where a perovskite top cell (with bandgap ~1.7–1.8 eV) is stacked on a silicon bottom cell (bandgap 1.12 eV)(Figure 7).

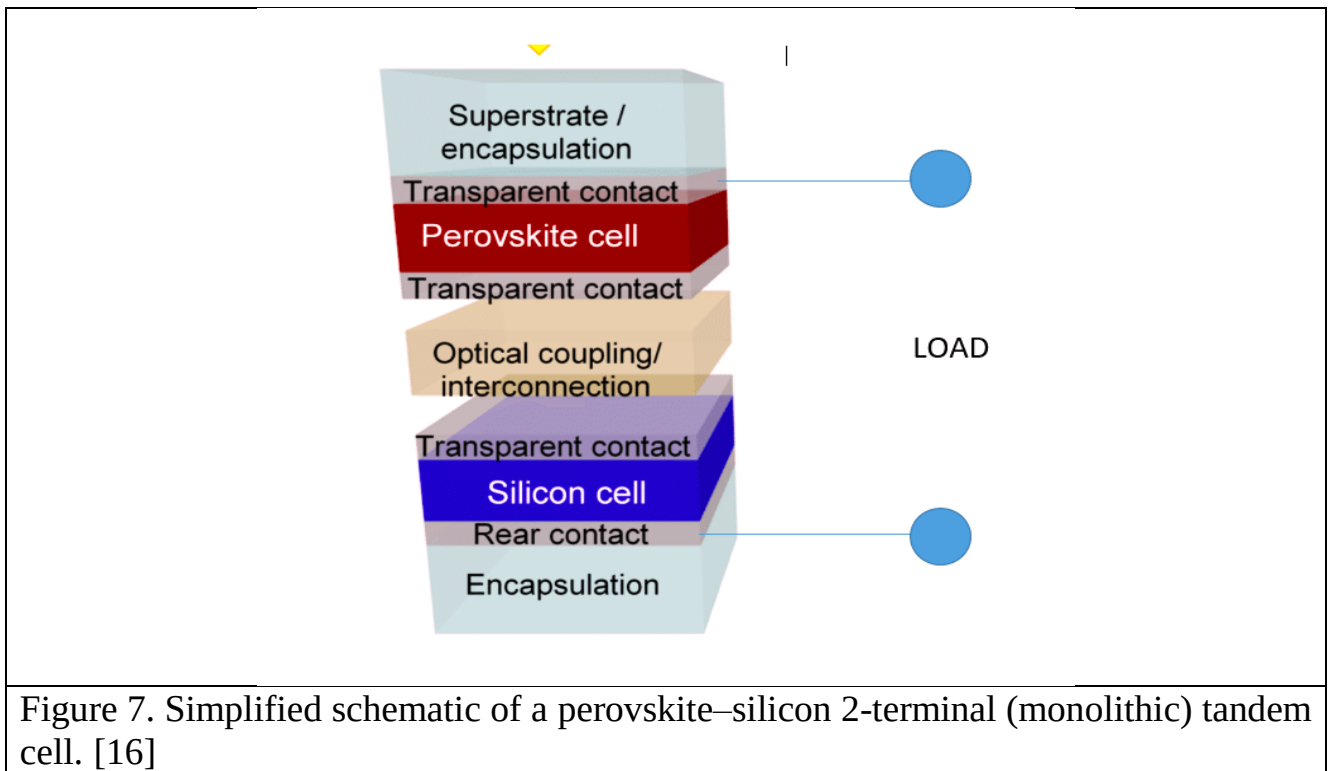


Figure 7: Simplified schematic of a perovskite–silicon 2-terminal (monolithic) tandem cell. A wide-bandgap perovskite top cell ($\approx 1.7\text{--}1.8\text{ eV}$, red layer) is stacked on a silicon bottom cell (1.12 eV , blue layer). Transparent conductive contacts and an interconnecting recombination layer join the sub-cells in series, so the tandem acts as a single device with two p–n junctions. In a 4-terminal configuration (not shown), the perovskite and silicon cells are fabricated separately with their own electrodes, and combined optically (either mechanically stacked or via a spectral splitter); each sub-cell operates independently, allowing separate optimum power extraction[16].

The perovskite absorbs the high-energy visible photons (blue/green light) while transmitting the red/infrared light for silicon to absorb, thereby utilizing a broader spectrum efficiently[1]. In a two-terminal (2T) monolithic tandem, the perovskite and silicon sub-cells are connected in series within one device (requiring interconnecting layers and current matching), whereas a four-terminal (4T) tandem simply stacks two independent cells (perovskite cell on top of a silicon cell) and does not require current matching (but needs separate contacts for each cell). Perovskite/silicon tandems have reached $\sim 34\text{--}35\%$ efficiencies as noted earlier. *Figure 8* illustrates a 2T and 4T perovskite-on-silicon tandem structure. Other tandem combinations include all-perovskite tandems (two different bandgap perovskites; e.g. a 1.8 eV wide-gap over a 1.2 eV narrow-gap) which have hit $\sim 30\%$ [55][56], and perovskite/CIGS or perovskite/organic tandems which are being explored for flexible applications (perovskite/CIGS tandems have reached $\sim 24\%$ in studies[9]).

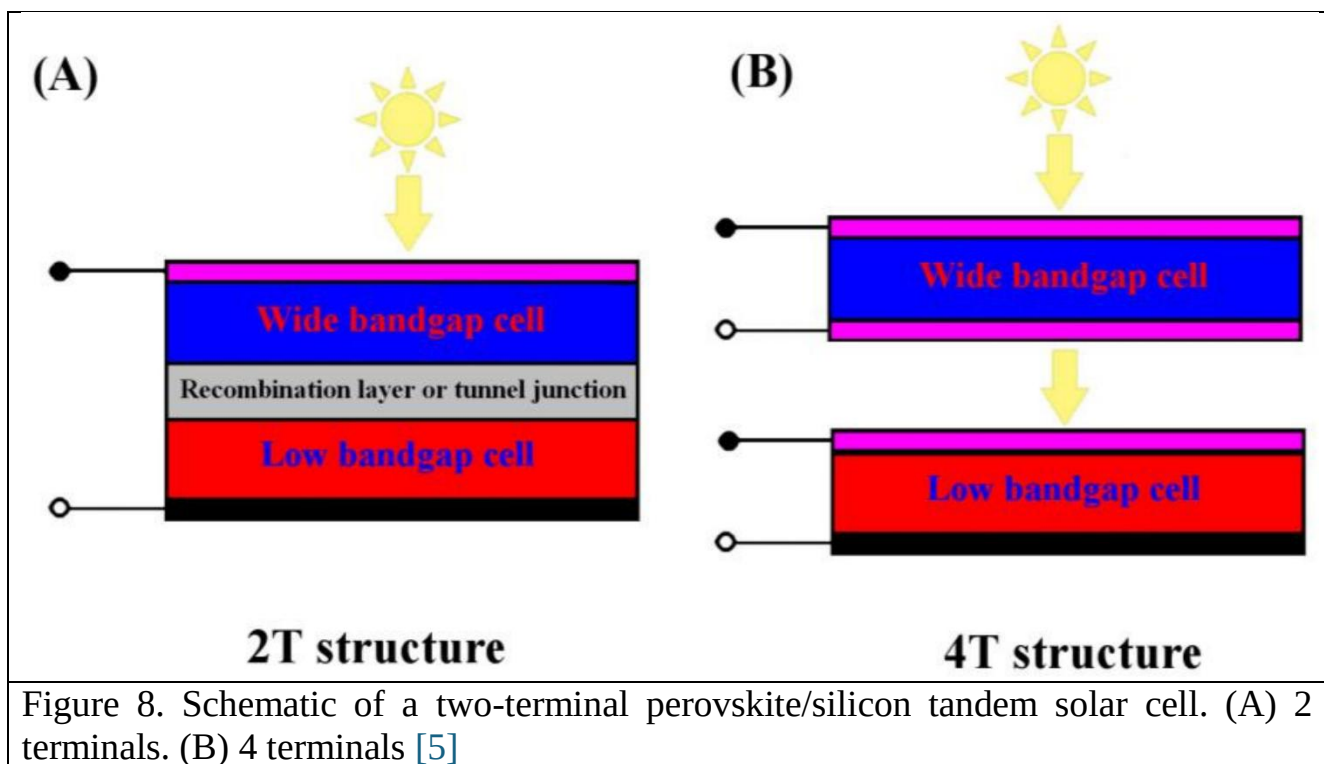


Figure 8: Schematic of a two-terminal perovskite/silicon tandem solar cell. A wide-bandgap perovskite top cell is deposited on a silicon bottom cell, with a recombination junction layer connecting them electrically in series. In this example, the top cell uses a transparent conductive oxide and electron/hole transport layers similar to a single PSC, and the bottom is a standard silicon p–n junction. Such tandems have achieved efficiencies in the mid-30% range, far above the single-junction silicon limit[5].

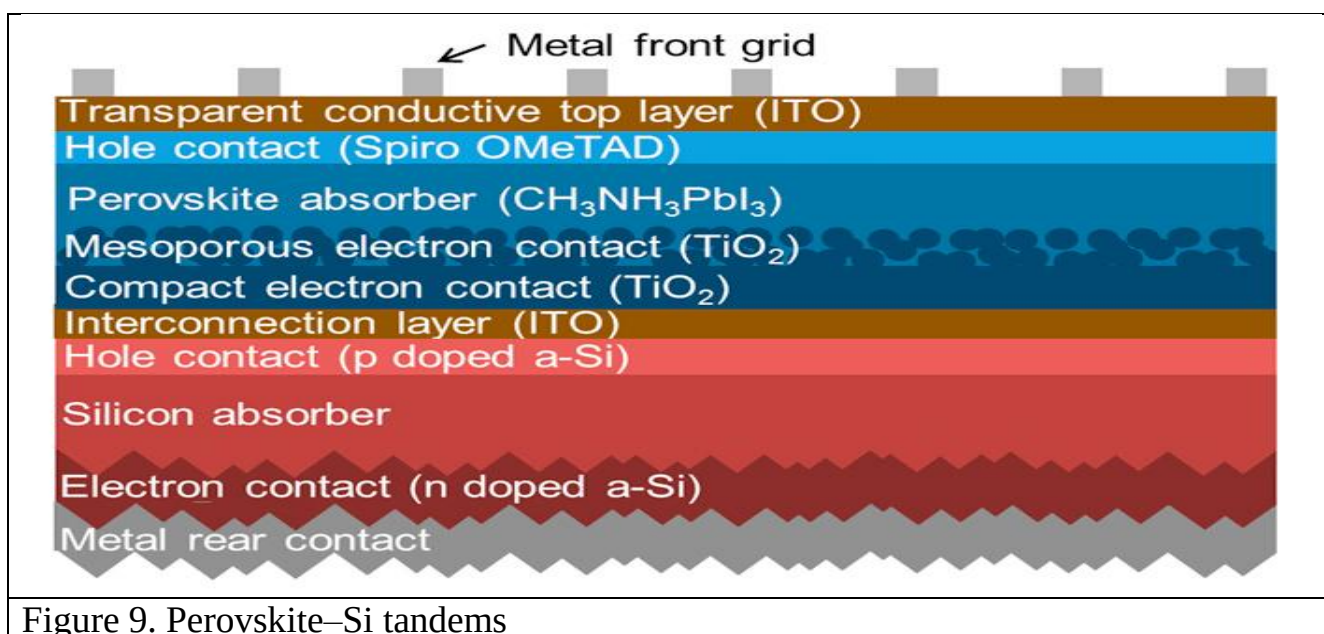


Figure 9 shows a Perovskite–Silicon monolithic tandem solar cell: The **top cell** is a mesoporous TiO_2 -based perovskite device. The **bottom cell** is a crystalline silicon heterojunction (SHJ).

Perovskite is labelled $\text{CH}_3\text{NH}_3\text{PbI}_3$ (MAPbI_3). HTL is Spiro-OMeTAD, typical for perovskite devices. ETL is TiO_2 (mesoporous + compact), again characteristic of perovskite technology. Bottom cell contains a-Si:H(p)/c-Si/a-Si:H(n) which is the architecture of silicon heterojunction (SHJ).

Operation of each layers:

1. Metal Front Grid

- Collects current from the transparent top electrode.
- Minimizes series resistance while maintaining high optical transparency.

2. Transparent Conductive Top Layer (ITO)

- Indium Tin Oxide (ITO) functions as the transparent electrode.
- Allows maximum light to reach the perovskite absorber while conducting extracted charge.

3. Hole Contact (Spiro-OMeTAD)

- A standard p-type organic hole transport layer (HTL) used in perovskite solar cells.
- Extracts and transports holes generated in the perovskite.

4. Perovskite Absorber Layer ($\text{CH}_3\text{NH}_3\text{PbI}_3$)

- The primary absorber of the top cell.
- Has a tunable bandgap ($\sim 1.55\text{--}1.7$ eV) suitable for tandem operation with silicon.
- Provides high absorption coefficient and long carrier diffusion length.

5. Mesoporous Electron Contact (TiO_2)

- Works as an electron transport layer (ETL).
- Enhances charge separation and facilitates electron extraction.

6. Compact Electron Contact (TiO_2)

- A dense TiO_2 blocking/transport layer.
- Prevents hole leakage and ensures selective electron extraction.

7. Interconnection Layer (ITO)

- Highly conductive recombination layer connecting the perovskite top cell and silicon bottom cell.
- Ensures proper current matching in two-terminal tandem devices.

8. Hole Contact (p-doped a-Si)

- Hydrogenated amorphous silicon (a-Si:H) doped p-type.
- Part of the standard silicon heterojunction (SHJ) architecture.

9. Silicon Absorber

- Crystalline silicon (c-Si) bottom cell absorber.
- Typically $\sim 150\text{--}180$ μm thick.
- Provides the low-bandgap layer (~ 1.1 eV) in the tandem stack.

10. Electron Contact (*n*-doped *a*-Si)

- Functions as the electron transport layer in the SHJ structure.

11. Metal Rear Contact

- Back electrode of the silicon bottom cell.
- Completes the device and ensures efficient carrier collection.

Working Principle: In a perovskite/Si tandem, the high-bandgap perovskite cell sits atop the silicon cell. The perovskite harvests the higher-energy (visible/UV) photons, converting them at a high voltage, while allowing lower-energy near-infrared light to transmit to the silicon bottom cell[16]. In a **2-terminal (2T)** monolithic tandem, the sub-cells are electrically connected in series – typically through a shared middle recombination layer (e.g. indium tin oxide or tunnel junction) that allows charge recombination between the top cell's bottom contact and the bottom cell's top contact[17]. This means the currents through each sub-cell must be matched. By contrast, in a **4-terminal (4T)** tandem, each cell has its own terminals; the two cells need not be current-matched and can operate at their individual maximum power points[16]. For 4T, often a semitransparent perovskite cell is stacked on a separate silicon cell; the outputs of each are combined electrically at the module level. The 4T design avoids the complexity of a monolithic interconnect and current matching, at the cost of additional optics and wiring[16].

Performance: Perovskite–Si tandems have achieved record efficiencies beyond single-junction limits. Early demonstrations by Bailie *et al.* (2015) showed ~17% for a 4T device (MAPbI₃ perovskite over a c-Si or CIGS cell)[18]. Monolithic 2T devices quickly followed: Mailoa *et al.* (2015) reported 13.7% with a perovskite on a flat silicon heterojunction cell[18]. Steady progress led to 2T tandems exceeding 20% by 2016–2017 (e.g. Albrecht *et al.* 18%, Werner *et al.* 21% by improving charge transport layers). A landmark was achieved in 2018 when Sahli *et al.* demonstrated a 25.2% monolithic perovskite–Si tandem, certified by Fraunhofer ISE[18]. That device used a textured silicon bottom cell and a p–i–n perovskite top cell with advanced light management to minimize reflection and parasitic absorption[18]. In the same year, Oxford PV announced a 27.3% tandem (perovskite on silicon heterojunction), and by 2020 at least two groups had crossed the 29% mark. Helmholtz-Zentrum Berlin (HZB) reported a certified 29.8% in late 2021[18], using a textured interface and a highly optimized wide-bandgap (~1.68 eV) perovskite absorber. As of 2025, the record 2T tandem efficiency is 34.5%, set by a collaboration involving industry (LONGi) and academia[19][18]. This tandem used an improved self-assembled monolayer for hole extraction and advanced interface passivation. Meanwhile, 4T perovskite–Si tandems are reported up to ~28–30% (Oxford PV has demonstrated ~28% in 4T configuration)[29], slightly lower than 2T records due to extra optical losses, but still advantageous for certain applications (e.g. building-integrated PV where two-terminal wiring is challenging).

Stability and Applications: A major advantage of the Si bottom cell is its proven longevity – but the tandem’s durability hinges on the perovskite top cell. Significant progress has been made: for instance, NREL demonstrated perovskite–GaAs tandems (a similar concept for space, see next section) with <5% degradation over 10,000 hours of UV exposure when properly encapsulated[30], giving confidence that perovskite–Si tandems can also be engineered for long lifetimes. Perovskite–silicon tandems are particularly attractive for commercial solar panels, as they promise a step-change in efficiency (30–35% range) with potentially only modest cost increase. Companies like Oxford PV are scaling 2T tandem cells for module production, aiming for >30% **efficient** silicon-based panels in the near future. In the lab, these tandems have small areas (typically 1 cm² devices), but efforts on up-scaling and stability (encapsulation, UV filters, lead management) are actively pursued. If stability and manufacturability are solved, perovskite–Si tandems could find widespread use in utility-scale solar farms (more power per area) and residential panels. Even in the interim, 4T configurations might see use in concentrator photovoltaics or as add-on layers to existing silicon cells. In any case, perovskite–silicon tandems represent the most mature and highest-performing tandem type to date[18][19].

Perovskite–CIGS Tandem Cells

Architecture and Principle: In this tandem, a perovskite top cell is paired with a polycrystalline **copper-indium-gallium-selenide (CIGS)** (Cu(In,Ga)Se₂) thin-film bottom cell. CIGS typically has a bandgap around 1.0–1.2 eV (depending on Ga content), making it a suitable infrared absorber under a ~1.7 eV perovskite. Like with Si, a 2T monolithic or 4T stacked configuration can be used. The perovskite can be deposited directly atop a CIGS cell for a monolithic device, though this requires compatible interlayers to avoid damaging the CIGS and to connect the two sub-cells. Early studies favored 4T approaches for simplicity: e.g. Bailie *et al.* showed a ~18.6% 4T tandem with a CIGS bottom (perovskite bandgap 1.6–1.7 eV)[21]. The working principle is identical to other tandem cells – divide the spectrum: the perovskite converts visible light, and the CIGS (which has strong absorption in red/IR) converts the rest.

Performance: Perovskite–CIGS tandems have achieved high efficiencies, though generally a few points behind perovskite–Si. A 4-terminal perovskite/CIGS tandem reached ≈23.9% *efficiency* (with each sub-cell ~17–18% on its own)[18]. This was achieved by using a very transparent top cell (e.g. employing a transparent conductive top electrode like IZO and a efficient wide-bandgap perovskite) to let sufficient light through to a high-quality CIGS bottom cell[18]. Monolithic 2T perovskite–CIGS tandems have been reported as well, though their efficiencies are lower, partly due to the challenging integration (CIGS often requires high-temperature processing incompatible with standard perovskites). One example is a solution-processed

monolithic perovskite/CIGS that reached ~21% PCE in 2020 (by optimizing the interfacial layers to reduce losses) – close to the ~22% record of single-junction CIGS (Figure 10b). The 26.4% record of a perovskite–organic tandem (see next section) has recently surpassed the best perovskite–CIGS, highlighting that there is still room to improve the perovskite/CIGS combination[19].

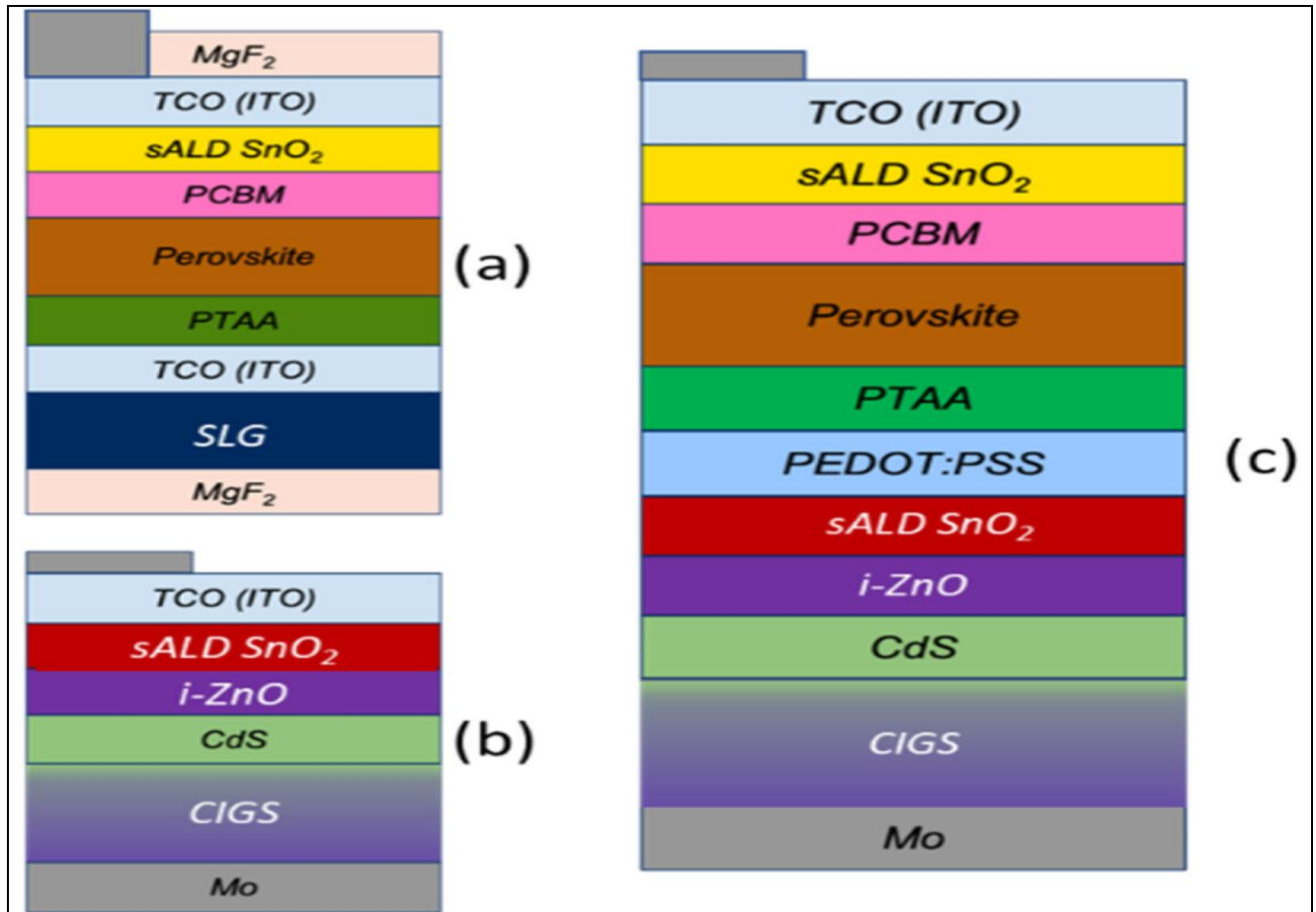


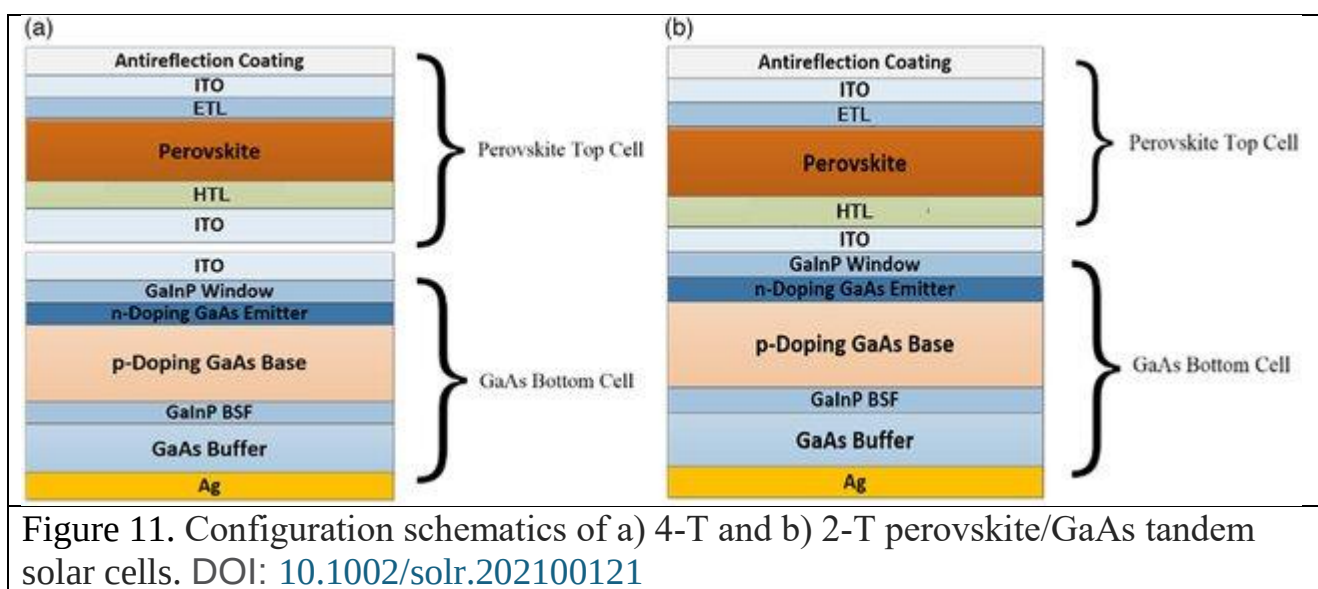
Figure 10. Schematic structures of single junction perovskite (a) and CIGS cells(b), as well as of perovskite/CIGS tandem solar cells(c). Image: Delft University of Technology, Solar Energy Materials and Solar Cells, Common License CC BY 4.0

Stability and Application: CIGS solar cells are thinner and lighter than silicon wafers and have better temperature coefficients (performance at high temperature), so perovskite–CIGS tandems could be attractive for weight-sensitive applications like rooftop PV or vehicles. Moreover, both sub-cells can be made flexible. The main challenges are chemical: the halides in the perovskite can interact with CIGS layers, and the deposition of perovskites must be done at low temperature to avoid damaging CIGS and its CdS buffer. Stability under illumination and heat needs careful encapsulation and perhaps isolation of the sub-cells (especially if using 4T with separate encapsulation). Potentially, a perovskite–CIGS tandem could achieve ~30% efficiency (theoretical) if each sub-cell is optimized, and efforts are ongoing to reach

upper-20% experimentally. If successful, these tandems could extend the life of the CIGS technology by boosting its efficiency beyond the ~23% single-cell limit while leveraging existing CIGS production techniques[18].

Perovskite–GaAs Tandem Cells

Architecture and Niche: GaAs (gallium arsenide) is a high-performance photovoltaic material (single-junction GaAs record ~29% PCE) used primarily in space and concentrator PV due to its high cost. Combining a perovskite top cell with a GaAs bottom cell yields an extremely efficient tandem because both sub-cells can operate near their radiative efficiency limits. A typical design is a 2-terminal monolithic device: a ~1.7–1.8 eV perovskite on a 1.42 eV GaAs. The perovskite top can be solution-processed onto the GaAs cell, or fabricated separately (4T). The working principle is similar to the Si tandem, but here the bottom cell (GaAs) is also a direct bandgap, high-quality cell that can even outperform silicon at high irradiance. Perovskite–GaAs tandems are especially considered for spacecraft and satellite power, where \$/W is less critical than weight and efficiency, and where GaAs-based multi-junctions dominate.



Performance: Perovskite–GaAs tandems have demonstrated exceptional efficiencies in laboratory tests. NREL recently reported a >32% efficient perovskite/GaAs tandem (2T monolithic)[20]. This result leverages the fact that both sub-cells have very high open-circuit voltages (the perovskite can exceed 1.1 V and GaAs ~1.0 V under one sun). Simulations indicate that with ideal bandgap pairing,

perovskite–GaAs 2T tandems could reach ~35–38% under standard conditions[21], comparable to state-of-the-art multi-junction III–V cells but at potentially lower cost. In practice, a 30.3% monolithic perovskite/GaAs tandem was demonstrated by Zhao *et al.* using an all-inorganic perovskite (CsPbI₂Br) optimized for 2T integration[22][23]. Four-terminal configurations have also been tested; for example, a 4T arrangement where a semitransparent perovskite is mechanically stacked on a GaAs cell can surpass 30% without current-matching constraints (one group reported ~31% in a 4T setup)[38]. These numbers are rapidly improving, suggesting perovskite–GaAs tandems are competitive with traditional dual-III–V tandems (like GaInP/GaAs).

Stability: GaAs solar cells are quite radiation-hard and stable, which is why they are used in space. The addition of a perovskite, however, introduces new stability considerations: UV exposure, thermal cycling, and potential diffusion of ions. Promisingly, in the NREL study, encapsulated perovskite–GaAs tandem samples showed <5% degradation after 10,000 hours of UV exposure[30], indicating that with proper encapsulation (and perhaps UV-filtering cover glass), the tandem can meet space mission durability requirements. This is a significant result because it demonstrates that perovskite-based tandems can achieve not just high efficiency but also excellent stability in challenging conditions.

Potential Applications: The primary application for perovskite–GaAs tandems is in the aerospace sector – satellites, high-altitude pseudo-satellites (HAPS), or rover missions – where the combination of ultra-high efficiency and lightweight is valuable. A perovskite top cell can be deposited as a thin film (a few hundred nm) adding minimal mass, potentially outperforming multi-junction III–V cells which require multiple epitaxial layers. Additionally, the ability to tune the perovskite’s bandgap allows optimizing for different spectral conditions (e.g. AM0 spectrum in space). While GaAs is too expensive for terrestrial farms, these tandems might also find niche use in concentrator PV systems or specialty portable power. The success of perovskite–GaAs tandems in space could also prove the long-term reliability of perovskite technology in general, accelerating confidence in other tandem formats[39].

Perovskite–Organic Tandem Cells

Architecture: Organic photovoltaic (OPV) cells – based on conjugated polymers or small molecules – can be paired with perovskites to form all-thin-film tandem devices. Typically, the perovskite (bandgap ~1.6–1.8 eV) serves as the high-bandgap top cell, and a low-bandgap organic cell (e.g. polymer:fullerene or non-fullerene acceptor system with bandgap ~1.1–1.3 eV) is the bottom cell[19]. Both sub-cells are solution-processable on flexible substrates, enabling monolithic integration with a recombination layer in between. A common configuration is 2-terminal monolithic, since organic sub-cells can be made semi-transparent by using transparent electrodes (e.g. silver nanowires or conductive polymers) and by thinning the active layer.

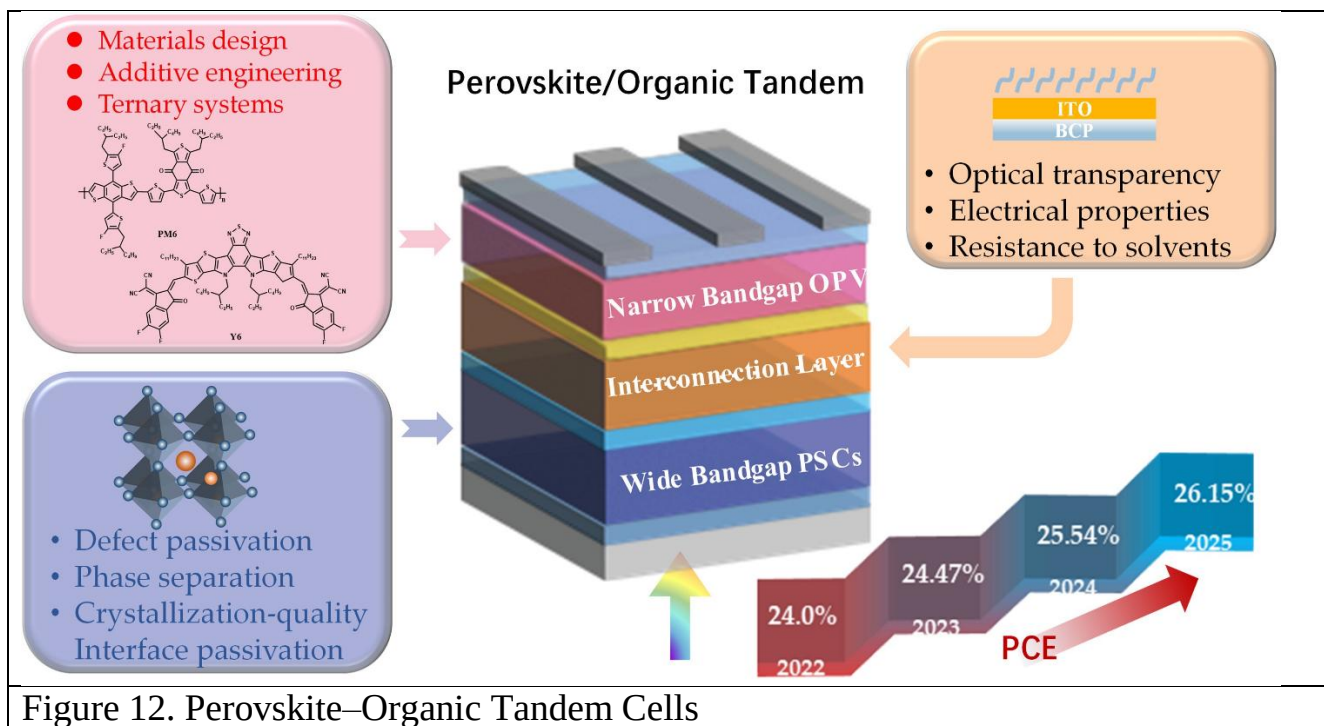


Figure 12. Perovskite–Organic Tandem Cells

Working Principle: The perovskite cell converts the high-energy part of the spectrum, while the organic cell (which can be tuned to absorb the near-infrared) converts the lower-energy photons that the perovskite misses. Organics typically have weaker absorption in the red/NIR, but by designing a low-bandgap polymer or dye that extends to ~900–1000 nm, the organic bottom cell can utilize the transmission of a 1.6 eV perovskite. The interconnecting layer in a monolithic perovskite/organic tandem often includes a ultrathin metal or metal-oxide to form an ohmic contact between the organic donor and perovskite electron-transport layer.

Performance: Remarkably, perovskite–organic tandems have recently set efficiency records among hybrid tandems. In 2023, researchers at NUS/SERIS achieved a **certified 26.4% PCE** (1 cm² device) for a 2T perovskite/organic tandem – the highest for any perovskite-based tandem outside of perovskite–Si[19]. They achieved 27.5% on a smaller area (0.05 cm²), indicating the tandem’s potential[19]. This breakthrough was enabled by a newly engineered **narrow-bandgap organic photovoltaic cell** using an asymmetric non-fullerene acceptor that absorbs well into the near-IR. By stacking it with a ~1.7 eV perovskite top cell, they overcame the long-standing NIR absorption bottleneck in thin-film tandems. Prior to this, perovskite/organic tandems had lagged behind (typical efficiencies were in the teens). For example, a few years ago, a tandem using a PBDB-T:SN6 (polymer:NFA) bottom cell achieved ~17%[19], and incremental improvements pushed that to ~20–25%. The recent 26.4% result, however, puts perovskite–organic tandems on the map as a viable

high-efficiency technology[19]. It's notable that 26.4% exceeded the best single-junction perovskite (25.7%) and even rivaled early perovskite–Si prototypes, highlighting how far OPV has progressed when combined with perovskites.

Stability and Uses: Both perovskite and organic cells have historically faced stability issues (sensitivity to oxygen, moisture, and UV). Yet, their combination in a tandem does not inherently worsen stability – in fact, the top perovskite can act as a UV filter protecting the organic, and the tandem can be encapsulated similarly to single cells. The NUS team's device was small-area and lab-tested, so long-term stability data is still forthcoming. Generally, organic cells can be made quite stable (multiple years) with proper encapsulation, and there's optimism that tandem architecture might even mitigate some stresses (for instance, the perovskite might reduce the photon flux and thermal load on the organic sub-cell).

Applications: The big appeal of perovskite–organic tandems is their mechanical flexibility and lightweight nature. As Hou *et al.* note, these tandems are ideal for niche applications like drones, wearable electronics, and IoT devices, where silicon's weight and rigidity are problematic. A flexible foil incorporating a perovskite/organic tandem could be integrated into fabrics or curved surfaces to provide on-board power (e.g. self-powered smart fabrics, sensors, or UAV wings). With efficiencies now in the mid-20s and prospects to exceed 30%[19], they combine the advantages of thin-film PV (lightweight, roll-to-roll producible) with efficiencies approaching those of glass-mounted silicon. Of course, challenges remain: both materials are moisture-sensitive, so robust encapsulation is needed, and scale-up to large-area modules will be non-trivial. But the recent records are encouraging. In summary, perovskite–organic tandems represent a pathway to high-efficiency, flexible solar panels that could enable new applications (building-integrated PV on curved surfaces, solar textiles, portable chargers) where conventional cells cannot go.

Perovskite–Dye-Sensitized Hybrid Tandems

Concept and Design: Dye-sensitized solar cells (DSSCs) and perovskite solar cells share some lineage – indeed, perovskites were first used as dyes in DSSCs. Hybrid tandem structures have been proposed that marry a DSSC with a perovskite cell to capture a broader spectrum. One approach is a 4-terminal tandem: for instance, a dye-sensitized TiO₂ cell (sensitized with a dye absorbing red/NIR light) can be placed behind a semi-transparent perovskite cell that absorbs the visible band. Each cell operates independently, yielding combined higher efficiency than either alone. Another approach is a monolithic integration: here, a DSSC (which typically consists of a mesoporous TiO₂ with dye and a redox electrolyte or solid hole conductor) is directly layered with a perovskite device. For example, researchers have explored a monolithic tandem where a **co-sensitized DSSC** (using multiple dyes to absorb broad spectrum) forms the top sub-cell and a perovskite device serves as the bottom sub-cell, sharing a common electrode[24]. This effectively stacks a photoanode of a DSSC on top of a perovskite p–i–n cell.

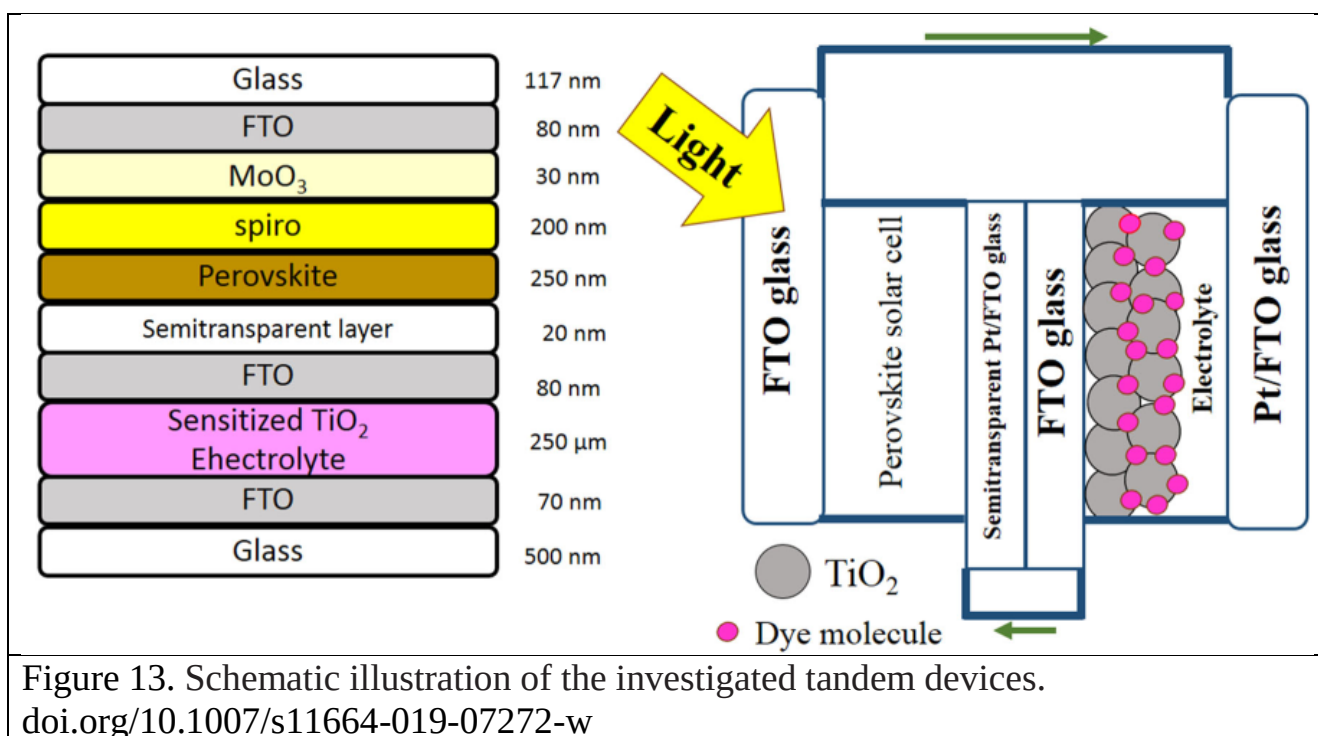


Figure 13. Schematic illustration of the investigated tandem devices.
doi.org/10.1007/s11664-019-07272-w

Working Principle: The DSSC part, with its ruthenium or organic dyes, excels at harvesting in regions where the perovskite might not (some DSSC dyes absorb strongly in the green-red or even NIR up to ~900 nm). The perovskite cell, on the other hand, has higher voltage and can cover UV-blue efficiently. In a tandem, the DSSC could take either the top position (if its dye is tuned for blue-green and the perovskite for red, though typically perovskites absorb most of visible), or more logically, the DSSC is bottom with a NIR dye so that the perovskite top cell (transparent in IR) feeds the red/IR light to the DSSC. A solid-state DSSC (with a solid hole transporter instead of liquid electrolyte) would be required for monolithic stacking to avoid solvent damage to the perovskite.

Performance: This is a niche research area, and efficiencies have historically been modest compared to other tandems. A 2018 study achieved **8.8% and 10.5%** tandem efficiencies using a perovskite top cell with two different DSSC configurations (one with an organic dye, one with the classic N719 dye) as the bottom cell[25]. These low efficiencies reflected the difficulties in combining the two – losses at the interface and suboptimal spectral split. However, there have been improvements: for instance, one group reported a monolithic tandem with a co-sensitized DSSC top and a PbS quantum-dot cell bottom that reached ~12%[25]. More impressively, very recent reports claim *lab-measured* (not certified) efficiencies in the 20–27% range by using co-sensitization and tandem layouts. For example, a 2020 report by Xu *et al.* combined a p-type DSSC and an n-type DSSC in tandem (a tandem DSSC) reaching 27% under specific conditions[27] – though that was a tandem of two DSSCs (p–n DSSC tandem) rather than DSSC+perovskite. As for DSSC–perovskite hybrids, one approach in 2021 achieved ~13% by four-terminal

stacking a MAPbBr₃ perovskite cell with a dye cell (since MAPbBr₃ only absorbs UV/blue, and dye did red)[28]. In summary, reported efficiencies for perovskite–DSSC tandems are generally *below those of other perovskite tandems*, often in the low teens. Claims of higher performance exist for experimental setups (one monolithic perovskite/DSSC was reported with ~27% under dual-LED illumination and ~27% under 1-sun in a conference paper), but these are not yet peer-reviewed widely.

Challenges and Outlook: The relatively lower performance stems from fundamental and practical issues: DSSCs have lower single-cell efficiency (~12% for the best dyes under 1-sun) and often use liquid electrolytes that are incompatible with stacking. If using a solid-state DSSC, the voltage is limited by the dye energetics and typically lower than perovskites. Additionally, combining a mesoporous DSSC structure with a planar perovskite layer without damaging either is non-trivial. Stability is a concern too – DSSCs with liquid electrolytes can leak or corrode, and even solid-state DSSCs can suffer dye degradation under heat. However, these hybrids could shine in low-light or indoor applications. DSSCs are known to maintain high efficiency under diffuse or low-intensity light (some tandem DSSCs have achieved over 30% under low light[29]). A perovskite–DSSC tandem might therefore target indoor photovoltaic applications, where the light is weaker and spectrum different (LED lighting), possibly outperforming silicon.

In conclusion, while perovskite–DSSC tandems are not as commercially relevant as perovskite–Si or perovskite–organic, they represent an interesting bridge of two technologies. They demonstrate the creative possibilities in tandem solar design and could find specialized use in situations where ultra-high efficiency under indoor or filtered light is needed. Ongoing work is exploring new red/NIR dyes that, when paired with a stable perovskite, could push tandem efficiency higher. For now, their performance is modest (on the order of 10–15% in practical terms[48]), but they remain a compelling research platform for understanding how to integrate disparate solar technologies into a single device.

Fabrication Methods of Perovskite Solar Cells

One attractive feature of perovskite solar cells is that they can be fabricated with relatively simple and low-cost techniques, especially compared to silicon photovoltaics. Because perovskites can be solution-processed, there is the potential for printed, high-throughput manufacturing. Here we outline the common fabrication methods:

Solution Processing (Spin Coating): In the lab, the most prevalent method to make perovskite films is spin-coating a precursor solution onto a substrate. This can be done in a one-step or two-step process. In the one-step deposition, a solution containing all the precursors (e.g. PbI₂ and methylammonium iodide, plus solvent and additives) is deposited and spun; the wet film crystallizes into perovskite upon solvent

evaporation and possibly an annealing step[3]. One-step spin coating is *simple and fast*, but it can be challenging to control the film uniformity and morphology – issues like incomplete coverage or irregular crystal grains can occur. Anti-solvent dripping or gas quenching is often used during spin-coating to rapidly induce crystallization and produce smooth, dense films[3]. In the two-step (sequential) deposition, the metal halide (e.g. PbI_2) is first deposited as a film (by spin coating or evaporation), and then the film is dipped or coated in the organic halide (e.g. $\text{CH}_3\text{NH}_3\text{I}$) which diffuses in and converts it to perovskite. The two-step method can yield better controlled crystallization; for example, the volume expansion during conversion can fill pinholes, resulting in high-quality, uniform films with fewer voids[3]. Both one-step and two-step solution methods have variations: solvent engineering (using additives like DMSO, DMF, GBL, etc.), vapor-assisted solution processing, anti-solvent baths, hot-casting, and more, all aimed at achieving large crystal grains and defect-minimized films[3]. Solution processing allows tuning of crystal growth by additives – e.g. Lewis base additives (like thiourea or pyridine) can slow down crystallization to form better perovskite domains[3].

Scalable Coating Techniques: While spin coating is convenient for small lab cells, it is a batch process not directly suitable for large-area manufacturing. To scale up, similar solution deposition can be done via blade coating (doctor blading), slot-die coating, spray coating, inkjet printing, or roll-to-roll coating on flexible substrates[3]. These methods coat the perovskite ink over large areas and have achieved impressive results at the mini-module scale (several cm^2 to tens of cm^2). A challenge is to maintain film quality (uniform thickness, no pinholes) over large areas and to control solvent drying for consistent crystallization. Techniques like slot-die coating combined with humid air quenching or flash infrared annealing have been used to make 20% efficient perovskite solar modules of $>100 \text{ cm}^2$ in area in research settings. The U.S. Department of Energy has outlined that improving manufacturability (high-throughput coating and printing) is a key step toward commercialization of PSCs[1].

Vapor Deposition: Another route is to deposit perovskite films via vacuum or vapor methods, akin to how OLEDs or some thin-film PV are made. In physical vapor deposition (PVD), the components (e.g. PbI_2 and MAI) can be co-evaporated from separate sources in a vacuum chamber to form the perovskite film on the substrate[3]. In chemical vapor deposition (CVD) or vapor-assisted processes, one precursor (like a lead halide film) is exposed to the vapor of the second precursor (organic halide or even a gaseous reactant) which converts it to perovskite. Vapor techniques tend to produce highly uniform and pinhole-free films with good reproducibility. They also enable easier layering of multiple films – for instance, one could sequentially deposit a wide-bandgap and a narrow-bandgap perovskite for a tandem cell without concern of solvent damage to underlying layers[73]. In fact, the first perovskite solar cells fabricated by thermal co-evaporation were demonstrated in 2013 (Malinkiewicz *et al.*), proving that vapor deposition works for PSCs. The advantages of vapor deposition are uniformity, scalability to large areas (already proven in the OLED

display industry), and compatibility with monolithic tandem fabrication (multi-stack). The disadvantages are higher equipment costs and potentially lower material utilization (more waste of raw materials) compared to solution methods. Nonetheless, companies like Oxford PV have been developing hybrid fabrication (solution for some layers, evaporation for others) for their tandem cells.

Printing and Patterning: Beyond deposition of the perovskite layer itself, complete module fabrication involves additional steps: printing or depositing the charge transport layers and electrodes, and patterning the cell stripes and interconnections (for monolithic modules). Laser scribing is typically used to pattern series connections in thin-film modules (known as P1, P2, P3 scribes for separating cells, connecting layers, etc.). Perovskite modules with aperture efficiency > 20% have been made on glass substrates by such techniques, though scaling to meter-sized panels with long-term stability remains an active area of development.

It should be noted that, currently, most of the highest efficiency cells are still made by spin-coating on small areas ($\approx 0.1 \text{ cm}^2$). As researchers transition these methods to larger areas, minimizing efficiency losses when scaling up is crucial[6]. Efforts like blade-coated or slot-die coated perovskite on textured silicon (for tandems) have shown promise with only a few percent absolute drop from small cell efficiency[3]. Overall, the availability of multiple fabrication techniques is a strength of PSC technology, offering flexibility in manufacturing approaches.

Performance Characteristics and Evaluation

To characterize a solar cell like a PSC, we look at its current–voltage (I–V) behavior under standard illumination and derive key performance parameters. These include the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}) (or current density J_{SC}), fill factor (FF), and the resulting power conversion efficiency (PCE). We will explain these terms and how to calculate efficiency, with reference to the typical J–V curve of a solar cell.

Power conversion efficiency (PCE): This is the fraction of incident solar power that the cell converts into electrical power. Under standard test conditions (1 kW/m² irradiance, AM1.5 spectrum, 25°C cell temperature), efficiency can be computed from the measured V–I curve. The maximum electrical output power from the cell is $P_{max} = V_{mp} \times I_{mp}$, where V_{mp} and I_{mp} are the voltage and current at the maximum power point on the I–V curve. The efficiency is then:

$$\text{PCE} = \frac{P_{\max}}{P_{\text{in}}} = \frac{V_{oc} \times I_{sc} \times FF}{P_{\text{in}}},$$

where P_{in} is the incident light power (100 mW/cm² in standard conditions), and the product $V_{oc} \times I_{sc} \times FF$ effectively gives the maximum power (since $FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$) [11]. In practice, one often uses current density (J in mA/cm²) instead of absolute current, so the formula becomes

$$\text{PCE} = \frac{J_{sc} V_{oc} FF}{P_{in}}$$

For example, if a PSC has $J_{sc} = 22 \text{ mA/cm}^2$, $V_{oc} = 1.10 \text{ V}$, and $FF = 0.80$, its PCE would be

$$\frac{22 \times 1.10 \times 0.80}{100} \approx 19.4$$

Modern champion cells achieve J_{sc} around 25 mA/cm^2 and $V_{oc} \sim 1.15\text{--}1.2 \text{ V}$ (for $\sim 1.6 \text{ eV}$ bandgap), with FF as high as 0.84 , yielding $\text{PCE} \approx 25\%$. For tandem cells, voltages add up (e.g. $\sim 1.8 \text{ V}$ total for perovskite+Si), and currents are a bit lower (limited by the sub-cell with smaller current), allowing even higher PCE as we saw.

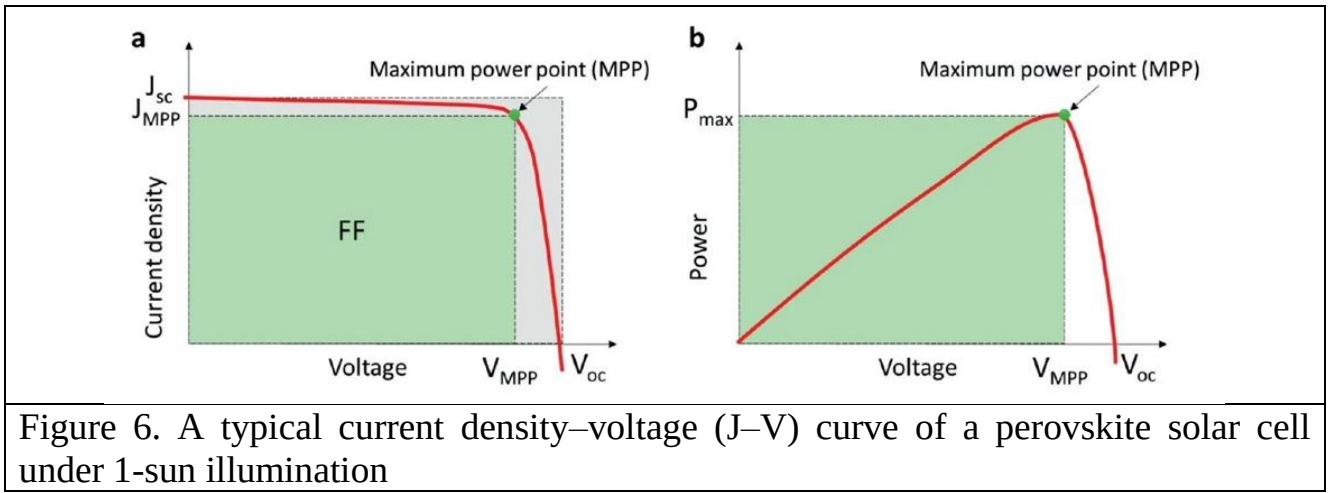


Figure 6: Typical current–voltage (J – V) characteristic of a solar cell under one-sun illumination. Key parameters are indicated: the short-circuit current (I_{sc}) at $V=0$, the open-circuit voltage (V_{oc}) at $I=0$, and the maximum power point (V_{mp} , I_{mp}) where the product $V \times I$ is maximized. The *fill factor* (FF) is the ratio of the areas of the green dashed rectangle ($V_{mp} \times I_{mp}$) to the red dashed rectangle ($V_{oc} \times I_{sc}$). A higher FF indicates a more “squared” curve and higher efficiency[12][13].

Current–Voltage (I – V) Curve: Figure 6 shows a typical J – V characteristic for a solar cell under illumination. When the cell is short-circuited ($V = 0$), the current is at its maximum, called the short-circuit current I_{sc} (or J_{sc} per unit area). This corresponds to the photocurrent generated by the cell when there is no voltage barrier. At the other extreme, when the cell is open-circuited ($I = 0$), the voltage rises to the open-circuit voltage V_{oc} , which is the maximum voltage the cell can provide (when no current is drawn)[12]. Between these points, the curve is non-linear (typically diode-like). The power at any point is $P = V \times I$ (or $V \times J$ for current density); it starts at zero at short-circuit (because $V=0$), then rises to a peak (at V_{mp} , I_{mp}), then drops to zero at open-circuit (because $I=0$). The fill factor (FF) is a measure of how “square”

the I–V curve is – it is defined as $FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$ [13]. Geometrically, it's the ratio of the area of the largest rectangle that fits under the I–V curve to the area of the rectangle defined by $V_{oc} \times I_{sc}$. A higher FF (closer to 1) means the cell maintains a high current until close to V_{oc} , which is desirable. Good silicon or perovskite cells have FF in the 0.75–0.85 range, whereas a poor cell with high resistive losses or recombination might have $FF < 0.5$. The I–V curve also provides insight into cell health: the slope near I_{sc} relates to shunt resistance, and the slope near V_{oc} relates to series resistance – but that goes beyond our scope here.

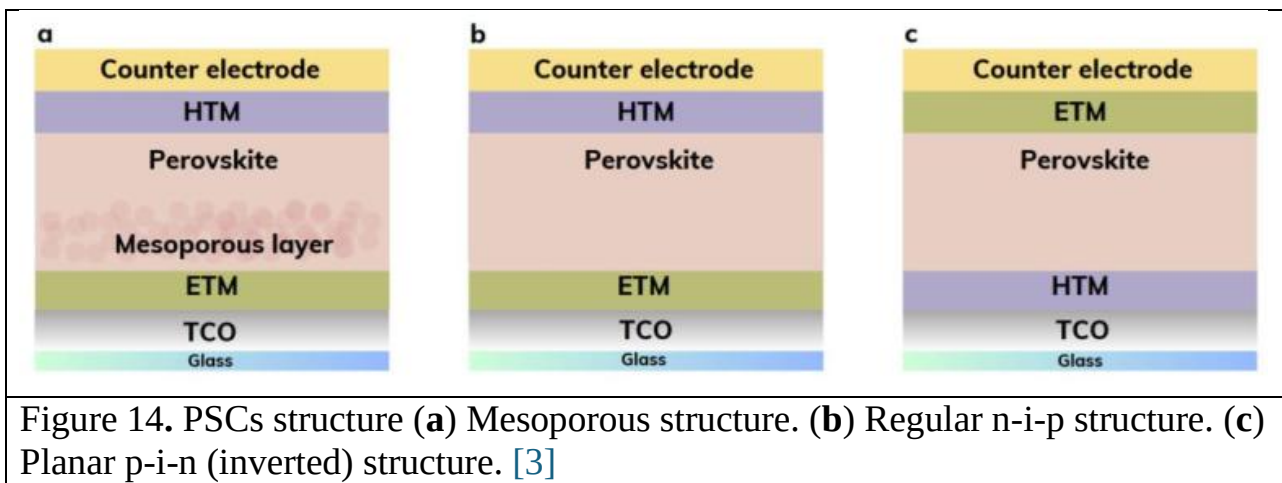
For perovskite solar cells, measuring the I–V curve must be done carefully due to the mentioned hysteresis and transient effects. Typically, a stabilized power output is measured (e.g. holding the cell at the V_{mp} and recording the current over time) to report the most reliable efficiency. The ideality of the curve (how closely it follows the Shockley diode equation) can reveal recombination mechanisms. Researchers often use the I–V data under varying light intensities or temperatures to extract parameters like series resistance, shunt resistance, diode ideality factor, etc., which help in understanding loss mechanisms.

External Quantum Efficiency (EQE): In addition to I–V, another important characterization is the spectral response or EQE of the cell – the fraction of incident photons of each wavelength that are converted to electrons. A good perovskite cell will have EQE above 80–90% across a broad wavelength range (typically ~400–750 nm for a 1.6 eV bandgap perovskite). Integrating the EQE with the solar spectrum predicts the J_{sc} , which should match the measured J_{sc} if calibrated correctly. For tandem cells, one measures EQE of both sub-cells (the perovskite top and silicon bottom) to ensure current matching in 2T devices.

In summary, evaluating a PSC involves measuring its efficiency (PCE) via the I–V curve and understanding the contributions of V_{oc} , J_{sc} , and FF. Today's record single-junction PSCs have $V_{oc} \sim 1.2$ V, $J_{sc} > \sim 25$ mA/cm², and $FF \sim 0.84$ [5], which are remarkable and underpin the >25% efficiencies. Continued improvements in these parameters (especially by reducing non-radiative recombination to push V_{oc} closer to the material's radiative limit, and by improved charge transport to keep FF high) are active areas of research.

Comparison of Different Perovskite Solar Cell Types and Configurations

Perovskite solar cells encompass a variety of device structures and material compositions. Here we compare several categories and models of PSCs, including how they differ in efficiency, I–V characteristics, and suitable applications:



- Mesoporous vs. Planar Structure**(Figure 14): The earliest high-efficiency PSCs (2012–2014) often used a **mesoporous TiO_2 scaffold**, inherited from dye-sensitized cell designs. In these, the perovskite penetrates the pores of a TiO_2 layer (150–300 nm thick), which provides a large interface for electron extraction. Mesoporous cells showed high photocurrents and were crucial in initial efficiency boosts (e.g. Burschka *et al.* 15% in 2013)[3]. However, it was later realized that a mesoporous TiO_2 is not strictly necessary – **planar heterojunction** cells (with a compact ETL and perovskite on top) can work as well or better. Planar cells are structurally simpler and avoid issues like TiO_2 photocatalytic degradation (TiO_2 can cause instability under UV unless filtered). By 2015, planar cells equaled and then surpassed mesoporous in efficiency, with easier fabrication (one less layer). Mesoporous cells can still be slightly more tolerant to thickness variations and sometimes yield higher initial J_{SC} , but planar cells typically achieve comparable FF and V_{OC} . Most current record cells use a planar architecture (either n–i–p or p–i–n) with carefully engineered interfaces for charge extraction.
- Regular (n–i–p) vs. Inverted (p–i–n)**: These refer to which charge contact is at the transparent front. In **regular (n–i–p)** cells, the transparent front contact is coated with an n-type ETL (e.g. TiO_2 , SnO_2), and the back contact has the p-type HTL (e.g. spiro-OMeTAD). This was the configuration used in many early devices and often yields very high V_{OC} and J_{SC} . The **inverted (p–i–n)** cells put a p-type layer at the front (commonly PEDOT:PSS or NiO for inorganic), and an n-type layer at the back (often fullerene derivatives like PCBM as electron acceptors)[3]. Inverted cells typically have negligible hysteresis and can be made without high-temperature processes (e.g. NiO or organic HTLs can be solution-processed, avoiding the 500°C sintering that TiO_2 requires). Historically, inverted PSCs slightly lagged in efficiency compared to regular cells (especially in J_{SC}), but recent advances have closed the gap. For instance,

an *inverted* cell with a certified 22.1% efficiency and a record fill factor of 84% was reported in 2022[5], showing that p-i-n cells can be just as performant. Inverted structures are advantageous for tandem integration (many perovskite-silicon tandems use a p-i-n top cell so that the tunnel recombination junction can be between the n-type of top and p-type of silicon bottom). In summary, **regular vs inverted** is more about manufacturing choices; both can reach >25% efficiency, with careful layer and interface design.

- **Lead-Based vs. Lead-Free Perovskites:** The state-of-the-art PSCs use lead (Pb) in the B-site of ABX_3 because Pb-based perovskites have superior semiconducting properties. There is interest in **lead-free perovskites** (e.g. using tin (Sn^{2+}) or germanium) due to toxicity concerns. Unfortunately, tin perovskites (like MA_2SnI_4 or $FASnI_3$) suffer from rapid oxidation of Sn^{2+} to Sn^{4+} and have much lower efficiencies so far (the best Sn-based cells are <10% efficient and very air-sensitive). Various strategies like tin-rich compositions, Sn+Ge mixes, or 2D capping layers show some improvements. Bismuth or antimony based perovskite-inspired materials have been tested, but these typically have wider bandgaps or worse transport properties. As of 2025, **lead-halide perovskites remain unrivaled in efficiency**, but research into less toxic alternatives or encapsulation to prevent Pb leakage is ongoing[3]. From a performance standpoint, any viable lead-free PSC would need to replicate the excellent V_{OC} and low defect density of lead perovskites – a high bar that Sn perovskites haven't reached yet.
- **Single-Junction vs. Tandem Cells:** A **single-junction PSC** uses one perovskite absorber (bandgap $\sim 1.5\text{--}1.6$ eV typically) and currently yields $\sim 26\text{--}27\%$ max efficiency on small area. A **tandem** that combines a perovskite with another cell (usually silicon) can harness more of the solar spectrum and as discussed has pushed into the 30% range. In terms of I-V characteristics, a single junction cell under 1 sun has a typical $I_{SC} \sim 20\text{--}25$ mA/cm² and $V_{OC} \sim 1\text{--}1.2$ V. A 2-terminal perovskite/silicon tandem will have roughly half the current (limited by silicon $\sim 19\text{--}20$ mA/cm² if series-connected) but about double the voltage ($V_{OC,tandem} \approx V_{OC,perovskite} + V_{OC,silicon}$, often $\sim 1.8\text{--}1.9$ V total) [8]. The tandem's fill factor can also be high (over 0.80 in the best cases). The net result is a much higher PCE. However, tandems introduce complexity: current matching in 2T devices, additional interface layers, and more fabrication steps. There is also the **all-perovskite tandem**, using two (or even three) different bandgap perovskite layers. The current record all-perovskite 2T tandem (around 30.1%[7]) uses a wide gap ~ 1.8 eV front and ~ 1.2 eV low-gap back cell, with interconnecting layers. All-perovskite tandems are attractive for their lightweight, flexibility, and potentially lower cost (no silicon), but they are still in early stages of development compared to perovskite-silicon tandems.

- **Flexible and other novel formats:** Because PSCs can be made on plastic or metal foil substrates at low temperatures, flexible PSCs have been demonstrated. These typically use a conductive plastic or metal foil as the substrate and often an inverted structure (to avoid cracking brittle layers). Efficiencies >18–20% have been reached on flexible cells, which is promising for applications like wearable solar or drones. The challenge is that depositing high-quality films on flexible substrates (often temperature-sensitive) can be harder. **Semi-transparent** perovskite cells are also possible by using transparent electrodes (like thin metal or conducting polymers) on both sides; these can be used in window-integrated PV. Their efficiency is lower (10–15%), but combined with another cell (tandem or window+BIPV) they could contribute. Additionally, **perovskite modules** (series-connected cells on glass) have achieved >17–20% efficiency at $\approx$ module size (tens of cm² active area), which is a good sign for scaling, though still a few absolute % lower than lab cells[3].

The table below summarizes and compares some of these PSC variants:

PSC Type/Architecture	Typical Efficiency (lab)	Features	Notes
Mesoporous n–i–p (TiO ₂ scaffold)	~15–20% (record ~ twenty%)	Thick TiO ₂ scaffold under perovskite; high J _{SC} was standard in early cells.	UV stability can be an issue (TiO ₂ can cause degradation); slightly more complex fabrication. Early 2013 records (15%[3]). Not needed for charge transport, as discovered later.
Planar n–i–p (compact ETL)	~20–26% (current records)	No mesoporous layer; just a thin compact ETL (e.g. SnO ₂) and perovskite on top. Highest efficiencies achieved in this structure.	Simpler fabrication, good V _{OC} . Requires excellent interfaces and surface passivation to reach top performance. Used in many record cells (e.g. Min <i>et al.</i> 25.7%[3]).
Planar p–i–n (inverted)	~18–24% (record ~23%)	Inverted layer order (HTL first). Often uses organic contacts (PEDOT:PSS,	Low hysteresis, easier integration on flexible substrates. Catching up in efficiency – e.g. 22% with fill factor 0.84

PSC Type/Architecture	Typical Efficiency (lab)	Features	Notes
All-Perovskite Tandem (2T)	~25–30% (record ~30%)	PTAA, PCBM). Low-temp processing. Two perovskite junctions (e.g. 1.8 eV + 1.2 eV) monolithically connected. Uses interlayer (recombination layer).	demonstrated[5]. Popular in tandem (perovskite/Si) devices. Potential for >35% efficiency and fully thin-film manufacturing. Needs careful current matching; stability of low-bandgap Pb-Sn cell is a concern. Demonstrated by academic groups (e.g. Nanjing Univ. 30.1%[7]).
Perovskite/Si Tandem (2T)	~25–35% (record 34.85%)	Perovskite top cell on silicon bottom cell. Industry interest (e.g. Oxford PV, LONGi).	High efficiency and uses existing Si tech. Challenges: adding perovskite without impacting silicon process, and long-term stability. Record 34.85% by LONGi (2025)[8].
Perovskite/Si Tandem (4T)	~29–32% (uncoupled cells)	Perovskite and Si cells made separately, optically stacked, but electrically independent (4 terminals).	Easier to prototype (no current matching), but requires dual junction boxes. Some building-integrated PV ideas use this (transparent perovskite on glass + silicon panel behind).
Flexible PSC (plastic or metal foil substrate)	~15–21%	Typically planar p–i–n on PET or steel foil. Uses low-temp deposited layers.	Lower efficiency than glass-based, but lightweight and rollable. Stability can be lower due to permeability of substrate unless encapsulated well.
Stable PSC with 2D/3D or interface	~17–20% (with ultra	Emphasis on longevity: e.g. 2D	One example achieved ~17% with projected 30-

PSC Type/Architecture	Typical Efficiency (lab)	Features	Notes
engineering	stability)	perovskite capping layers, all-inorganic compositions (CsPbI ₃), etc.	year lifetime (Zhao <i>et al.</i> , 2022)[4]. Often a trade-off: adding stabilizing layers can reduce initial efficiency slightly.

As seen, different “models” of PSCs may emphasize peak efficiency, flexibility, or stability. The combination of perovskite cells with other types (tandems) currently yields the highest efficiencies overall. Meanwhile, purely perovskite devices are improving in stability. It is expected that *hybrid approaches* – for instance, a moderately lower-bandgap perovskite paired with another polycrystalline thin-film cell (like CIGS or even organic PV) – could carve out niches (for semi-transparent PV, etc.). Already, a perovskite/CIGS 4-terminal tandem reached 24.2% (EPFL, 2020) [9], showing the versatility of perovskites to boost other PV technologies.

In terms of I–V characteristics differences: A lower efficiency cell (say 15%) might have a lower fill factor and/or V_{OC} compared to a high efficiency one. For example, early MAPbI₃ cells had $V_{OC} \sim 0.9$ V and FF ~ 0.6 – 0.7 [3], whereas today’s optimized cells have $V_{OC} > 1.1$ V and FF ~ 0.80 – 0.85 . Tandems, by virtue of series-connecting sub-cells, show “S-shaped” I–V if currents are mismatched, but when matched well, they have high FF. Single junction vs tandem also differ: single junction has one diode curve; a 2T tandem effectively behaves like a single diode with higher V_{OC} . So the main I–V difference is just extended voltage.

Ultimately, the best configuration depends on the application: if one wants the absolute highest efficiency, a tandem (perovskite+Si or multi junction perovskite) is the way to go. If one wants low-cost printable panels, single-junction all-perovskite on flexible substrates might be preferred, even if efficiency is a bit less, because of simpler manufacturing. Researchers are actively exploring all these options.

Theory and Application: Outlook for Perovskite PV

Theoretical limits: A single-junction perovskite cell with bandgap ~ 1.6 eV has a detailed-balance (Shockley–Queisser) efficiency limit of about 30–33%[14]. We are already in the mid-20s, so future single cells might asymptotically approach ~ 27 – 29% by eliminating remaining losses (improving quantum yield in the red part of spectrum, pushing V_{OC} closer to the radiative limit by passivating all defects, etc.). There is still headroom, evidenced by the fact that the external luminescence efficiency of current cells is not at the level of the best GaAs or silicon yet. In theory, if a perovskite cell can be made to re-emit 10–20% of absorbed photons (a sign of very low non-radiative recombination), its V_{OC} could approach the bandgap in volts minus 0.2 V or so, which for 1.6 eV (~ 1.1 V bandgap-equivalent) means ~ 1.3 – 1.4 V possible. That could yield

28–30% single-junction efficiency if J_{SC} and FF remain high – an ambitious but not impossible goal.

Tandem and multijunction perovskite devices have even higher theoretical limits (43% for an ideal dual-junction, ~50% for three-junction under 1 sun). Practically, the roadmap being discussed is reaching ~40% with a perovskite/Si tandem (or all-perovskite triple-junction) in the coming decade. The tandem demonstrated by LONGi at 34.85% already exceeded the single-junction limit[8], and further gains may come from better current balancing and optical management (e.g. minimizing reflection, using textured interfaces to boost infrared absorption in Si). A recent triple-junction perovskite cell (all-perovskite) with three bandgaps was reported with ~20% on a large area[15], indicating progress toward even more junctions.

Stability and commercialization: The biggest hurdle for application is ensuring long-term stability. There have been significant milestones – for instance, in 2022, a group demonstrated a **30-year equivalent lifetime** device (with encapsulation, under certain test conditions) by using a 2D capping layer to stabilize interfaces (Zhao *et al.*, *Science* 2022)[4]. That device had lower efficiency (~17%) but proved that **perovskites can be made durable**. Efforts like encapsulation improvements, intrinsic stability via composition (replacing volatile MA with FA/Cs, using inorganic HTLs that don't induce perovskite degradation) and self-healing additives are all under intense study. Some startups (Oxford PV, Microquanta, Saule Technologies, etc.) are already building pilot manufacturing lines. Oxford PV, for example, plans to **commercialize tandem cells** with an initial product efficiency of ~27% and claims of 20-year lifetimes for encapsulated tandem modules[5]. Building-integrated photovoltaics (BIPV) is a target market: semi-transparent perovskite panels could be used as windows or facade elements if stability is ensured.

Applications: If challenges are met, PSCs have diverse applications. Their high efficiency and low weight could enable solar-powered drones or vehicles. Their flexibility and semi-transparency could integrate solar power generation into windows, greenhouses (tinted for plants), or wearables. Tandem perovskite/Si panels could upgrade existing silicon solar farms by replacing top sheets with perovskite layers to boost output (some are exploring “retrofit” tandems that laminate a perovskite layer onto finished silicon cells). Off-grid and space applications are also considered: the high power-to-weight ratio of PSCs is attractive for space, though radiation hardness is a question (initial tests show fast degradation under proton irradiation, but some mitigation is possible by additives).

Environmental and safety considerations: Lead in PSCs is a concern; however, the actual amount of lead in a m² of perovskite (~0.1 g) is much less than in a car battery, for instance, and strong encapsulation can prevent leakage[3]. Research on lead sequestration coatings (that capture lead in case of panel damage) is ongoing. Meanwhile, teams work on lead-free variants as discussed, but none are near the performance of lead-Pb perovskites yet.

In conclusion, perovskite solar cells represent a fusion of solid-state physics, chemistry, and materials engineering, and they have in a short time become **key contenders for next-generation photovoltaics**. From a scientific perspective, they are fascinating due to their unique defect physics (tolerance of defects, ionic movement) and tunability. From an application perspective, they promise to lower solar energy costs further and enable new uses of solar power. The story from 2009's 3.8% cell to 2025's 35% tandem is one of the most dramatic in renewable energy research, and it is still being written. With continuous improvements in stability and scale-up, we may soon see perovskite solar technology complementing or even surpassing conventional solar panels in the marketplace, bringing us closer to a sustainable energy future.

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5.1. BACK-CONTACT (BC) SOLAR CELLS

Introduction: Back-contact (BC) solar cells relocate all electrodes to the rear side of the device, eliminating front-side metal and enabling full sunlight absorption[1]. As Van Kerschaver and Beaucarne (2006) note, research into BC cell architectures dates back to Schwartz's first proposal in 1975[1]. BC designs fall into three main categories: - **Interdigitated Back-Contact (IBC)** or **back-junction (BJ)** cells, with both p–n junctions on the rear; no emitter on the front (Fig 1. below)[2].

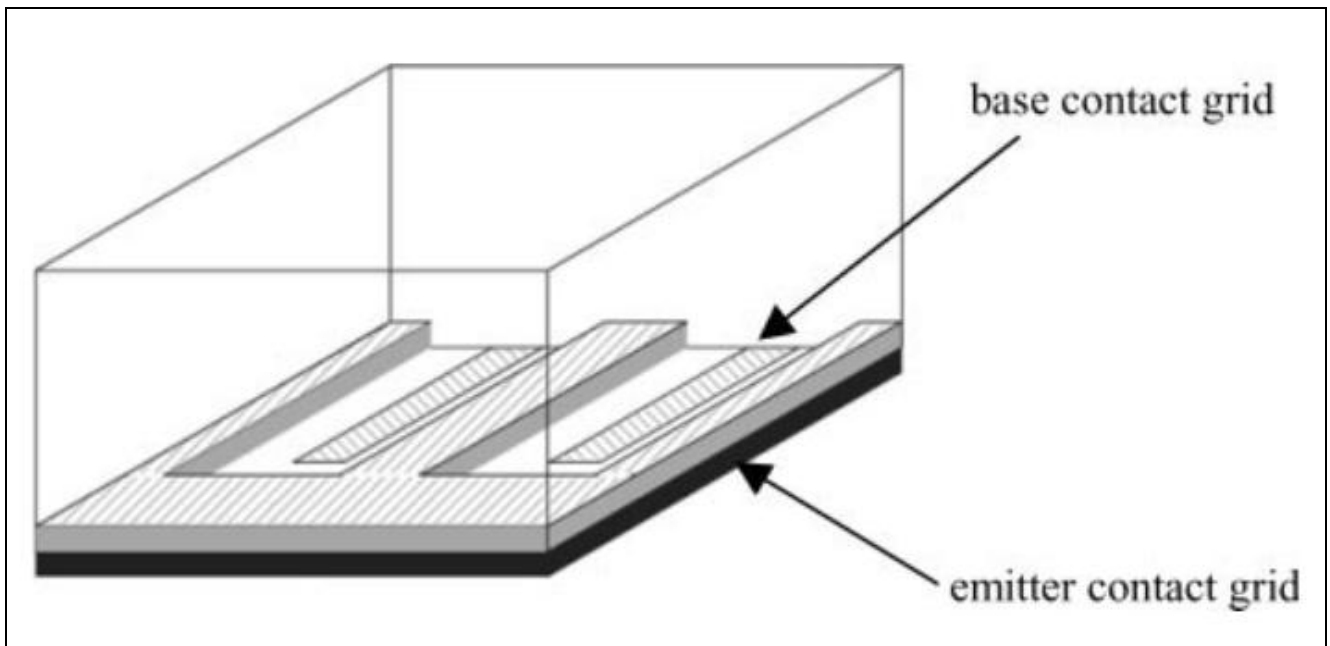


Figure 1. Schematic representation of a back-junction solar cell(DOI: 10.1002/pip.657)

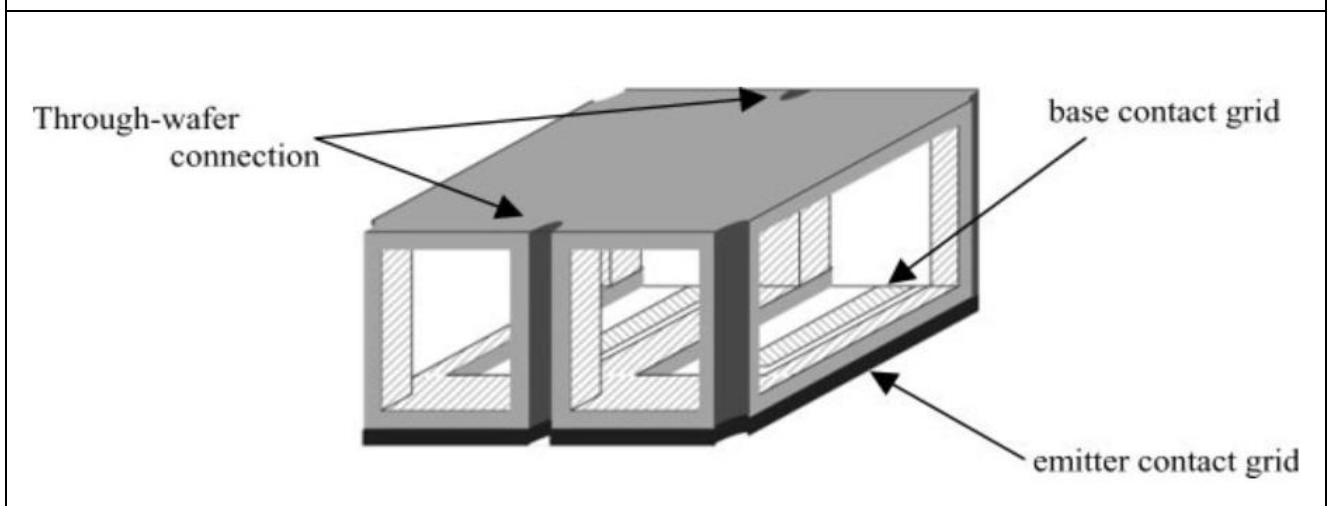
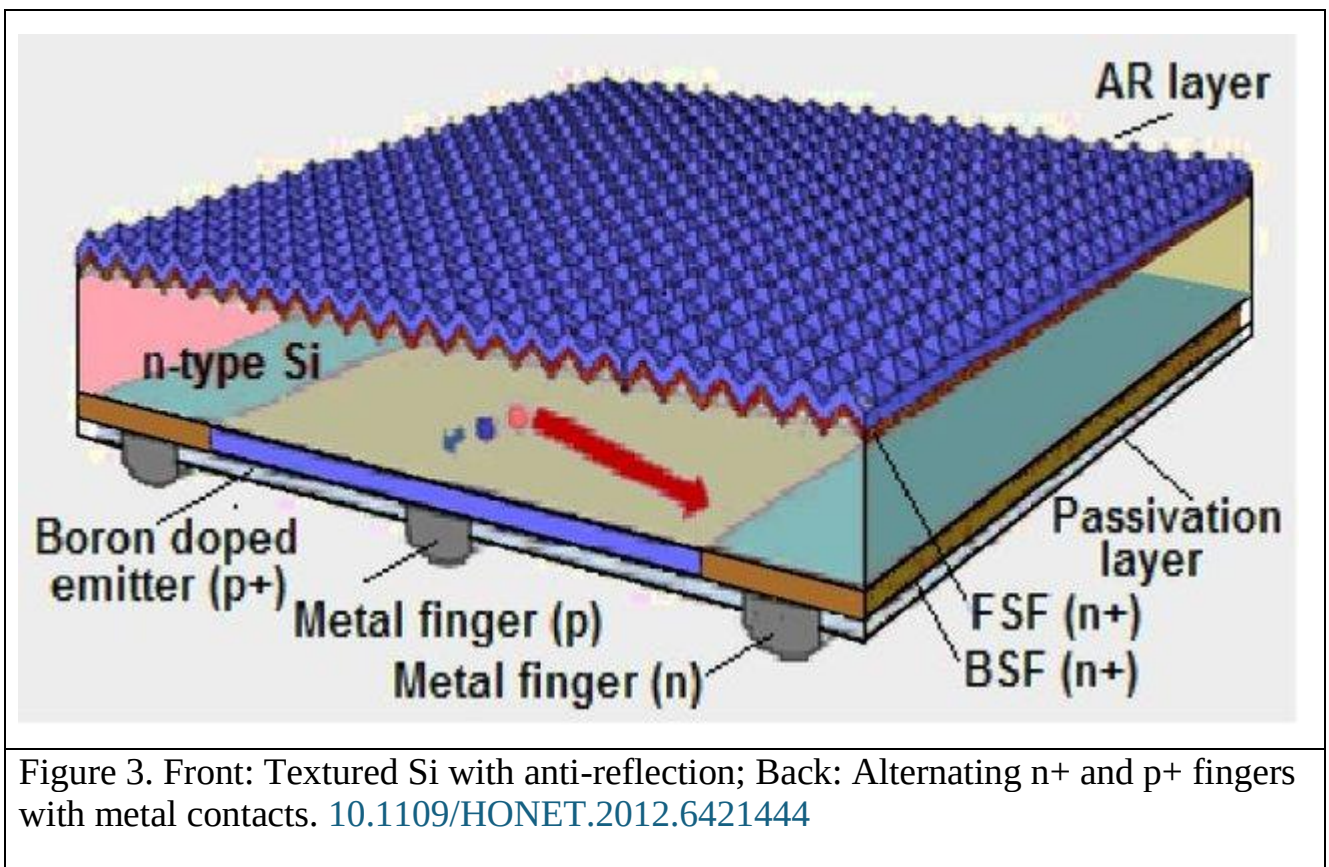


Figure 2. Schematic representation of an emitter wrap-through solar cell(DOI: 10.1002/pip.657)



- **Emitter Wrap-Through (EWT)** cells, where the emitter remains near the front but contacts are “wrapped through” to the back via holes[1].
- **Metallization Wrap-Through (MWT)** or **contact-wrap-through (CWT)**, retaining a front metal grid but routing interconnections to pads on the back[1].

IBC cells **eliminate front shading** (no front contacts) and allow high rear metallization area, lowering series resistance[1]. However, they **require very high-quality material**: long carrier diffusion lengths and excellent surface passivation (low front-surface recombination) to avoid carrier loss[1]. In fact, IBC cells often use high-resistivity silicon and minimize front recombination so that almost only the rear-side diode governs current. Van Kerschaver and Beaucarne explain that with no trade-off between series resistance and shading, the rear junction can be optimized for minimal saturation current and high fill factor. This makes BC cells especially promising in tandem devices: as the bottom subcell, a BC silicon cell can dump excess current through its rear contacts without current-matching losses in the front (avoiding series connection through the entire stack)[1].

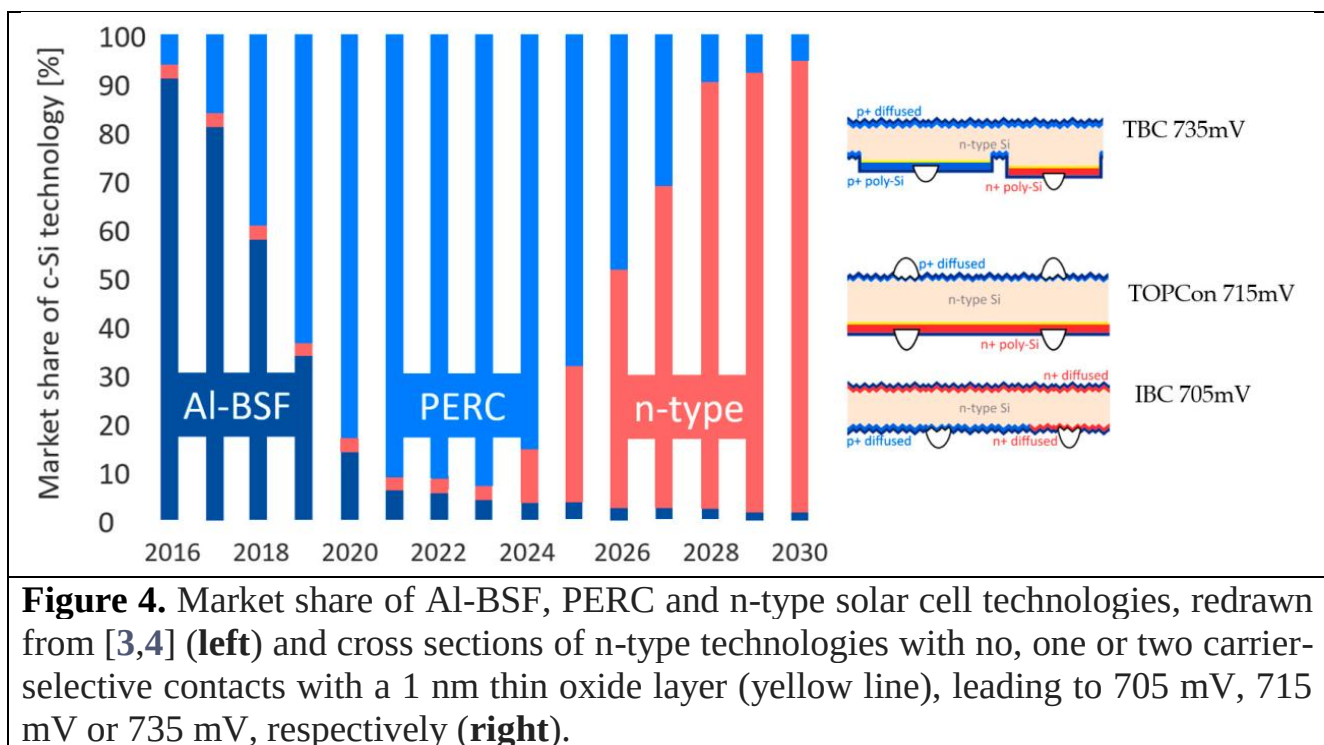


Figure 4: Left – historic and forecast market shares of Si cell types; right – schematic n-type Si cell cross-sections. Adding one or two tunnel-oxide passivated contacts (middle/right) raises V_{OC} ($\approx 705 \rightarrow 715 \rightarrow 735$ mV)[2]. (Red=p-type regions, blue=n-type, yellow=passivating oxide.)

Development Timeline and Efficiency: BC solar cells have evolved significantly. Early work at Purdue and Stanford (1980s–90s) demonstrated IBC cells for concentrators, later extended to flat-plate use (e.g. SunPower’s world solar car in 1993[1]). By the mid-1990s SunPower achieved >22% average on large-area IBC cells. Continuous R&D has pushed records ever higher: recent IBC silicon cells exceed 27% efficiency. For example, SunPower’s *heterojunction IBC* (using amorphous Si passivation) reached 27.09% (25.6%-area)[3], and Tong *et al.* (2025) reported 27.03% for a 350 cm² *tunnel-oxide back-contact* (TBC) cell[4]. Similarly, perovskite cells have begun exploiting BC designs: Blackburn *et al.* (2025) report that BC perovskites climbed from ~6.5% (2016) to over 11%[5] (with recent *microgrooved* modules stabilizing near 12.8%[5]). These advances are illustrated in the NREL chart below:

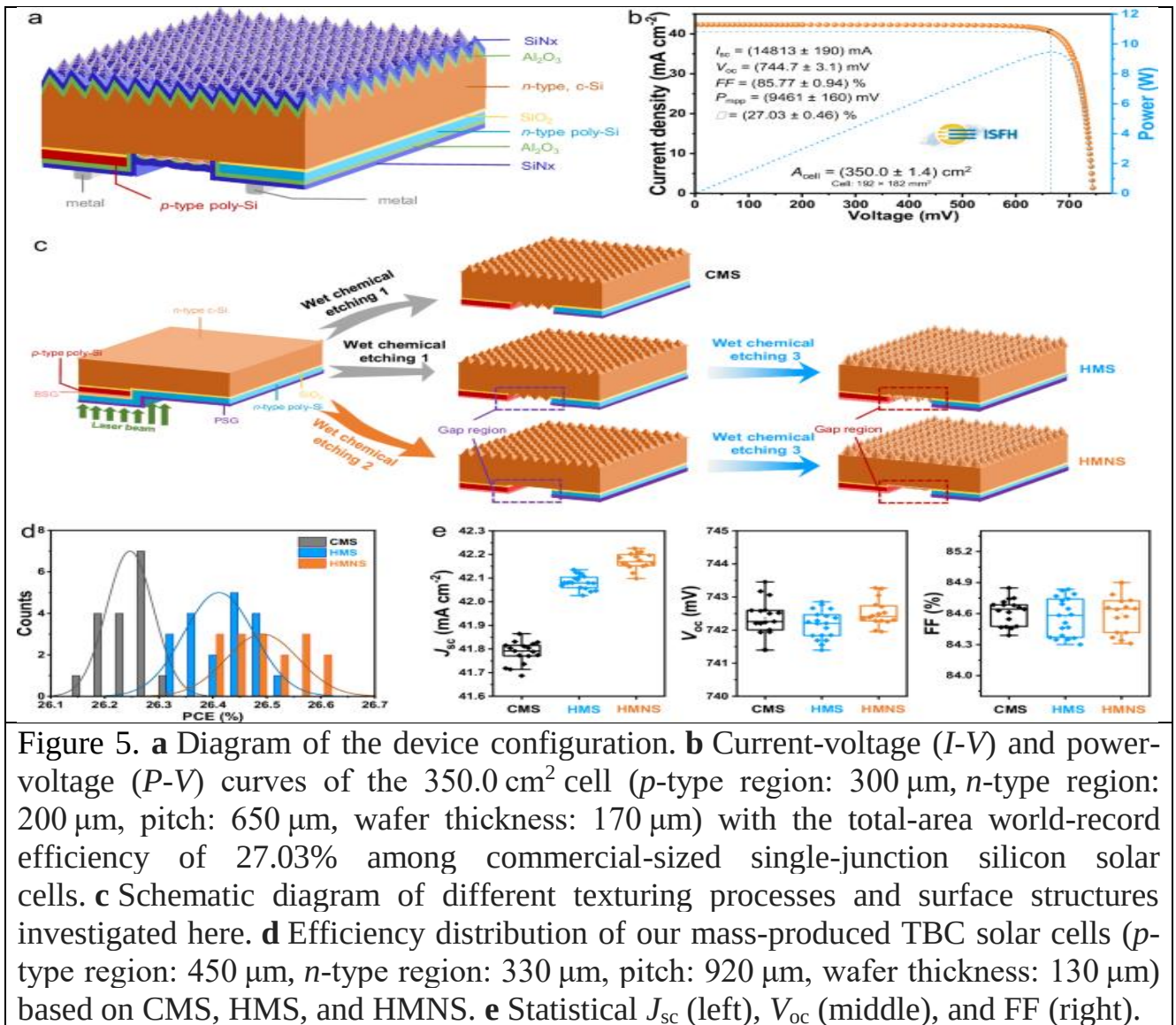


Figure 5. **a** Diagram of the device configuration. **b** Current-voltage (*I*-*V*) and power-voltage (*P*-*V*) curves of the 350.0 cm² cell (*p*-type region: 300 μm , *n*-type region: 200 μm , pitch: 650 μm , wafer thickness: 170 μm) with the total-area world-record efficiency of 27.03% among commercial-sized single-junction silicon solar cells. **c** Schematic diagram of different texturing processes and surface structures investigated here. **d** Efficiency distribution of our mass-produced TBC solar cells (*p*-type region: 450 μm , *n*-type region: 330 μm , pitch: 920 μm , wafer thickness: 130 μm) based on CMS, HMS, and HMNS. **e** Statistical J_{sc} (left), V_{oc} (middle), and FF (right).

Figure 5: Silicon IBC (Single-junction c-Si, blue) now reaches ~27%^{[4][3]}. Perovskite-silicon tandems (bottom right) exceed 30%, and tandem III-V devices exceed 47%. (Data from NREL^[14].)

Efficiency Improvements in BC Solar Cells

Efficiency (η) in solar cells is the ratio of output electrical power to input solar power. BC cells have improved from ~15% in the 1970s to over 27% today due to reduced optical losses, better passivation, and advanced materials.

Key Factors Driving Improvements:

- **Elimination of Front Shading:** Traditional cells lose 5-10% efficiency to front grids; BC designs capture 5-7% more light (Structuring IBC, 2024).

- **Passivation Enhancements:** Layers like SiO₂ or Al₂O₃ reduce recombination, increasing Voc from 0.6V to 0.75V (Improved Passivation, 2025) .
- **Carrier Collection Optimization:** Interdigitated patterns minimize series resistance (Rs), boosting FF from 70% to 85% (Bifacial IBC, 2018) .
- **Material Shifts:** From p-type to n-type silicon, reducing boron-oxygen defects; integration with HJT or TOPCon adds 2-3% efficiency (Interdigitated Back Contact, 2025) .
- **Bifaciality and Scaling:** Modern BC cells are bifacial, absorbing rear light for +20% output (Kim et al., 2022) .

Historical Efficiency Timeline (Table 1):

Year	Model/Type	Efficiency (%)	Key Improvement	Reference
1977	Early IBC Prototype	15-18	Interdigitated doping	Lammert & Schwartz
1997	SunPower IBC	22	Laser patterning	Verlinden et al.
2014	Panasonic HJT-IBC	25.6	Amorphous Si passivation	Taguchi et al.
2017	POLO-IBC	26.1	Poly-Si contacts	Richter et al.
2022	ALD IBC	18.6 (large-area)	Maskless fabrication	Procel-Moya et al.
2024	SHJ-BC	27.09	Laser contact opening	Chen et al.
2025	BC-TOPCon Hybrid	27.5+	Optimized antireflection	Li et al. [web:52, web:59]

Efficiency is improving via nanotechnology and AI-optimized designs, targeting 30% by 2030 (FuturaSun, 2023).

From this chart and the literature, we see that **IBC silicon** cells dominate single-junction Si records ($\approx 27\%$ [4][3]). Perovskite BC devices, still emerging, are in the low-double-digits ($\geq 11\%$ [12]). In contrast, multi-junction (2+ junction) tandem cells have already far higher record efficiencies ($\approx 47\%$ [6]). Importantly, when reporting BC results one calculates power conversion efficiency (PCE) in the standard way:

$$\text{PCE} = \frac{P_{\max}}{P_{\text{in}}} = \frac{J_{\text{MP}} \times V_{\text{MP}}}{P_{\text{in}}} = \frac{J_{\text{SC}} V_{\text{OC}} \text{FF}}{P_{\text{in}}},$$

where J_{SC} is the short-circuit current density, V_{OC} the open-circuit voltage, and FF the fill factor[7]. For example, Tong *et al.* report a 27.03% TBC cell with $J_{SC} \approx 42.3 \text{ mA/cm}^2$, an unusually high current for crystalline Si[4]. Under illumination the I–V curve (below) typically shows zero current at V_{OC} and I_{SC} at zero voltage[7]. The maximum power point (MPP) lies in between, defining FF[7].

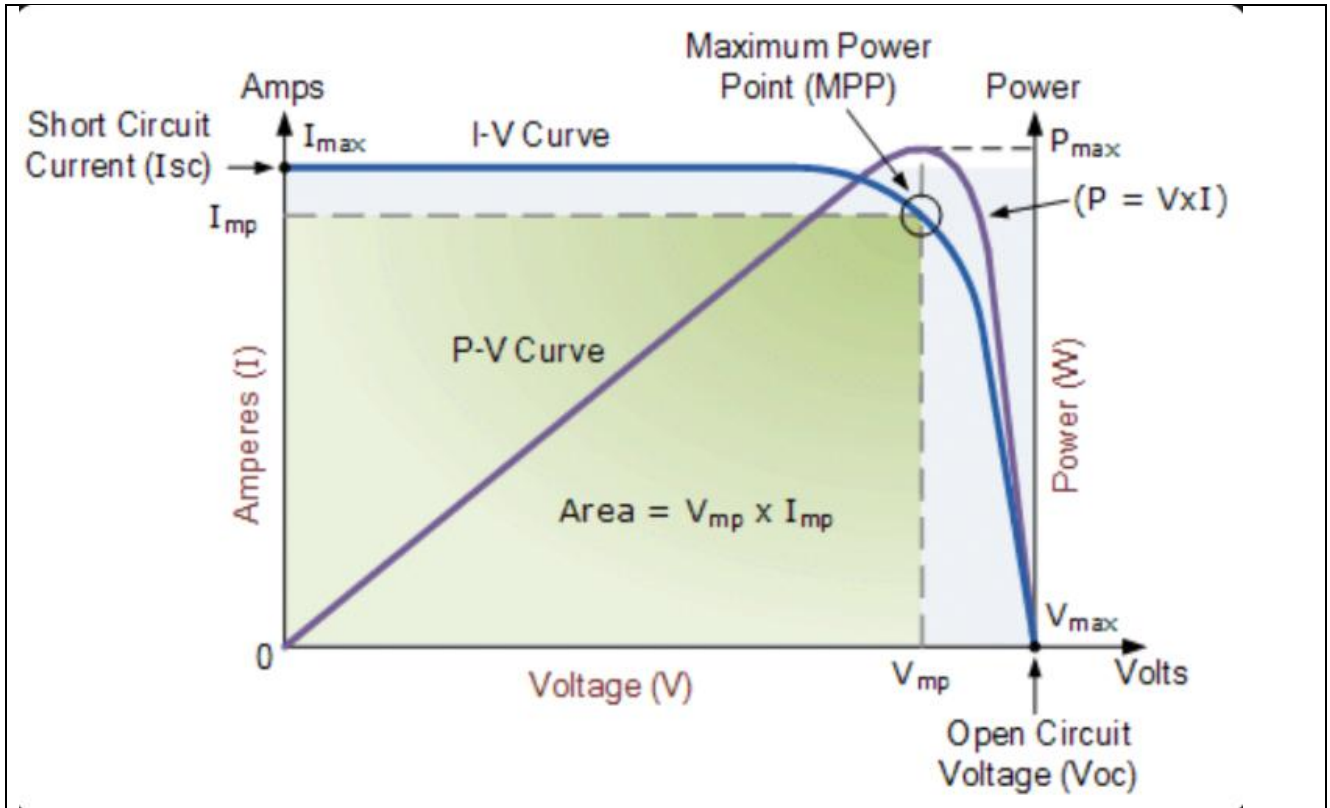


Figure 6. The ideal solar cell equation: $I = I_L - I_0 (\exp(qV/kT) - 1)$, where I_L is light-generated current, I_0 reverse saturation current, q electron charge, k Boltzmann constant, T temperature (Theory of Solar Cells, Wikipedia) .

Device Physics: In BC cells the junction is buried at the rear. For silicon IBC, one rear region is p^+ -doped and the alternating region is n^+ -doped, both diffused into the wafer back. The built-in electric fields lie at these rear p – n junctions. Electrons generated in the bulk must diffuse laterally (or drift via doping gradients) to the n^+ regions, while holes go to the p^+ regions. The charge transport follows the standard semiconductor continuity and drift–diffusion equations (Poisson’s equation determines band bending, and carrier currents $J = q\mu nE + qD \frac{dn}{dx}$ flow to the contacts). The net current–voltage behavior still follows a diode-like Shockley equation:

$$J = J_0 [\exp(qV/nkT) - 1] - J_{ph}$$

with saturation current J_0 reflecting recombination. High-quality BC cells aim for low J_0 (via long lifetimes and low surface recombination) to achieve high V_{oc} and FF. In practice, high-efficiency IBC silicon cells employ excellent passivation (e.g. thin ALD oxides or amorphous Si layers) so that surface recombination is minimal[1][4]. For instance, Chu *et al.* report an IBC process (without special contacts) already achieving $V_{oc} > 700 \text{ mV}$ [2], which increases further if an ultrathin tunnel oxide is added to each contact.

Indeed, as Fig. 4 (above) shows, adding one or two tunnel-oxide/passivating layers raises the achievable V_{oc} by $\sim 10\text{--}30 \text{ mV}$: on average about 705 mV with no oxide, 715 mV with one contact passivated, and 735 mV with both contacts passivated[2]. Chu *et al.* report *actual* IBC devices exceeding 700 mV with standard screen-printed metallization[2]. This gain in voltage (and concomitant increase in FF) is critical for pushing efficiency higher. In general, we see that each added carrier-selective contact improves voltage and fill factor – at the cost of extra processing. Thus, the most advanced BC cells use “TOPCon-like” contacts (stacking a very thin SiOx plus doped poly-Si) on both polarities of the back surface[4][2].

Fabrication Methods: Manufacturing BC cells is more complex than standard cells. Typical processing steps include: front-surface texturing/passivation, backside diffusion patterning, dielectric deposition, contact opening, and metalization – all from the rear. For example, modern IBC cells often start with plasma or wet texturing on the front (using the entire front as passivation with SiNx or Al₂O₃), then perform patterned diffusion on the backside. Photolithography or laser patterning can define the interdigitated p⁺/n⁺ regions[4]. In high-end R&D cells, multiple photolithography steps deposit oxide/poly-Si stacks at precise positions (as in Tong *et al.*[4] and Wang *et al.*[3]). Laser doping is also used: recent work used femtosecond lasers to dope selective regions for a heterojunction IBC process, greatly simplifying mask steps[4].

Fabrication Process (Application):

1. **Wafer Preparation:** Start with high-purity silicon ingot sliced into wafers via diamond wire sawing (Solar PV Basics, DOE) . Clean and texture front surface chemically (e.g., KOH etching) for anti-reflection.
2. **Doping for Interdigitation:** Create alternating p⁺ (boron-doped) and n⁺ (phosphorus-doped) regions on the back using masked diffusion, ion implantation, or laser doping (PV-Manufacturing.org) . Laser doping is maskless and cost-effective (Maskless Plasma, 2023) .
3. **Passivation Layers:** Deposit SiNx or Al₂O₃ via PECVD or ALD for surface passivation, reducing recombination (TopCon Process, 2024) .
4. **Contact Formation:** Screen-print or evaporate metal fingers (Ag/Al) on back contacts. For bifacial, add transparent layers (Back Side Contact, Patent) .
5. **Anti-Reflection Coating:** Apply SiNx on front via PECVD.

6. Annealing and Testing: Hydrogenation anneal to passivate defects, then test I-V characteristics (Screen Printed, PVEducation) .

Alternative low-cost patterning methods have been explored. For example, microsphere (self-assembled bead) lithography can create fine rear patterns without cleanroom photolithography[8]. Roll-to-roll embossing of polymer films with groove patterns has been used to produce large-area back-contact perovskite modules[5]. In industry, SunPower's early IBC used a "p" and "n" diffusion on full wafers followed by selective etches and plating, whereas newer efforts (e.g. ISC Konstanz "ZEBRA" cells) adapt screen printing to IBC: Chu *et al.* describe an adapted Ag screen-print for IBC, achieving uniform 700+mV open-circuit voltages in mass production[1]. Figure 7,8 (below) compares process flows for various cell types, including IBC.

New BC Architectures

Figure 7 depicts the cross sections of three different major IBC solar cell concepts that are on the PV market already or in R&D at institutes or by industry.

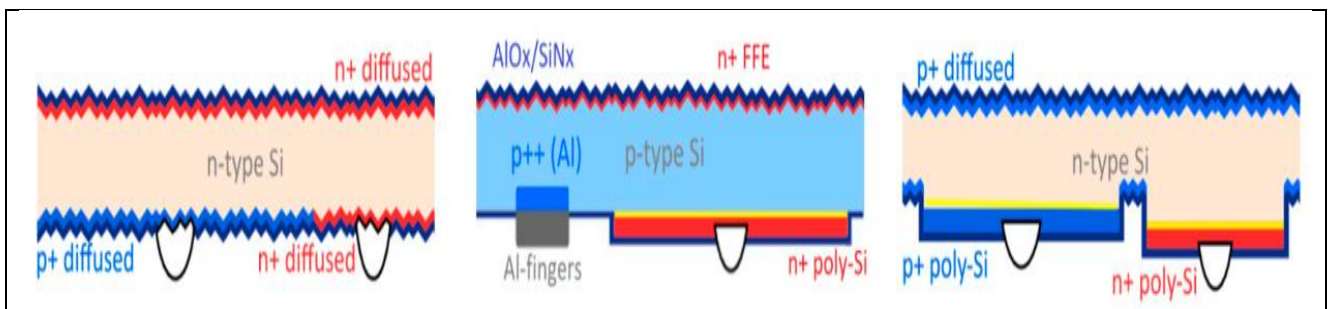


Figure 7. Cross sections of 3 major different IBC cell concepts with no, one and two carrier-selective contacts. Red colour represents n-type doped regions, blue p-type doped and yellow a thin tunnelling oxide. <https://doi.org/10.3390/solar3010001>

On the far left(Figure 7), the cross section shows a simple IBC solar cell concept (as, e.g., ZEBRA) that is totally diffused and has no carrier-selective contacts yet implemented, which is limiting, on the one hand, the voltage to about 705 mV;

On the far right(Figure 8), an ultimate IBC device with both carrier-selective contacts is shown, which has the highest efficiency potential of 25 + % on the solar cell level. As it is a combination of TOPCon and IBC technology, the PV community has started to call it TBC (TOPCon Back Contact) technology.

Figure 3 illustrates once more why there are different IBC concepts that coexist. Different institutes and companies have different strategies for upgrading their double-sided contacted solar cell architectures. LONGi and ISFH, staunch supporters of PERC technology, have developed a simple upgrade of PERC technology that ECN/TNO was proposing 5 years ago. ISC Konstanz, ipv Stuttgart and companies such as Jolywood, SPIC and Valoe are pursuing an upgrade of the nPERT technology and, thus, also IBC by further development to the TBC route.

SunPower and Aiko have opted directly for TBC technology. There is still a fourth prominent path to IBC that is not shown here—HJT IBC. This was first demonstrated by Kaneka and is now being pursued by REC, Meyer Burger and ENEL.

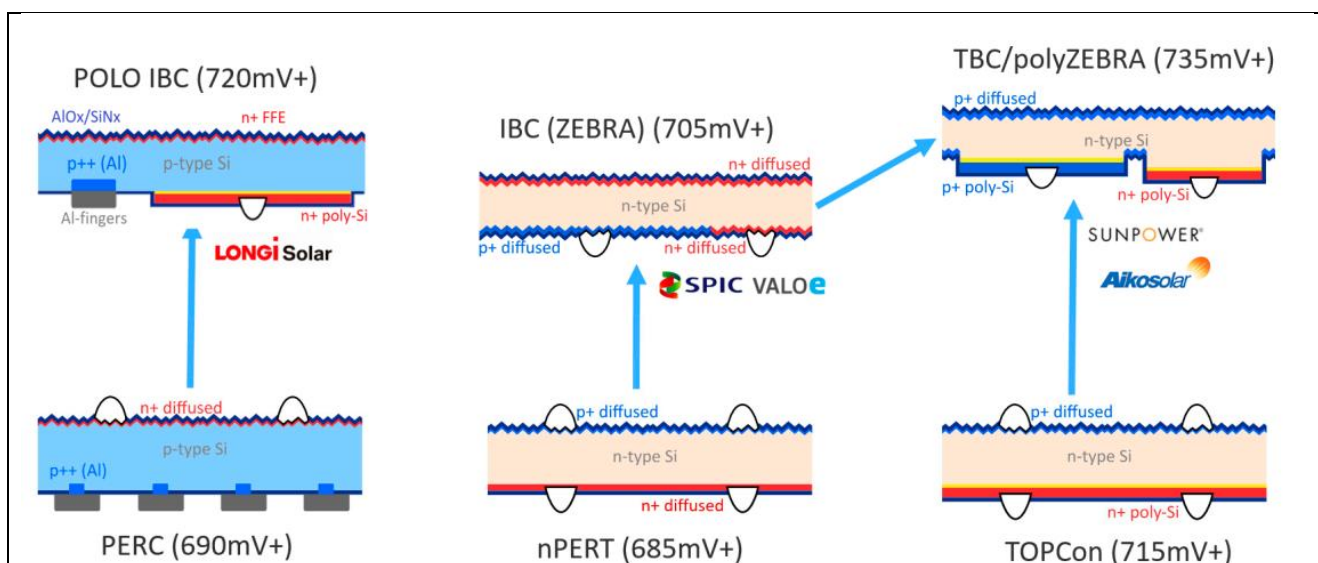


Figure 8. Different structures of IBC solar cells as evolutions from different both-sided contacted solar cells. <https://doi.org/10.3390/solar3010001>

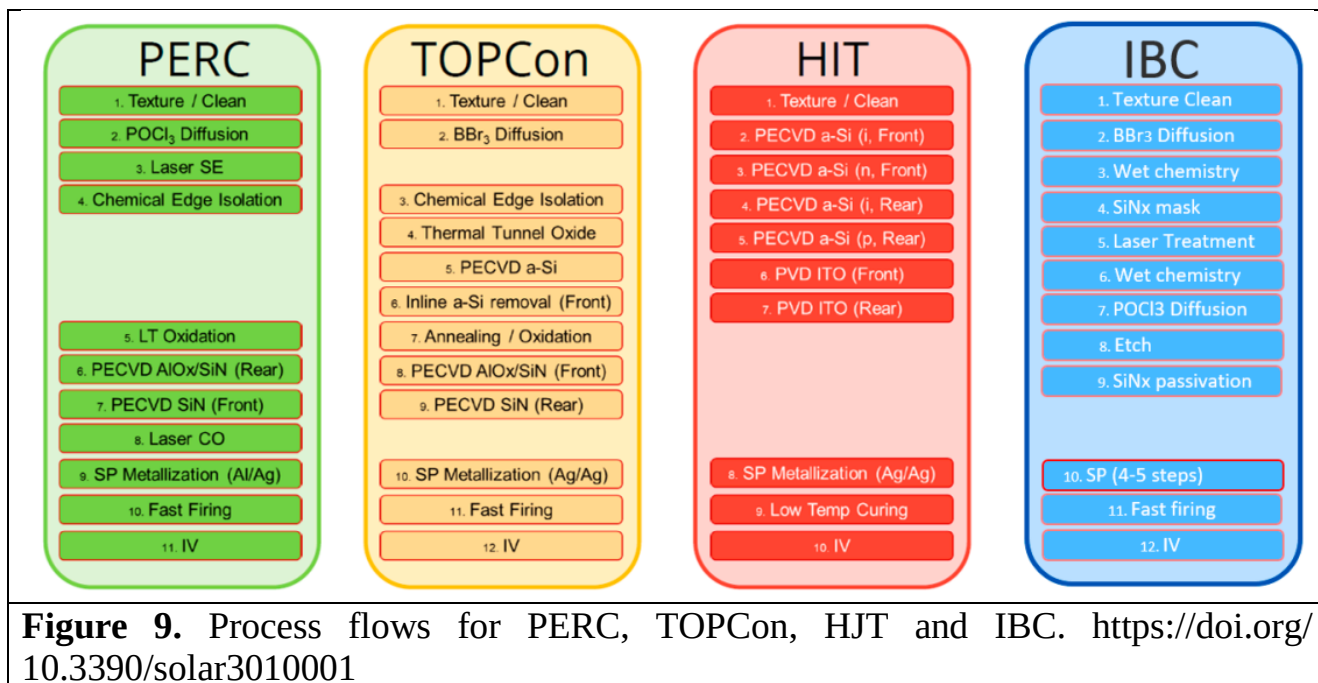
Figure 8: Example process flows for major Si cell types[2]. Note the extra diffusion and patterning steps in IBC (blue column) compared to, e.g., PERC. (Adopted from Chu et al. 2023[2].)

Table 2 summarises the most prominent IBC solar cell concepts in R&D and in the PV market.

	IBC Without Passivating Contact (PC)			POLO IBC One PC	TBC Both PC		
Company/ institute	SPIC/ISC	ipv Stuttgart	Jollywood	ISFH/ISC	SunPower	LG electronics	TRINA
Brand name	ZEBRA/ Andromeda2.0	MESA	-	POLO IBC	Maxeon 6	NeonR	-
Type	n-type	n-type	n-type	p-type	n-type	n-type	n-type
In production	yes	no	yes	no	yes	no	no
Efficiency	24.6% [6,7]	23.3% [8,9]	23%	22.3% [10]	25%	25%	25.04% [11]
PERC related	80%	75%	70%	90%	0%	0%	20%
Module efficiency	22.3% [1] can be bifacial	unknown	unknown	unknown	22.8% [1]	22.3% not listed any more [1]	unknown

Tandems

Figure 9 shows the process flows of the main cell concepts that co-exist in the PV market. The market shares for PERC and n-type technologies are shown in Figure 4. There is no question that n-type technologies are replacing PERC technology. However, the question is which of the n-type concepts will take over the market leadership—TOPCon, HJT or IBC.



Researchers continue to innovate BC designs. Variations include hybrid combinations (e.g. EWT + IBC features), all-back-contact “tunnel” cell concepts (TBC) with ultra-thin oxides, and multi-terminal cells. Interestingly, BC concepts are now being applied to tandem devices. For example, a recent four-terminal Si/perovskite tandem was demonstrated with *both* the HJT-silicon bottom cell and the perovskite top cell having interdigitated back contacts[9]. In that study, simulations gave a 19.3% IBC silicon subcell and 12.7% perovskite subcell, for a combined 32% tandem PCE[9]. Figure 10 illustrates this design: the patterned top cell even acted as an optical grating to enhance light trapping[9]. Such tandem IBC devices show the flexibility of BC architecture when combined with other solar cell types.

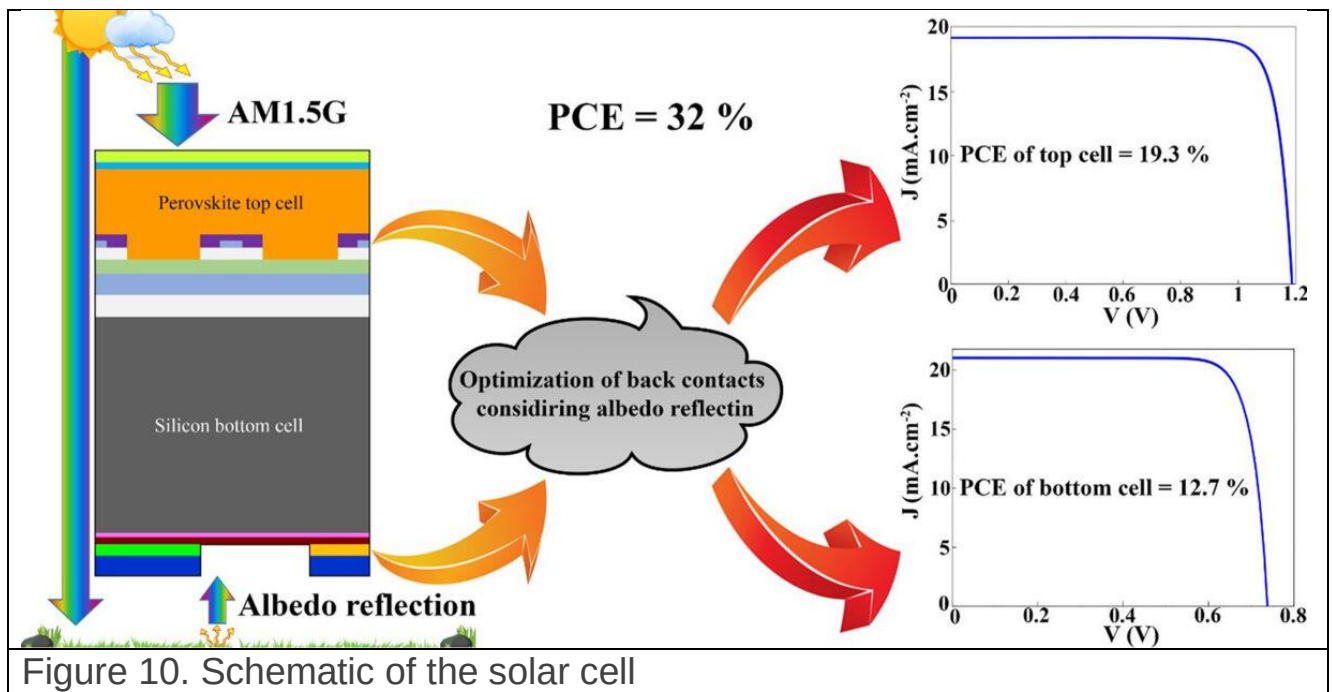


Figure 10. Schematic of the solar cell

Figure 10: I–V (J–V) curves from a simulated 4-terminal bifacial perovskite/silicon tandem with IBC architectures[9]. The bottom HJT-IBC cell reaches 19.3% and the top perovskite-IBC 12.7% PCE (total 32%). Embedding the perovskite top on an IBC silicon (instead of planar) improved photocurrent via diffractive light trapping[24]. (Adapted from Abbasiyan et al. 2025[9].)

Perovskite-Si BC Tandems

BC silicon (often IBC) is ideal as bottom cells in tandems due to high efficiency and compatibility. Perovskite-Si tandem solar cells with back contacts are an advanced configuration that places all electrical contacts on the rear of the silicon bottom cell, improving efficiency by eliminating shading and simplifying charge extraction. This design is implemented in both three-terminal (3T) and four-terminal (4T) configurations, with the 3T design particularly benefiting from the back-contacted silicon (IBC-Si) base.

Perovskite-Si BC Tandems: Perovskite top (1.7-1.8 eV bandgap) absorbs short wavelengths; BC-Si bottom (1.1 eV) handles IR. Efficiencies >30% (e.g., 31.3% in 2023) (Werner et al., 2023) . Theory: Stacked via transparent electrodes, summing Voc. Application: Low-cost, scalable (Pathways, 2024)

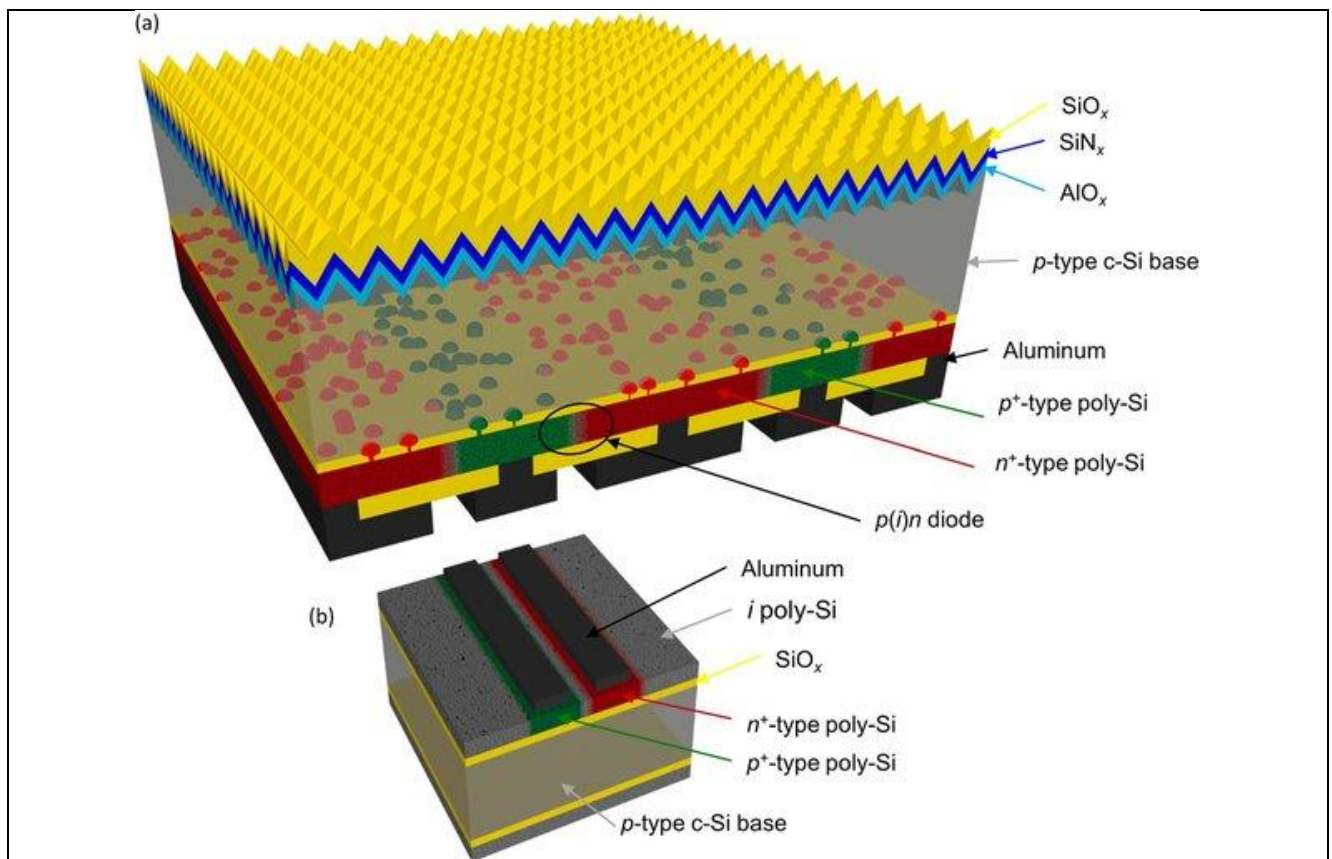


Figure 11. Top: Perovskite layer; Intermediate: Recombination layer; Bottom: IBC Si with rear contacts(<https://doi.org/10.1038/s41598-019-57310-0>)

Figure 11. (a) Schematic drawing of the structure of an IBC solar cell with n⁺- and p⁺-type poly-Si contact fingers separated by an initially intrinsic poly-Si region. (b) Sketch of a p(i)n test structure.

Organic-Perovskite Tandems with BC

Organic-Perovskite Tandems with BC" refers to tandem solar cells that combine an organic solar cell (OSC) and a perovskite solar cell (PSC) with a bottom cell (BC)(Figure 12). These devices use the BC to capture lower-energy photons that pass through the top cell, increasing overall efficiency by capturing a broader spectrum of sunlight. BCs are often silicon, but can also be another perovskite, organic cell, or other semiconductor material.

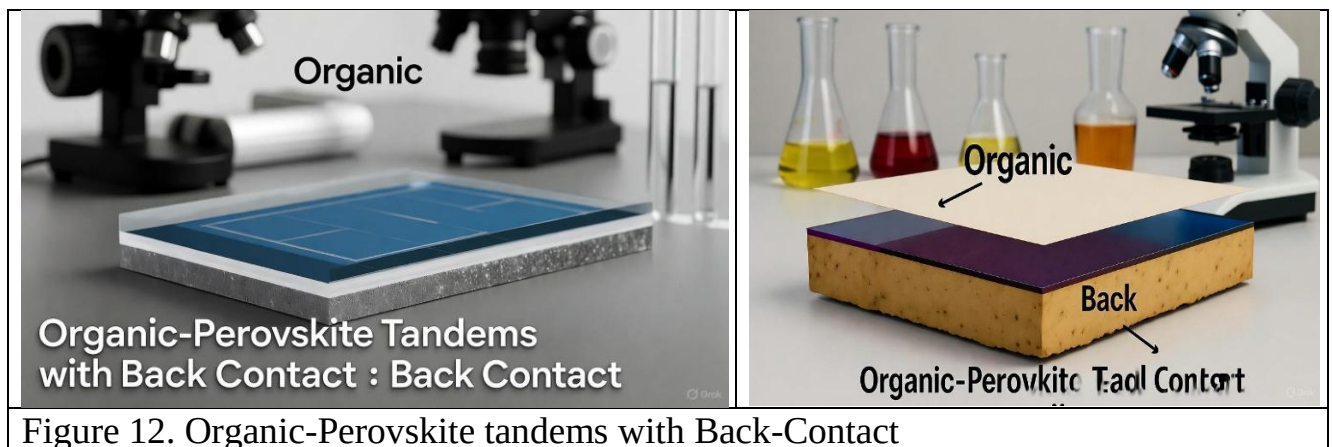
Operating of Organic-Perovskite Tandems with BC

Tandem structure: A perovskite cell is stacked on top of an organic cell. The perovskite cell captures high-energy photons (blue/green light) and the bottom organic cell captures lower-energy photons (red/infrared light) that pass through the top cell.

Back-contact design: Instead of a traditional "sandwich" architecture with a transparent front electrode, the back-contact design places both the positive and

negative electrodes on the back of the device. This eliminates the need for a front electrode, which can block or reflect light, and increases the amount of sunlight reaching the solar cell.

Interconnection: The two sub-cells are connected by a charge recombination layer that allows electrons from one cell to recombine with holes from the other, completing the circuit.



Comparison of BC Types: Each BC architecture has trade-offs. The pure **IBC/BJ** design (no front junction) offers the highest theoretical efficiency (minimized shading), but demands the most complex processing and highest material quality. **EWT** and **MWT/CWT** reduce some complexity by leaving the emitter on front or keeping a partial front grid, respectively, at the cost of some shading loss. In practice, IBC cells hold the efficiency lead ($\approx 27\%$ vs. $\leq 24\%$ for any wrap-through variants to date[1][4]). Table 1 (below) summarizes typical performances: IBC cells reach the highest V_{oc}/FF , whereas EWT/MWT cells tend to have slightly lower voltage but simpler fabrication. Back-contact **perovskite** cells currently trail silicon, but their potential is underscored by the recent jump to $\sim 11\text{--}12\%$ PCE in novel module formats[5]. Organic and other thin-film BC designs are still mostly exploratory (no high-efficiency records reported), though the BC concept may help reduce optical losses if implemented.

Efficiency and I-V Comparison (Table 3):

BC Type	Representative Material	Efficiency / record (PCE)	Voc (approx)	Key Features
IBC (back-junction)	Crystalline Si (c-Si)	~27.1% [3] [4]	~740–760 mV	No front metal; highest PCE; complex process
IBC (TBC/HJT)	c-Si with passivated contacts	27.03% (Tong <i>et al.</i> 2025) [4] ; 27.09% (Wang <i>et al.</i> 2024) [3]	~750–770 mV	Uses tunnel-oxide/POLy-Si for near-ideal contacts
Emitter Wrap-Through (EWT)	c-Si	~~21% (small cell) [1]	~~700 mV	Front emitter diffused; contacts via holes
Contact Wrap-Through (CWT/MWT)	c-Si, thin films	~~20–22% [1] (SunPower)	~~700–730 mV	Front grid kept; back contact pads connect via vias
BC-Perovskite	Perovskite (e.g. MAPbI ₃)	~11–12.8% (module) [5]	~~1.0 V	Interdigitated rear electrodes; emerging tech
BC-Organic (concept)	Organic PV	Low (<10%, early R&D)	~~0.6–0.8 V	Mostly experimental; could use patterned electrodes

Model	Efficiency (%)	Voc (V)	Isc (mA/cm ²)	FF (%)	Advantages/Disadvantages
Standard IBC	22-24	0.72	41	80	High Voc; complex fab
HJT-IBC	26-27	0.75	42	83	Better passivation; costly
TOPCon-BC	25-26	0.73	41.5	82	Low Rs; scalable
Perovskite-BC	23-25	1.1	25	78	Tunable bandgap; unstable (He <i>et al.</i> , 2025)

BC models outperform front-contact (e.g., PERC at 23%) in Voc and FF due to no shading (Comparison Diagram, [\[Figure 9\]](#)).

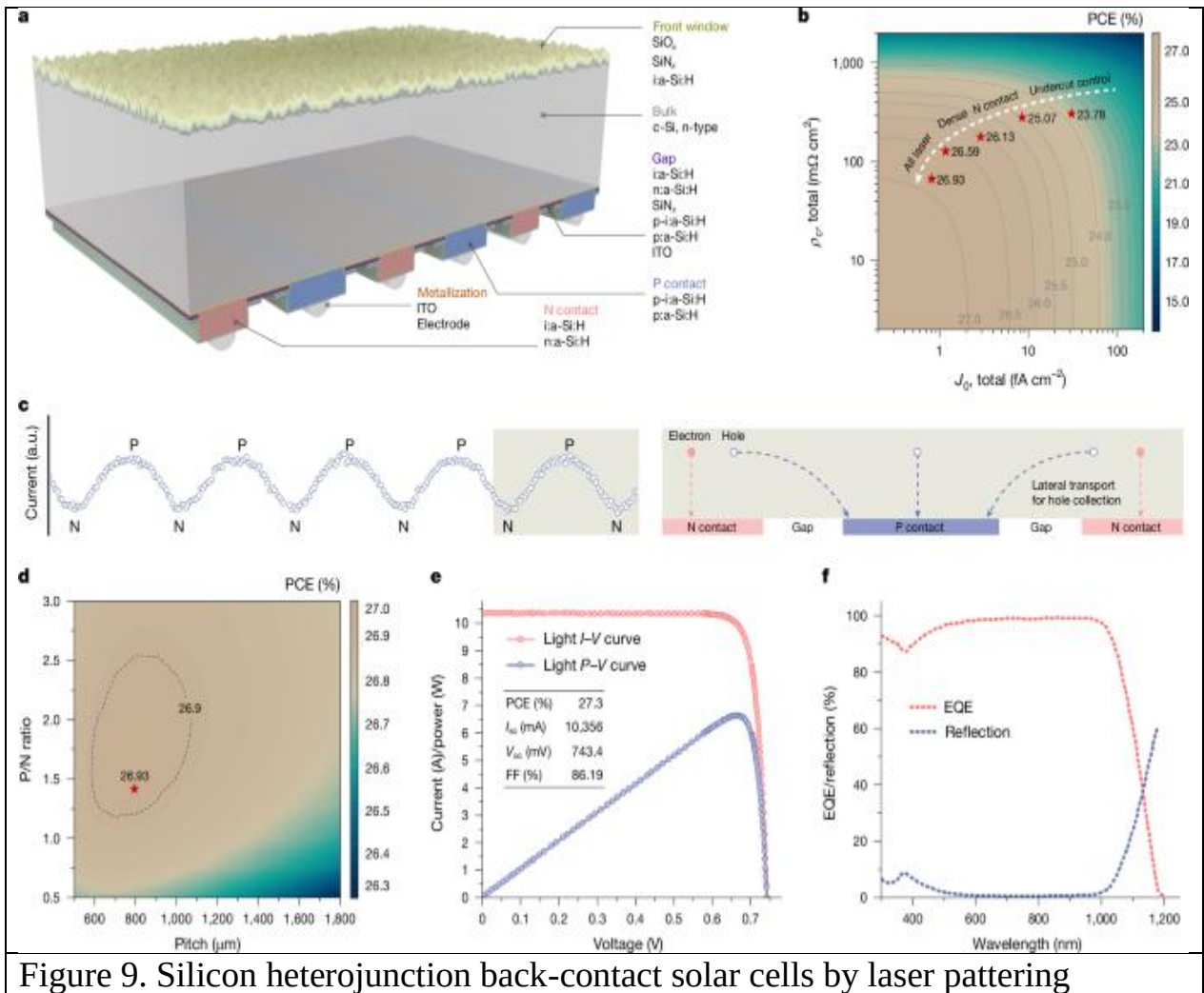


Figure 9. Silicon heterojunction back-contact solar cells by laser patterning

Conclusions: BC solar cells represent an advanced architecture that can yield record-high efficiencies by eliminating front-side losses. The theoretical advantages – reduced shading and freedom to optimize each contact independently – have motivated decades of development[1]. Modern IBC silicon cells have validated the concept, reaching >27% PCE[3][4], albeit with intricate fabrication. Recent work extends BC ideas to perovskite and tandem cells[5][9]. While fabrication remains challenging, innovative patterning methods (e.g. laser, self-assembly) and continued materials improvements promise further gains. Ongoing research explores novel BC variants (like combined wrap-through/IBC designs and large-area modules) to capitalize on the unique charge-collection geometry[10][11]. In all cases, device physics must be carefully managed: the band structure is engineered so that photogenerated carriers diffuse laterally to the rear contacts, and efficiency is calculated by standard methods ($PCE = (J_{SC} \cdot V_{OC} \cdot FF) / P_{in}$) [4][7]. By marrying detailed semiconductor physics with practical engineering, BC solar cells continue to push the frontiers of photovoltaic performance.

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Chapter VI

6. DYE-SENSITIZED SOLAR CELLS (DSSC)

Dye-sensitized solar cells (DSSC), also known as Grätzel cells, are a class of thin-film solar cells that use dye molecules to capture light and generate electricity. Since their inception in the late 20th century, DSSCs have evolved from early laboratory curiosities to more efficient and stable devices. Below, one can find a step-by-step overview of DSSC development – from the first prototypes to the latest advances – as well as explain how they work, how efficiency is calculated from their current-voltage characteristics, and how new DSSC designs compare (including tandem cells and hybrid combinations with other solar technologies).

Historical Development of DSSCs

The concept that dyes can generate electricity upon illumination was first explored in the 1960s. In 1972, researchers at UC Berkeley demonstrated a photoelectrochemical cell using chlorophyll extracted from spinach to mimic photosynthesis – effectively a primitive dye-sensitized solar cell. However, these early dye cells suffered from very low efficiency and poor stability, as the organic dyes would degrade and the system could not sustain power output. It took until the late 1980s for significant progress: Brian O'Regan and Michael Grätzel co-invented the modern DSSC, developing a nanostructured TiO_2 electrode coated with sensitizer dye. In 1991, O'Regan and Grätzel published their landmark Nature paper demonstrating a 7.1% efficient dye-sensitized TiO_2 solar cell[1]. This device used a ruthenium-based dye on a porous TiO_2 film with an iodide/triiodide liquid electrolyte, achieving surprisingly high efficiency for a low-cost cell and garnering worldwide attention (Grätzel was later awarded the 2010 Millennium Technology Prize for this work).

Following this breakthrough, rapid improvements were made in the early 1990s. In 1993, Nazeeruddin et al. (working with Grätzel) reported a DSSC efficiency of $\approx 10.3\%$ using a new ruthenium bipyridyl dye known as “N3”[1]. The N3 dye had a broader light absorption and simpler structure, which helped boost the conversion efficiency by roughly 40% over the 1991 result. By the end of the 1990s, incremental refinements – such as a transition from the original “tris(2,2'-bipyridyl)” Ru complex dye to the so-called N719 dye (di-tetrabutylammonium version of N3 for better solubility and stability) – led to improved stability and similar efficiency ($\sim 10\text{--}11\%$ under standard conditions). In 2001, Grätzel's group introduced a “black dye” (a tri-cyanoruthenium terpyridine complex) that achieved about 10.4% efficiency under AM1.5 sunlight[2], notable for its absorption extending farther into the red/infrared spectrum. Throughout the 2000s, DSSC efficiencies for single-junction cells remained in the $\sim 7\text{--}11\%$ range, while researchers focused on addressing durability issues (as discussed later).

A major advance came in the 2010s with the development of new sensitizers and redox mediators. In 2014, Mathew et al. engineered a zinc-porphyrin dye in combination with a cobalt-based electrolyte, achieving a certified 13% power conversion efficiency[4]. This was a record for DSSCs at the time, and it was accomplished by molecularly expanding the light absorption range and raising the device voltage. By sensitizing TiO₂ with a donor- π -acceptor porphyrin dye and using a Co²⁺/³⁺ redox shuttle (which offers a higher voltage than the traditional I⁻/I₃⁻ couple), the team significantly increased the photovoltage while maintaining strong photocurrent[4]. *(Mathew's 2014 result was a milestone indicating that DSSCs could indeed rival amorphous silicon cell efficiencies in direct sunlight.)*

In parallel, an important variant of DSSC emerged: solid-state dye solar cells. In 2012–2013, researchers found that *organometal halide perovskites* (such as CH₃NH₃PbI₃) could serve as excellent light-absorbing “dyes” when infiltrated into a mesoporous TiO₂, in conjunction with a solid hole-conductor instead of a liquid electrolyte. These solid-state dye cells – which quickly evolved into the field of perovskite solar cells – achieved 15% efficiency by 2013. For example, Burschka *et al.* (2013) used a two-step deposition of perovskite into a TiO₂ film, creating a hybrid DSSC/perovskite cell that reached ~15% PCE. This achievement blurred the line between DSSCs and conventional thin-film cells, as the perovskite effectively acted as both dye and charge transport layer. *However, in the context of classic DSSCs (with molecular dyes and liquid electrolyte), the record efficiency remains around 13–14%.* As of the mid-2020s, laboratory DSSCs typically achieve 11–12% efficiency with the best designs reaching ~14% under standard sun illumination[3]. Importantly, these higher efficiencies have been accompanied by improved stability (through better sealing, robust dyes, and new electrolytes), though stability and scale-up remain key challenges before DSSCs can see broad commercial use.

Structure and Working Principle

A DSSC generally consists of four main components: a photoanode, a sensitizer dye, an electrolyte, and a cathode. The photoanode is a transparent conducting substrate (glass or flexible plastic) coated with a thin, porous layer of nanocrystalline titanium dioxide (TiO₂) particles. This TiO₂ film (typically a few micrometers thick) is highly porous, providing a large internal surface area onto which the sensitizer dye molecules can attach[5]. The dye — often a ruthenium-polypyridyl complex or a metal-free organic dye — forms a monolayer on the TiO₂ surface and is the light-absorbing material (analogous to chlorophyll in plants)[5]. An electrolyte solution, usually containing a redox couple such as iodide/triiodide (I⁻/I₃⁻), surrounds the dye-coated TiO₂ and penetrates into the pores. Finally, a counter electrode (cathode), typically a glass or foil substrate coated with a thin platinum catalyst or carbon, is placed opposite the anode. The sandwich is sealed so that the electrolyte fills the

space between the electrodes. Figure 1 below illustrates the basic structure of a DSSC and its operating mechanism.

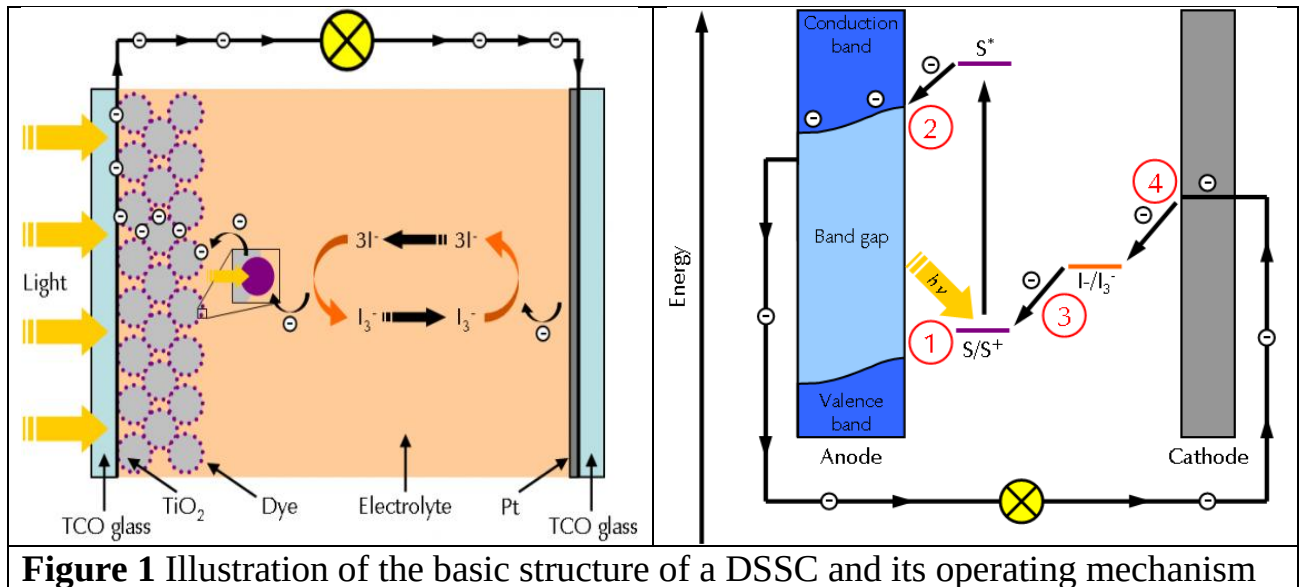
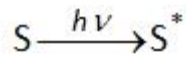


Figure 1: Schematic of a dye-sensitized solar cell. The device consists of a transparent conducting oxide (TCO) glass anode coated with a mesoporous TiO_2 layer that is sensitized by dye molecules, an electrolyte containing a redox couple (commonly I^-/I_3^-), and a catalyst-coated cathode[5][6]. When sunlight hits the cell, dye molecules (represented in purple) absorb photons and inject electrons into the TiO_2 conduction band (process ①). **Electron excitation:** The absorbed light energy excites an electron within the dye molecule, moving it to a higher energy state. **Electron injection:** The excited electron is immediately injected from the dye into the conduction band of the porous semiconductor material (e.g., titanium dioxide), leaving the dye oxidized(process ②). The electrons percolate through the TiO_2 network to the TCO anode and flow out as electric current to an external load[5]. Meanwhile, the dye molecules that lost electrons become oxidized, but they are quickly regenerated by electron donors (iodide ions) in the electrolyte (process ②). The iodide is oxidized to triiodide in this process. **Electron transport:** The electrons now travel through the network of the semiconductor nanoparticles to a transparent conducting oxide (TCO) electrode. The electrons travel through the external circuit to the cathode, where they catalytically reduce the triiodide back to iodide (process ③), thus completing the circuit[5]. This regenerative cycle allows continuous operation: the dye is restored to its ground state after each photon, and the electrolyte shuttles charges between the electrodes without permanent consumption of materials. Below it is shown all steps of chemical process.

STEP 1: The dye molecule is initially in its ground state (S). The semiconductor material of the anode is at this energy level (near the valence band) non-conductive.

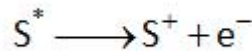
When light shines on the cell, dye molecules get excited from their ground state to a higher energy state (S^*), see equation 1.



Eq. 1

The excited dye molecule has now a higher energy content and overcomes the band gap of the semiconductor.

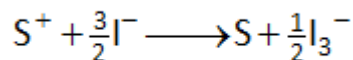
STEP 2: The excited dye molecule (S^*) is oxidized (see equation 2) and an electron is injected into the conduction band of the semiconductor. Electrons can now move freely as the semiconductor is conductive at this energy level.



Eq. 2

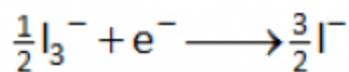
Electrons are then transported to the current collector of the anode via diffusion processes. An electrical load can be powered if connected.

STEP 3: The oxidized dye molecule (S^+) is again regenerated by electron donation from the iodide in the electrolyte (see equation 3).



Eq. 3

STEP 4: In return, iodide is regenerated by reduction of triiodide on the cathode (see equation 4).



Eq. 4

The above mechanism in Figure 1 shows that a DSSC separates the functions of light absorption and charge transport between different materials: the dye absorbs light and generates excited electrons, which are injected into the TiO_2 (an n-type semiconductor) and conducted away, while the electrolyte transports positive charge (holes) by redox diffusion to the cathode. This **decoupling** of roles permits the use of very chemically stable, optically active dyes and a wide-bandgap semiconductor scaffold to collect charges, rather than a single material doing all tasks as in a silicon solar cell. However, it also introduces some voltage and resistance losses (e.g., at the

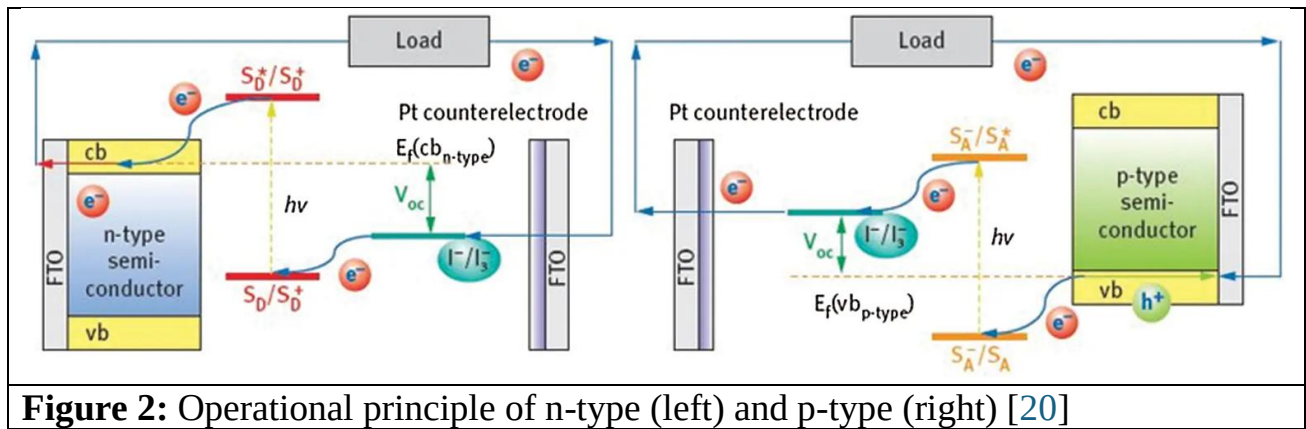
dye/TiO₂ interface and within the liquid electrolyte), which limit the efficiency compared to an idealized device.

n-Type and p-Type of DSSC

A DSSC is a photovoltaic semiconductor-based device that directly converts natural as well as artificial radiation into electricity. Unlike traditional systems, where the semi-conductor performs both absorptions of light and charge separation and transport phenomenon, the two functions are segregated in a DSSC. Each part of the system heavily decides the cost and conversion efficiency of DSSCs. Improving the properties of absorption of light can be accomplished by optimizing the dye. In contrast, the properties of transport of charges can be enhanced by improving the semi-conductor and electrolyte composition [6].

n-Type

In the category of materials of n-type, the dye absorbs light which is connected to the surface of mesoporous electrodes of n-type semi-conductor, as shown in Fig. 2a. N-type DSSCs, such as TiO₂ or ZnO mesoporous films, are accumulated on top of indium-tin-oxide (ITO) or fluorine-doped tin oxide (FTO) surfaces and comprises of the photoanodes. Here, the charge separation occurs at the dye/electrode interchange by injection of an electron into the semi-conductor conductive band from the photoexcited dye [7–10].



p-Type

In the case of p-type semi-conductor network, firstly, light is absorbed via a dye, that is placed on the surface of p-type semi-conductor mesoporous electrodes as proven in Fig. 2b. P-type DSSCs, which are especially based totally on NiO electrodes on ITO and/or FTO substrates. In this kind of DSSCs, as soon as the dye is photoexcited, charge separation injects the electrons to the photoexcited dye from the valence band of the semi-conductor [11–14]. Hence, the common phenomenon in

both types discussed above is the regeneration of the oxidized or reduced dye through a redox mediating electrolyte.

Overall, to this point maximum scholars are focusing on n-type dye-sensitized solar cells (DSSCs): the usage of conventional ruthenium and zinc porphyrin dyes, power conversion efficiencies attain 12% and 13%, respectively [15,16]. Relatively, the efficiency of p-type DSSCs continuous to be low. Generally, in p-type DSSCs, a semi-conductor used is NiO with over 2.5% conversion performance which signifies the first-class file inside the area of p-DSSCs [17]. However, these dyes are not favourable for the massive-scale utility because of the excessive cost of metal dyes, tedious separation process, and environmental problems. On the other hand, mass production of this technology might be realistically possible with the development of the low-temperature synthesis of electrodes and cost-effective substances. Hence the review at the improvement of various sorts of DSSC technology for identifying low cost and higher conversion efficiency has come to be high significance within the implementation of new DSSC technologies, which is the essential focus of this review paper.

Materials:

In DSSC, on the one hand, the absorption of photons and on the other hand is the transfer of electrons that is mediated by two different media, i.e., dyes and n-type nanocrystalline TiO_2 , respectively. When the holes are passed through a substance conveying a hole which may be:

1. Liquid electrolyte
2. Solid electrolyte
3. Quasi-solid-state electrolyte

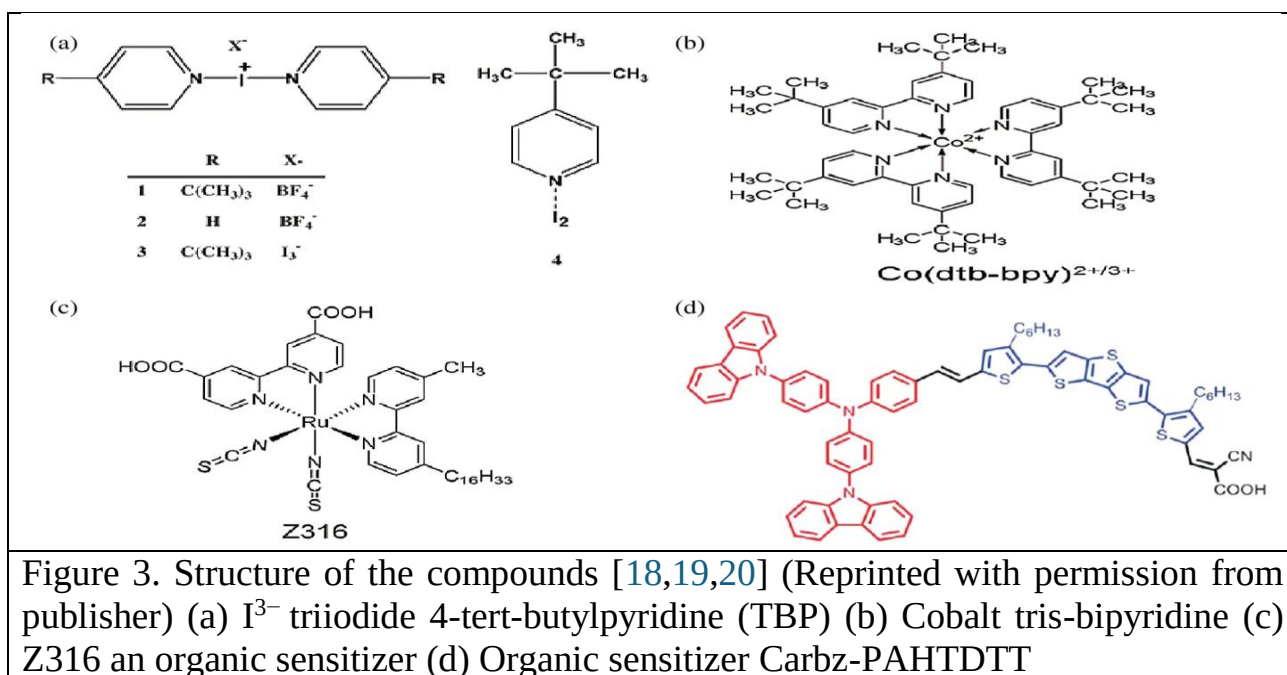


Figure 3. Structure of the compounds [18,19,20] (Reprinted with permission from publisher) (a) I_3^- triiodide 4-tert-butylpyridine (TBP) (b) Cobalt tris-bipyridine (c) Z316 an organic sensitizer (d) Organic sensitizer Carbz-PAHTDTT

Liquid electrolyte

The structure of triiodide liquid electrolyte with the addition of TBP as shown in Fig. 3a which is a very effective electrolyte in DSSC [18]. Apart from the iodide/triiodide electrolyte, most commonly reported another redox couple for high-performance DSSC is cobalt tris-bipyridine ($[\text{Co}(\text{bpy})_3]^{2+/3+}$) with Z316 an organic sensitizer [19,20] as shown in Figs. 3b and 3c. Another redox couple that has unique features and extraordinary electrochemical properties is ferrocenium/ferrocene. A ferrocene/ferrocenium based redox couple with a metal-free organic sensitizer (i.e., Carbz-PAHTDIT) as shown in Fig. 3d has resulted in the conversion efficiency of more than 7.5% in DSSCs. This surpassed the efficiencies of iodide/triiodide electrolyte based DSSCs. Hence, ferrocene-based electrolytes with organic sensitizer prove to be compatible with future DSSC devices [22,21].

Solid Electrolyte Type DSSC

Over the past decade, research has focused on solid-state electrolytes to replace liquid ones due to easier fabrication, simpler sealing, and better potential for monolithic cell connection—improving performance and reducing DSSC cost.

Studies show that solid-state DSSCs (e.g., with P3HT as a hole transport layer) have lower efficiency than liquid-based cells because of higher carrier recombination. Other materials like CsSnI_3 (efficiency up to 10.2%) and Ag_2Se (about **5.89%**) show promise. A 2018 study reported **2.56% efficiency** under 80 mW/cm^2 light. Despite lower efficiency, solid-state electrolytes offer greater stability than liquid ones. Chung et al. also introduced the first perovskite-based DSSC, inspiring further research.

Overall, solid electrolytes have good stability, but the power conversion efficiency is decreased by weak contact of the electrode, cell penetration and low ionic diffusion [53]. Nevertheless, the benefit of solid-state DSSCs over other devices is obvious: fewer problems in the manufacturing of the device, simpler possibility to manufacture monolithically interconnected devices, easier sealing and module encapsulation.

Quasi-Solid Electrolyte Type DSSC

Electrolytes are crucial in DSSCs, significantly impacting power conversion efficiency. Quasi-solid polymer electrolytes address limitations of liquid and solid types, offering superior stability and ionic conductivity. The polymer matrix traps liquid solvent to prevent evaporation while providing redox couple channels. Permeable polymer membranes enhance liquid retention, electrode contact, and conductivity over solid-state [23].

Pioneering work by Kim et al. used PMMA copolymer-based porous membranes, achieving 2.4% efficiency [24]. Other studies reached 9.48% (vs. 8.84% liquid) [25]; graded gel integration yielded 8.64% under one sun [26]; high recombination resistance enabled 12.23% at 200 lux [27]; PAniNT/rGOA aerogel achieved 5.47% [28]; PIL/polyindole/PMMA combo delivered 5.96% with improved stability [29]; and polymer gelators showed 9.72% (comparable to 9.79% liquid) with enhanced long-term stability under 1 sun at 50°C [30]. Polymer structure plays a key role in efficiency.

Overall, the power conversion efficiency of DSSCs produced with a certain polymer electrolyte was found to be comparable to that of liquid electrolyte based solar cells. However, there are inherent improved sealing advantages in these quasi-solid-state devices. They have lower ionic conductivity and weak pore penetration in the mesoporous matrix as compared to the liquid counterpart [31]. Therefore, for these systems, there is a deficiency of accurate long-term stability data available. However, the recent growth of laboratories is likely to create further industrial research interests in the future.

The standard DSSC dye (in classic designs) has been ruthenium-based complexes such as N3, N719, or the “black dye,” which offer broad absorption across visible wavelengths and reasonably long-term stability[1]. Ruthenium dyes have a high quantum yield for electron injection into TiO₂ and a suitable ground-state potential to be regenerated by the iodide electrolyte. In recent years, many metal-free organic dyes (e.g., donor– π –acceptor dyes) and porphyrin dyes have been developed to avoid expensive metals and to tune the absorption spectra[2][3]. These new dyes have achieved efficiencies comparable to or exceeding the traditional Ru dyes, especially when paired with new redox shuttles. The nanocrystalline TiO₂ remains the workhorse photoanode material due to its appropriate band gap (~ 3.2 eV, which yields ~ 0.7 – 0.8 V photovoltage with typical dyes) and abundance. Alternatives like ZnO and SnO₂ have been researched, but they generally have not outperformed TiO₂. The electrolyte in a DSSC is crucial: it completes the circuit by mediating charge transfer between the dye and the cathode. The conventional electrolyte is an organic solvent (e.g., acetonitrile or valeronitrile) with iodide/triiodide redox species. This I[–]/I₃[–] couple has favorable kinetics (fast dye regeneration) but also causes a voltage loss of a few hundred millivolts due to its redox potential being somewhat low relative to the dye’s excited state[3]. To raise the cell voltage, researchers have introduced alternative redox couples such as cobalt(II/III) bipyridyl complexes and copper(I/II) complexes, which can increase V_{oc} by having higher redox potentials. Indeed, the 13% porphyrin cell mentioned above used a Co^{3+/2+} shuttle to attain a higher V_{oc}. The downside is that some new redox shuttles diffuse more slowly, reducing current, or can complex with the dye, so careful molecular engineering is required. The cathode is typically a thin Pt layer which catalyzes the reduction of triiodide to iodide efficiently[5]. Because platinum is costly, many studies have explored alternative counter electrode materials – such as carbon nanotubes, graphite,

conductive polymers, and transition metal compounds (e.g. NiS, Co₃Se₄, etc.) – some of which show comparable performance to Pt[32].

Fabrication

A hallmark of DSSC technology is its relatively simple and low-temperature fabrication process, which does not require crystal growth or high-vacuum deposition. Typically, a TiO₂ nanoparticle paste is doctor-bladed or screen-printed onto the TCO glass and then sintered at ~450 °C to form a mechanically stable but porous electrode[5]. (For plastic substrates, low-temperature particle suspensions or chemical sintering methods are used instead.) After cooling, the TiO₂ film is immersed in a solution of the dye for several hours, allowing the sensitizer molecules to chemisorb as a monolayer on the large internal surface area (a process sometimes called “dye loading” or sensitization)[5]. Excess dye is rinsed off, and the dyed electrode is assembled into a sandwich cell with a counter electrode – often using a thermoplastic sealant (e.g., Surlyn) as a spacer. The liquid electrolyte is introduced through a fill hole or during assembly by capillary action, and then the cell is sealed. This *printing and dipping* process is amenable to scale-up; indeed, companies have employed roll-to-roll printing on flexible substrates to make DSSC modules. The relative ease of fabrication and use of mostly low-cost materials (glass, TiO₂, organics) means DSSCs can have a favorable price/performance ratio in theory[5]. Furthermore, DSSCs can be made semi-transparent and in different colors (the color depends on the dye used), which opens up applications in building-integrated photovoltaics and consumer products where aesthetics matter. For example, DSSC panels in various tints have been installed as energy-generating windows in Switzerland and elsewhere[20].

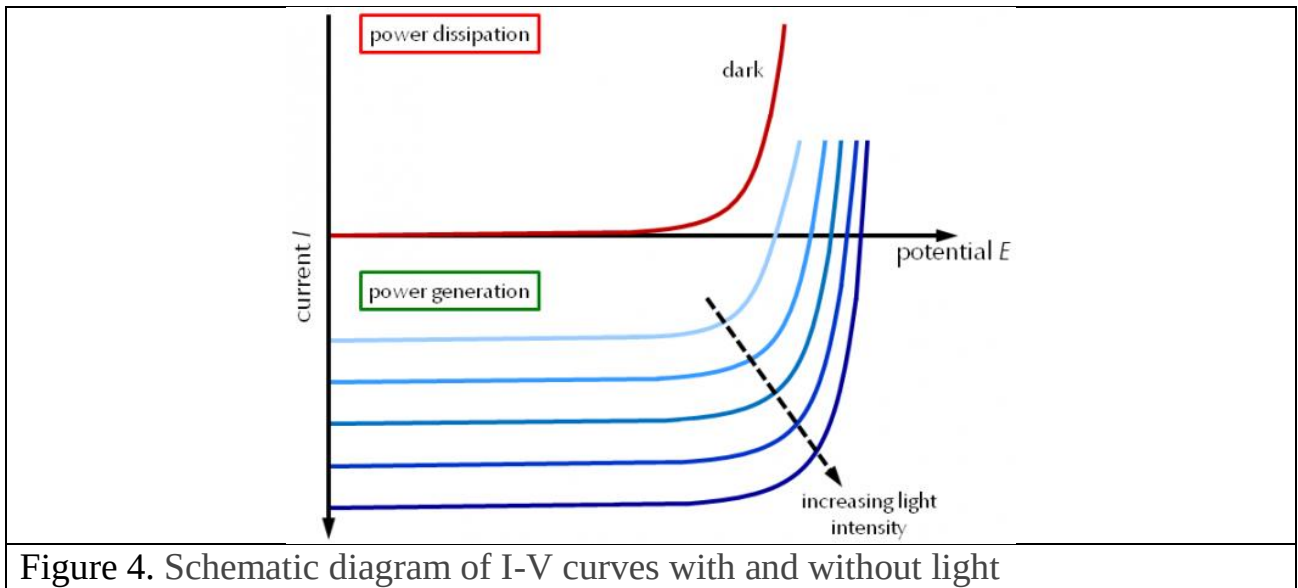
Despite their manufacturing simplicity, stability and sealing are vital concerns in DSSC assembly. The liquid electrolyte contains volatile organic solvents and must be tightly sealed to prevent leakage and evaporation. Long-term exposure to UV light and heat can also degrade some dyes and electrolyte components. To address this, researchers developed ionic liquid electrolytes (which are non-volatile) and quasi-solid gels that improve stability. Replacing the liquid electrolyte entirely with a solid hole-conductor (as in perovskite solar cells or other solid-state DSSCs) removes leakage issues but can introduce new problems like lower pore infiltration and faster recombination at the TiO₂ interface[32]. Encapsulation techniques, UV filters, and robust dye structures (e.g., alkoxy shield groups to prevent dye aggregation and decomposition) are all employed to extend DSSC device lifetimes. Today’s state-of-the-art DSSCs can remain stable for thousands of hours under light soaking at 60 °C or higher, but achieving 20+ year outdoor lifetimes (comparable to silicon PV) is an ongoing endeavor.

Photovoltaic Performance and Efficiency Calculation

A solar cell generates current when light shines on it. The output current depends strongly on the potential of the cell as well as intensity of the incident light. Current-potential curves (also called I-V curves) illustrate the relationship.

Similar to standard cyclic-voltammetry experiments, a potential E is applied and swept between an initial and final potential. The current I of the cell is measured. In addition, a light source with a constant intensity is focused on the solar cell to generate power.

Figure 4 shows a typical I-V curve of a solar cell for increasing light intensities and when no light is present.

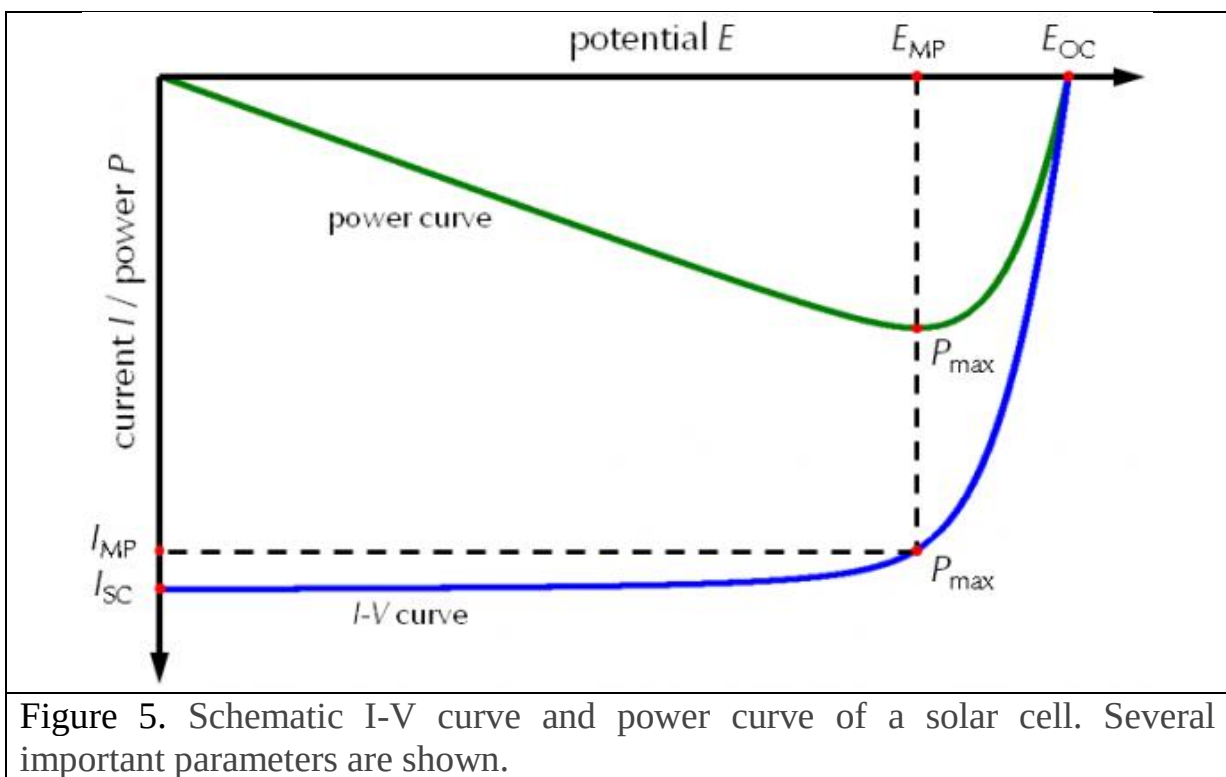


Like all solar cells, DSSCs are characterized by their current–voltage (I–V) behavior under illumination. **Figure 5** shows a typical I–V curve of a solar cell, along with the power output curve. Several key performance metrics can be defined from such a curve[5]:

Short-circuit current (I_{SC}) – the current through the cell when the voltage across it is zero (terminals shorted). Hence the generated power is also zero.

$$I_{SC} = I_{max} = I(E = 0)$$

The short circuit current increases with increasing light intensity. This corresponds to the maximum current the cell can deliver, occurring at the upper left intercept of the I–V curve. For DSSCs under one-sun illumination, I_{SC} is typically on the order of 15–25 mA/cm² (for comparison, a silicon cell of the same area might deliver ~35 mA/cm² under 1 sun). I_{SC} depends on the light absorption and charge collection efficiency – it is proportional to the number of photons absorbed by the dye and subsequently converted to electrons.



Open-circuit voltage (V_{OC}) – the voltage across the cell at zero current (circuit open). The open circuit potential E_{OC} is the highest voltage of a solar cell at a given light intensity. It is also the potential where current flow through a solar cell is zero.

$$E_{oc} = E_{max} = E(I = 0)$$

V_{OC} is the maximum voltage the cell can provide, given by the intercept of the I–V curve on the voltage axis (lower right). In DSSCs, V_{OC} is governed by the difference between the semiconductor Fermi level (quasi-Fermi level of TiO_2 under illumination) and the redox potential of the electrolyte, minus any kinetic loss at the interface. With the iodide/triiodide electrolyte and common Ru dyes, V_{OC} usually falls in the **0.6–0.8 V** range[3]. Using electrolytes with higher redox potentials (e.g., cobalt complexes) or modifying the TiO_2 surface (to suppress electron recombination) can raise V_{OC} to ~0.9–1.0 V in some cases. For instance, a cobalt bipyridine shuttle with a porphyrin dye achieved $V_{OC} \approx 0.91$ V in the 13% efficient cell. Generally, V_{OC} increases slightly as light intensity is lowered (because recombination currents decrease), which is one reason DSSCs maintain good efficiency in dim light.

Fill factor (FF) – a measure of the “squareness” of the I–V curve, defined as $FF = (V_{mp} \cdot I_{mp}) / (V_{OC} \cdot I_{SC})$, where V_{mp} and I_{mp} are the voltage and current at the **maximum power point (MPP)** on the curve[5]. The Fill factor is the ratio of maximum generated power P_{max} to theoretical power maximum P_{theo} of a solar cell. The general formula for the Fill Factor is:

$$FF = \frac{P_{max}}{P_{theo}} = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$$

The MPP is the operating point where the product $V \cdot I$ (i.e., power output) is highest, as indicated by the peak of the power curve in **Figure 6**. A perfect cell with no resistive losses would have $FF = 1$ (a rectangular I - V shape), but real cells have $FF < 1$. Typical fill factors for DSSCs are in the range of **0.6–0.75**. Lower FF can result from internal series resistance (from TCO, contacts, electrolyte resistance) and shunt resistance (leakage pathways), as well as the intrinsic diode characteristics of the cell[4]. A well-optimized small-area DSSC might achieve $FF \approx 0.70$ – 0.75 .

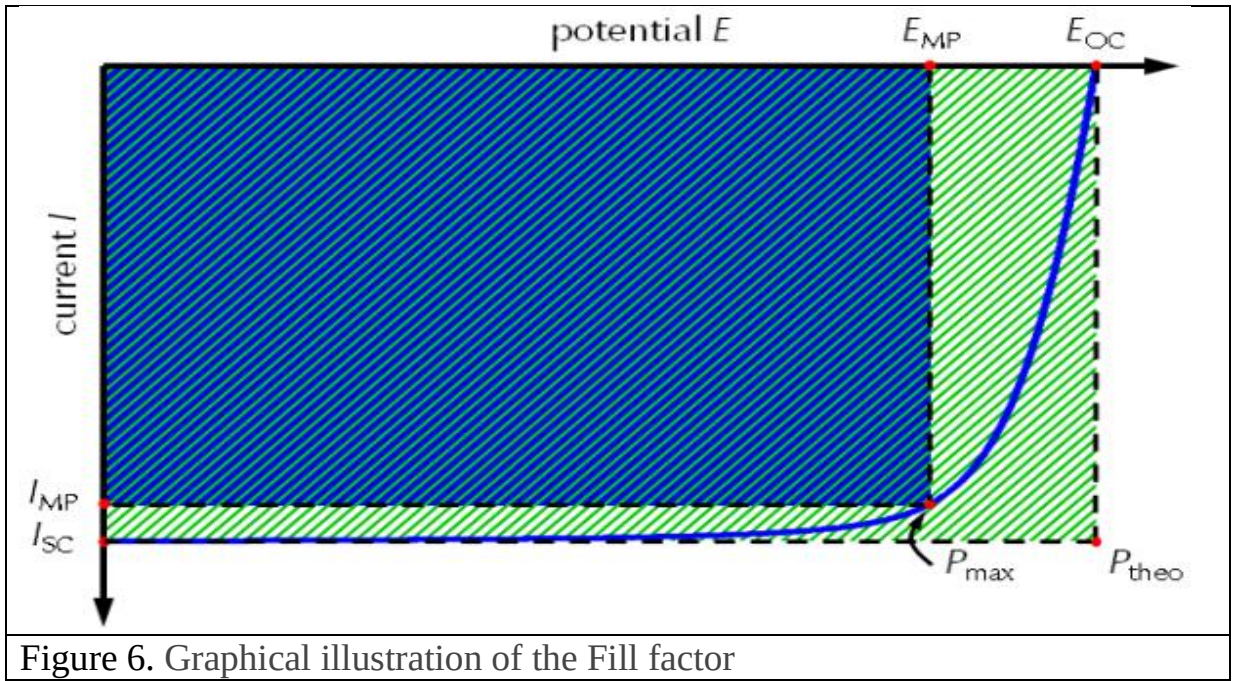


Figure 6. Graphical illustration of the Fill factor

Power Conversion Efficiency (PCE or η) – the percentage of incident light power that the cell converts into electrical power at the MPP. Efficiency is given by:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{mp} I_{mp}}{P_{in}} = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

where P_{in} is the incident light power (for standard tests, $P_{in} = 100 \text{ mW/cm}^2$ which is 1 sun, AM1.5 global spectrum)[5]. For example, if a DSSC has $V_{oc} = 0.75 \text{ V}$, $I_{sc} = 20 \text{ mA/cm}^2$, and $FF = 0.70$, then the maximum output is $V \cdot I = 0.75 \cdot 20 = 15 \text{ mW/cm}^2$, and $\eta \approx 15 \text{ mW}/100 \text{ mW} = 15\%$. In practice, to measure efficiency, the cell area must be accurately defined and a calibrated solar simulator is used. Under standard conditions, a cell producing 10 mW from 1 cm^2 area is 10% efficient[33].

High-efficiency DSSCs ($\geq 13\%$) under 1 sun have V_{OC} around 0.9 V, $I_{SC} \sim 18 \text{ mA/cm}^2$, and FF ~ 0.75 , for example[3].

Figure 6: Typical **I–V curve** (black line) of a solar cell under illumination, along with the **power–voltage curve** (blue line). Key points are the short-circuit current (I_{SC}) at $V=0$, the open-circuit voltage (V_{OC}) at $I=0$, and the maximum power point (MPP) where the product $V \cdot I$ is highest. The **fill factor (FF)** is the ratio of the area of the dark blue rectangle ($V_{mp} \times I_{mp}$) to the light gray rectangle ($V_{OC} \times I_{SC}$), representing how “square” the I–V curve is[5]. A higher FF indicates a more ideal diode behavior with lower internal losses. Typical DSSC fill factors range from 0.6 to 0.75. Both I_{SC} and V_{OC} of a DSSC depend on illumination conditions: under low light, I_{SC} drops proportionally, but V_{OC} drops only logarithmically – a reason DSSCs maintain relatively high efficiency in dim light.

Dynamic behavior: It is worth noting that DSSCs, due to their electrolytic charge transport, have different dynamic response compared to solid-state PV. The I–V curve can show slight “S-shape” distortion at high currents if mass transport of the iodide/triiodide in the electrolyte is limiting (in larger cells or at very high light intensities). Techniques like electrochemical impedance spectroscopy are used to analyze DSSC internal resistances (TiO_2 /dye charge transfer resistance, Nernst diffusion resistance of I^-/I_3^- in electrolyte, etc.). For the scope of this overview, we focus on the steady-state performance metrics as above.

Advances, Variations and Combination with Other Cells

Over three decades of research, many **variants of DSSCs** have been explored, aiming to improve efficiency, stability, or to adapt the cells for specific applications. Here we summarize several important developments and compare their performance characteristics:

Sensitizer improvements: The earliest DSSCs used simple Ru(II) bipyridyl dyes (like N3). Since then, a plethora of new dyes have been designed, including N719 (a relative of N3 with thiocyanate ligands replaced by thiocyanate–phosphonate for better binding), the “Black Dye” (Ru terpyridyl complex) which extended absorption into the near-IR, and various metal-free organic dyes (e.g., coumarin dyes, indoline dyes, triarylamine-based Donor– π –Acceptor dyes) which achieved efficiencies 9–12% in different studies[3][1]. Organic dyes often have very high molar extinction coefficients, meaning they can use thinner TiO_2 films (reducing recombination losses). Porphyrin dyes (such as the YD2-o-C8 and SM315 used by Mathew et al. 2014) combine a large absorption cross-section with tunable spectra and have led to record efficiencies $\sim 13\%$ [3]. Researchers also investigated natural dyes (from berries, etc.) for education and ultra-low-cost cells; while these can make functioning DSSCs, their efficiencies are only a few percent at best (e.g., chlorophyll $\sim 4\%$, anthocyanin $\sim 1\text{--}2\%$)[1]. Today’s focus is on robust synthetic dyes that can harvest more of the

solar spectrum (including red/near-IR photons) and on cosensitization – *using two or more dyes together* to cover complementary parts of the spectrum. Cosensitized DSSCs (with, say, a porphyrin for visible and an organic dye for red/NIR) have achieved higher currents and pushed efficiencies above 14% in some reports by capturing more sunlight.

Electrolyte and redox mediators: The traditional iodide/triiodide liquid electrolyte offers a good balance of fast dye regeneration and availability of iodide in solution, but it has drawbacks: a relatively low redox potential (limiting V_{oc}), corrosiveness (iodine can etch metals), and volatility of the solvent. New redox mediators have been introduced to tackle these issues. Replacing I^-/I_3^- with cobalt(II/III) complexes (e.g., $[Co(bpy)_3]^{2+/3+}$) raises the redox potential by ~ 0.3 V, thus increasing V_{oc} and overall efficiency – as demonstrated by several $>12\%$ efficient DSSCs[3]. However, cobalt complexes have slower diffusion and can suffer from recombination with electrons in TiO_2 , so additives and surface treatments (like TiO_2 blocking layers) are used to mitigate this. Copper coordination complexes have also emerged as mediators that can give high voltages (~ 1 V) and have lower reorganization energy. Beyond liquid electrolytes, there is extensive work on quasi-solid or solid electrolytes: for example, ionic liquid-based electrolytes (which are liquid salts with no vapor pressure) improve thermal stability and have enabled DSSCs that endure $>100^\circ C$, though often with a slight performance hit. Hole-transport materials (HTMs) like Spiro-OMeTAD (a solid organic semiconductor) have been used to make solid-state DSSCs, but these are essentially the forerunner of perovskite solar cells and have their own set of challenges (e.g., pore filling and stability)[32]. An intriguing alternative electrolyte is the ferrocene/ferrocenium couple, which is very stable and yields high V_{oc} (~ 0.9 V), but its diffusion is extremely slow, limiting current – new gel and polymer electrolytes seek to address such issues. In summary, electrolyte innovations aim to *increase voltage and stability* without sacrificing the fast dye-regeneration kinetics that iodide affords.

Solid-State and Hybrid DSSCs: As mentioned, replacing the liquid electrolyte with a solid hole-conductor turns a DSSC into a hybrid thin-film device. The prime example is the perovskite solar cell – where the organometal halide perovskite serves as both the light absorber and the transporter of positive charge, eliminating the need for a liquid electrolyte. Solid-state DSSCs with Spiro-OMeTAD and organic dyes were tried in the mid-2000s but had modest efficiency ($\sim 5\text{--}8\%$) due to poor pore filling. The perovskite breakthrough in 2012–2013 circumvented that by forming an actual semiconductor in the pores. Within a year, perovskite-based DSSCs (no liquid) exceeded 15% and rapidly evolved beyond the DSSC framework (perovskites now reach $>25\%$ efficiency as separate photovoltaic devices). Another solid-state variant is the p-type DSSC, which is essentially a dye-sensitized photocathode using a p-type semiconductor (like NiO) and a dye that injects “holes” into the NiO valence band. P-

type DSSCs are much less efficient (record $\sim 2.5\%$) [3] but are useful in constructing tandem cells (see next). In recent research, combining n-type DSSC and p-type DSSC in a tandem configuration has been explored to utilize both electron injection and hole injection dyes. While a few tandem p–n DSSCs have been made, the overall efficiency so far has remained low (1–3% range) because the p-DSSC side limits the current. For instance, He et al. (2014) achieved a tandem cell with NiO(p)/TiO₂(n) that gave 1.91% efficiency – higher than either the p- or n-cell alone, but far below standard n-DSSCs. Theoretically, however, a properly optimized p–n dye tandem could surpass 15% or more, if the p-side current can be raised.

Tandem and multi-junction configurations

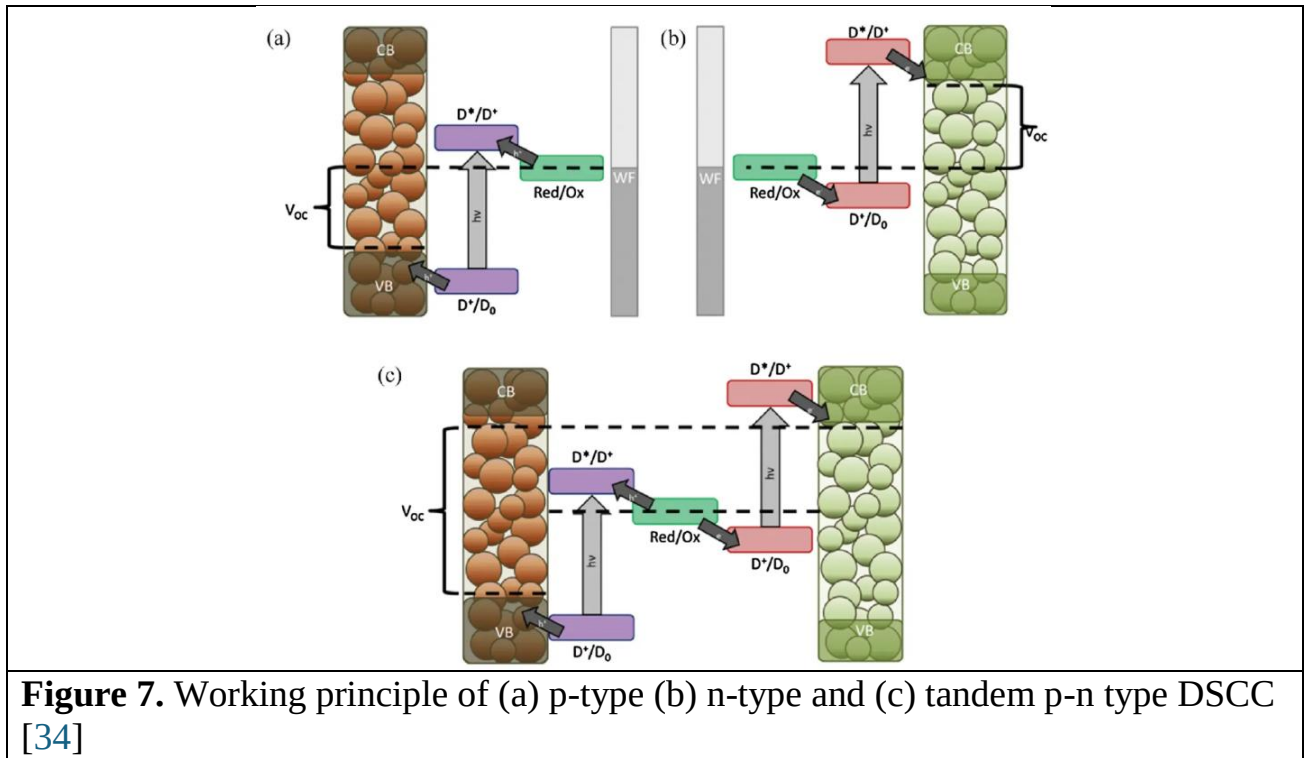
The photocathode comprises of a p-type semi-conductor and a dye attached as illustrated in Fig. 7a. When the photoexcitation occurs, this dye injects a hole into the conduction band of the p-type semi-conductor. It can also be considered as this hole results in an electron being injected to the dye from the semi-conductor. When this charge transmittance is completed, a redox-active electrolyte neutralizes the dye by oxidizing it back. Afterwards, this hole is transported to the external circuit via the mesoporous network of the p-type semi-conductor. Then the typical counter electrode coated with catalytic material (typically platinum) maintains the charge balance by oxidizing the reduced species in the electrolyte. In comparison, upon the photoexcitation in the n-type DSSC as illustrated in Fig. 7b, the electron is injected into the conduction band from the dye, which then transported to the external circuit via the mesoporous network. Afterwards, the electrolyte reduces the dye and again the typical counter electrode coated with catalytic material (typically platinum) reduces the electrolyte by charges at the working electrode. Additionally, in the case of tandem structure, when both of the p and n-type are stacked together as shown in Fig. 7c. As two systems are connected in series and if charge generation is balanced, the two systems will create a higher V_{OC} [34].

n-n Type Tandem DSSC

To push efficiencies beyond single-junction limits ($\sim 14\text{--}15\%$ for DSSC), researchers have stacked cells with complementary absorption. One approach is an “**n–n tandem DSSC**,” where two TiO₂ photoanodes with different dyes are stacked in series (or connected optically in parallel) [3].

In this type of device, two separate n-type semi-conductive electrodes, called ‘n-n tandem structured DSSC’ connected in series in the tandem position that increases the device higher short-circuit photocurrent density. The top cell uses a dye absorbing higher-energy (blue/green) light and is semi-transparent to red light, which the bottom cell’s dye then absorbs.

Firstly, a tandem structure was developed by Wataru et al., a front cell made up of N719 sensitized connected with black dye-sensitized bottom cell. He had the tandem DSSCs with PCE of 7.6% of tandem DSSCs in the first iteration, higher than each cell [34].



The tandem structure design focused on two completed cells attained improved efficiency, depending on various mixtures of dyes, more effective than near-infrared dyes being applied. Nelles et al. registered a total power conversion efficiency of up to 10.5% tandem by combining an N719-sensitized cell and a “black dye”-sensitized cell in series[3]. He that two stacked DSSCs could indeed produce higher voltages (sum of each V_{oc}) and currents matched to the smaller of the two [35]. A series-tandem DSSCs with optimized dye combination were stated by Hironori Arakawa and collaborators. TiO_2 layer obtained the higher output of 1450 mV and 10.8 mA cm^{-2} and 10.4% [36]. Another by H. Arakawa’s group achieved about **10.4%** with a 1.45 V output (two ~ 0.72 V cells in series)[3]. These were improvements over single-cell ~ 7 –8% devices at the time. One more study in 2010, by optimizing the thickness of TiO_2 films in the separate cells in terms of tandem DSSC output with different series or parallel contact modes. The integrated parallel-linked tandem DSSCs resulted in the best power conversion efficiency of 10.6% [37]. Ma and coworkers later documented a related tandem with a multilayered photoanode DSSC. The multilayered photoanode structure increased the density of the photocurrent and the maximum efficiency of 11.05% was attained [38].

Overall, the power conversion efficiency with these designs have been improved significantly in past but there is no recent reporting's made on these systems. However, future growth is likely to create more interests in this area in future for higher performance.

p-n Type Tandem DSSC

In this type of device, dye-sensitized p-type and n-type electrodes are connected in series to one another which we refer as 'p-n tandem structured DSSC' that can generate a higher photovoltaic voltage. The efficiency of this type of solar cells has been reported minimum because of the inefficient performance of the p-DSSC. A major reason is that this type of structure cannot utilize the full spectrum of solar radiations [39]. One of the innovative approaches was developed by Sobus et al. in 2014, to exploit the energy emitted from the solar spectrum. They employed the semiconductor of the n-type as TiO_2 , a p-type dye-sensitized semiconductor as NiO, and a redox mediator between them. The p-n-DSSC designed shows improved conversion efficiency compared to n-DSSC [40]. Another benefit of serially connected tandem solar cells is the increase in photovoltage in comparison to the individual n-DSSC and p-DSSC, which results in an overall increase in efficiency. In recent years, p-DSSC research had been targeted on developing new sensitizers and redox structures and the improvement can notably growth the overall performance of the p-DSCs, frequently due to an increase inside the photovoltage [41]. Wei et al. doped metal atom into active NiO layer in 2016 to boost the p-DSSC photovoltaic efficiency [42]. Ho et al. implemented a simple technique of a compact NiO blocking layer into an active NiO photocathode network of p-DSSC and p-n DSSC in 2018 and additionally from previous research in 2016 to improve the power conversion efficiency. The designed p-n DSSC displays an improved photovoltage comparison to n-DSSC, ensuing in the conversion efficiency of 1.486% overall. This increase can be further enhanced to 1.913% by addition of an optimized NiO [43,44].

Overall, the efficiency with these designs have been improved significantly in past but again there are very limited recent reporting's made on these designs. However, the future growth of laboratories can create more developments in the future in this area.

The tandem approach for DSSC is conceptually appealing because the Shockley–Queisser limit for a tandem (with two bandgaps) is much higher (the Grätzel quote: ~32% single, ~46% dual gap)[33]. However, executing a tandem DSSC is non-trivial: the two cells must be internally connected (either mechanically stacked with a transparent intermediate electrode or monolithically integrated) and currents must be matched for series connection[3]. Ensuring the second cell gets enough light (requiring first cell to be partly transparent) and that both dyes and electrolytes are

compatible introduces complexity. Recently, **monolithic tandem DSSCs** have been reported, for instance using a TiO_2 photoanode on one side and a NiO photocathode on the other within one cell. If perfected, a tandem p–n DSSC could exceed 15–20% efficiency (since the theoretical V_{oc} could be ~ 1.4 V and higher current via broader spectrum absorption)[3].

Hybrid Tandems with other solar cells: CGIS-DSSC Tandem Solar Cells

Another exciting direction is combining a DSSC with a different type of solar cell in a multi-junction stack. Because DSSCs are effective at harvesting visible light and can be made transparent to infrared, they can be used as the top cell in a tandem with a lower-bandgap bottom cell like CIGS or silicon.

Copper indium gallium selenide (CIGS)-DSSC tandem architecture assembly is a very helpful technique for increasing the efficiency of photoelectric conversion by optimizing the use of solar spectrum in individual cells [45]. These tandem solar cells are manufactured using the optimized DSSC and CIGS, where DSSC is used as the top cell and CIGS as the bottom cell. For the series connection, the positive DSSC electrode and the negative CIGS electrode are connected by an electrical cable, which resulted in a tandem structure with two terminal electrodes as illustrated in Fig. 8. This approach increases open-circuit voltage and ultimately improves the conversion efficiency of DSSC [46].

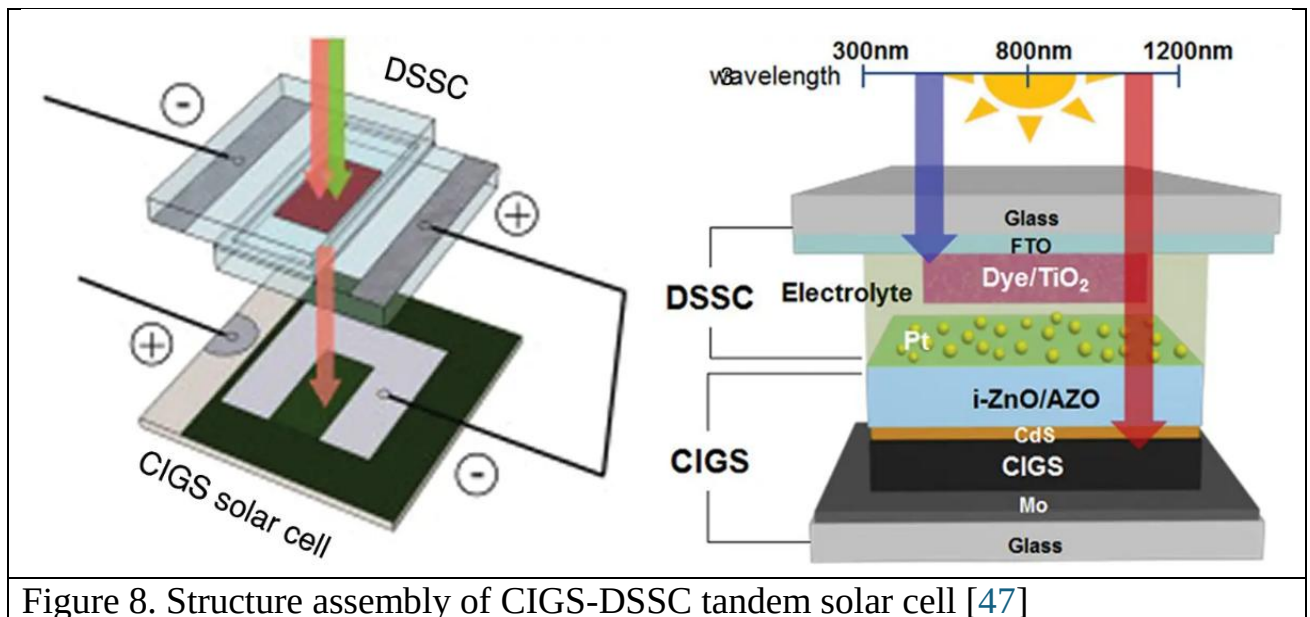


Figure 8. Structure assembly of CIGS-DSSC tandem solar cell [47]

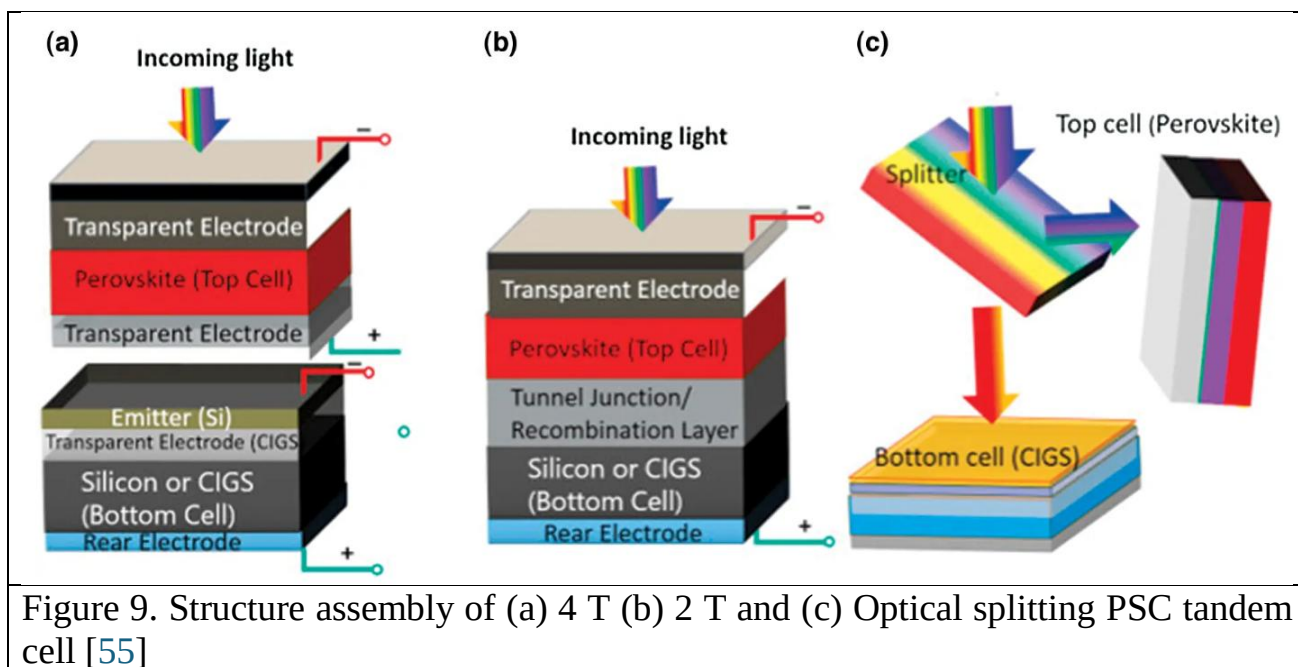
Accordingly, tandem structure by DSSC series connection with low bandgap p–n junction solar cells is considered as one of the methods for improving output voltage.

As DSSC are prepared as a semi-transparent device, therefore tandem cells are built by positioning a DSSC as a top cell [48].

In 2006, **Liska et al.** demonstrated a *mechanically stacked* tandem of a DSSC (top) and a Cu(In,Ga)Se₂ thin-film cell (bottom), achieving about **15% efficiency** (approximately 7% from the DSSC and 8% from the CIGS)[3]. This hybrid approach took advantage of the high voltage output of the DSSC (~0.8 V) plus the silicon/CIGS (~0.5–0.6 V) to yield ~1.4 V overall, with each subcell absorbing different parts of the spectrum. More recently, monolithic integration was attempted: for example, merging a DSSC directly onto a CIGS cell by coating a TiO₂/dye layer onto a modified CIGS surface. A monolithic **DSSC–CIGS tandem** by Yum *et al.* (2017) reached **12.35% efficiency** with an impressive Voc of 1.435 V[49]. In that device, the photocurrent was limited by the semi-transparent DSSC top cell (~14 mA/cm²), but the voltage added up from each part. Such hybrid tandems are promising for applications needing higher voltage outputs (for example, driving electrolysis or charging batteries directly). Likewise, DSSC-on-silicon tandems have been explored, though silicon's bandgap is not as ideally matched as CIGS for pairing with DSSC. Nevertheless, these results show the versatile ways DSSC technology can be combined with others.

PSC-DSSC Tandem Solar Cells

Remarkable performance and economical prices of perovskite solar cells (PSCs) have been the center of the photovoltaic research field in recent years [50]. Inorganic-organic halogen perovskite has a higher absorption coefficient relative to conventional dyes, which supports its use as a sensitizer in DSSCs. As a sensitizer, nanocrystals from perovskite (CH₃NH₃PbI₃) were first presented into DSSC in 2009 [51]. It has become evident that perovskites can act as both hole and electron conductors, and also bulk solid perovskite film can withstand charge formation and transport. However, the efficiency is not high due to the instantaneous dissolution of perovskite in a liquid electrolyte [52,53,54]. Tandem heterojunction is a novel strategy for improving the spectral response in NIR regions with long wavelengths. A perovskite tandem solar cell can be formed in three different structures, depending on how the junctions between the top and bottom cells are electrically coupled. The mechanically stacked solar cells are called a 4-terminal (4 T) tandem, a monolithic tandem solar cell called a 2-terminal (2 T) tandem solar cell, and a tandem solar cell with optical splitting as shown in Figs. 9a–9c, respectively.



Perovskite-based 4T tandems with chalcogenide and c-Si bottom cells achieved efficiencies of 20.5% and 22.8% [56], while mechanically stacked perovskite-silicon cells reached 26.4% [57]. Monolithic 2T perovskite tandems obtained 23.6% PCE with stable performance [58]. Optical splitting tandems showed ~40% relative efficiency gain over single junctions [59].

Studies integrated perovskites with thermo-electric modules for >23% efficiency (18.3% from PSC) [60]. Ruthenium-based DSSC/perovskite tandems using spectral splitting yielded 21.5% [61]; mechanically stacked DSSCs with DX1/N719 sensitizers achieved 12% under reduced sunlight. Panchromatic DX3 DSSC reached 18.4% alone and 21.5% in tandem [61]. Recent perovskite/DSSC tandems using thioindigo (C₁₆H₈O₂S₂) or N719 dyes as bottom-cell sensitizers delivered 8.77% and 10.54% PCE, respectively; reverse configuration (top DSSC, bottom PSC) was first demonstrated with organic dye, showing high V_{oc} but J_{sc} limited by bottom DSSC [62].

Recent advances in perovskite tandems, via optimized band gaps and materials, have significantly boosted efficiencies. Future research promises further progress.

Overall, in this section comparison of different types of DSSCs based on the physical appearance and architectural assembly is presented. This section can be summarized as: proper selection of electrolytes greatly affects the performance of DSSC devices, and we found from the literature that the quasi-solid and polymer gel-electrolyte, proves to be a better option because of good ionic conductivity and contact with electrode resulting in enhanced photovoltaic performances. Also, it can be summarized that tandem can achieve good performance because the performance for both individual cells could be optimized separately.

Flexible and indoor applications

Because DSSCs can be made on plastic or metal foil substrates (replacing the glass), they are well-suited for flexible solar cell applications. Companies have produced flexible DSSC cells for use in indoor or portable chargers, wireless sensors, etc. In indoor lighting conditions (far lower light intensity and more towards the visible spectrum), DSSCs actually outperform many other solar cell types. They have achieved over 30% power conversion efficiency under 1000 lux of fluorescent lighting, for instance, whereas silicon or perovskite cells drop off more at low light. This makes DSSCs attractive for powering small IoT devices and calculators, where they can be designed as aesthetically pleasing, translucent panels. Indeed, DSSCs are sometimes dubbed “artificial photosynthesis” and can even be made in colors and patterns (there are demonstrations of DSSC-powered decorative indoor objects and toys). The ability to work in diffuse and dim light is a unique strength of DSSC – stemming from the fact that they have no significant threshold for current generation (they do not “turn off” at low light like some silicon cells do when recombination overtakes photogeneration).

Temperature performance

DSSCs tend to have better performance at higher temperatures compared to silicon cells. In silicon panels, as they heat up, the voltage drops significantly (around $-0.45\%/^{\circ}\text{C}$ relative efficiency drop). DSSCs, on the other hand, have a smaller temperature coefficient for efficiency, partly because they operate via chemical potentials. For example, a DSSC might even see *increased* photocurrent at higher temperature (due to faster dye regeneration kinetics), and although V_{oc} drops, the net effect is that DSSC efficiency doesn’t degrade as steeply with heat. This could be an advantage in hot climates or in applications like solar-powered sensors that may experience indoor heat.

Challenges and outlook

Despite many advantages (low-cost materials, simple fabrication, flexibility, good indoor performance, and colorful transparency), DSSCs face challenges that have so far limited their widespread adoption. The chief issues are conversion efficiency (still lower than mainstream silicon, which easily exceeds 20%, or perovskites at $\sim 25\%$) and long-term stability. The best reported DSSC efficiencies of $\sim 13\text{--}14\%$ were achieved with volatile electrolytes and anti-reflective coated cell designs under lab conditions[3]. When translating to larger modules, efficiencies often drop into the single digits. Stability-wise, modern DSSCs can be quite stable if properly sealed – some reports show only minor degradation over thousands of hours at moderate light and temperature – but ensuring 20+ year outdoor stability under UV, heat, and freeze/thaw cycles remains non-trivial[32]. The liquid electrolyte can leak or dry out over time, and the iodide/triiodide redox couple can attack metal contacts (though

using epoxy seals and barrier coatings helps). Replacing the liquid electrolyte with a solid or gel is an active area of research, which has seen progress (ionic liquid-based DSSCs, polymer gel electrolytes, etc., show improved thermal stability)[32]. Another challenge is the use of rare elements like ruthenium and platinum in classic DSSCs – there is a push to develop entirely metal-free dyes and cheaper carbon-based catalysts to bring costs down and avoid supply issues.

Moving forward, continued research on DSSCs is exploring: novel redox mediators (to raise Voc further and prevent recombination), upconversion or co-sensitization techniques (to utilize lower-energy photons beyond the dye's range), and tandem configurations to overcome the single-junction efficiency ceiling. On the manufacturing side, efforts are being made to upscale DSSC printing and building-integrated applications. One notable commercial example is the EPFL SwissTech Convention Center, which incorporated 300 m² of colorful DSSC panels as part of its facade – a demonstration of the technology's architectural integration potential.

In summary, dye-sensitized solar cells have progressed from 7% in 1991 to ~14% by 2020[2], a testament to improvements in dye chemistry and cell engineering. They remain one of the most successful “third-generation” solar technologies in terms of scientific impact. While they may not replace silicon for large-scale power production in the near future, DSSCs are carving out niches in indoor photovoltaics, transparent PV windows, wearable power, and other applications where their unique properties (flexibility, color, low-light performance) give them an edge. Ongoing innovations – and synergy with emerging fields like perovskite solar cells – continue to enhance the efficiency and stability of DSSCs. With theoretical efficiencies in the several tens of percent (for tandem designs)[3] and the possibility of mass production via printing, DSSCs hold promise as a complementary photovoltaic technology that can broaden the use of solar energy in areas traditional cells cannot easily serve.

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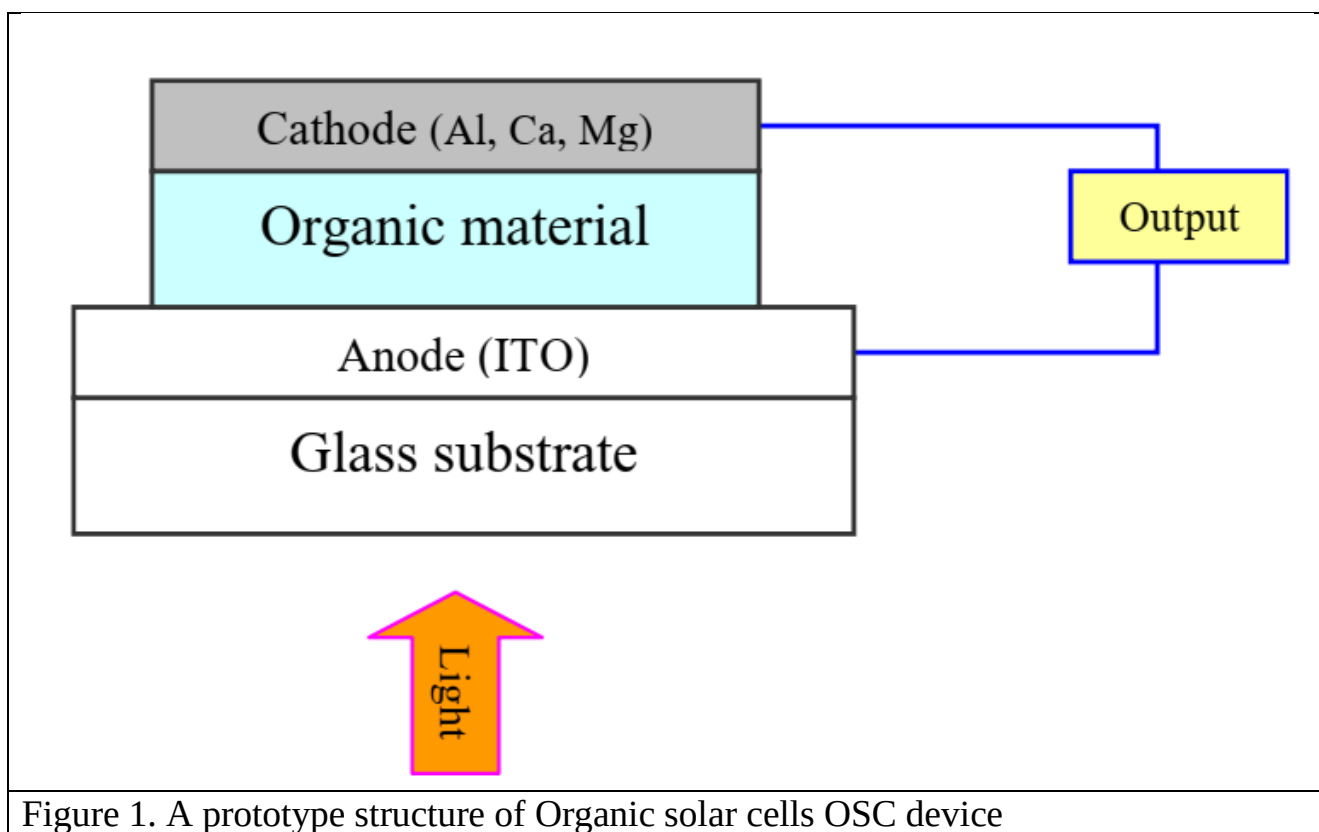
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Chapter VII

7. ORGANIC SOLAR CELLS

Organic solar cells (OSCs) use carbon-based (organic) materials as the light-absorbing semiconductors. They trace back to early discoveries of photoconductivity (e.g. anthracene in 1906) and the first organic photovoltaic effect. Tang *et al.* (1987) at Kodak created the first bilayer OSC using copper phthalocyanine (CuPc) and C₆₀, achieving nearly **1%** power conversion efficiency[1]. This two-layer donor–acceptor design launched OSC research. Figure 1 shows a prototype structure of OSC device. These devices promise to open up new markets for solar energy, potentially powering everything from watches and calculators to laptop computers.



In the 1990s, conjugated polymers and fullerene acceptors (e.g. P3HT:PCBM) enabled the **bulk heterojunction** concept, boosting efficiency (Yu *et al.*, 1995; Heeger *et al.*, 2012). By the 2010s, tandem (multi-junction) OSCs exceeded 10%[2]. Most recently, record certified efficiencies around **19–20%** have been reported, reflecting rapid progress[3][4].

The table 1 below summarizes key milestones:

Year (Group)	PCE (%)	Notes (Materials/Configuration)	Source
1987 (Kodak, Tang <i>et al.</i>)	~1%	CuPc/C ₆₀ bilayer OSC[1]	Tang et al. (1987)[1]
2013 (Heliatek, Le Séguillon)	12.0%	Vacuum-deposited small-molecule tandem (2-stack)[5]	Heliatek (2013)[5]
2015 (Zhang <i>et al.</i>)	~10%	Solution-processed polymer tandem (certified 10.6%)[2]	NREL (2015)[2]
2023 (Hong Kong PolyU)	19.3%	Non-fullerene polymer solar cell record[2]	Zhan et al. (2023)[2]
2024 (Chen <i>et al.</i>)	20.82%	Single-junction OSC with crystallization control[4]	Chen et al. (2025)[4]
2025 (Sun <i>et al.</i>)	19.96%	Low-cost polymer (CF ₃ -substituted) OSC[6]	Sun et al. (2025)[6]
2025 (Kanazawa Univ.)	8.7%	All-organic (CNT/PEDOT:PSS electrodes) OSC[7]	Jowett (2025)[7]
2025 (NUS, Hou <i>et al.</i>)	26.4% (T)	Perovskite–organic tandem (certified)[8][9]	Hou et al. (2025)[8][9]

These breakthroughs stem from novel donor/acceptor materials (e.g. non-fullerene acceptors like Y6), improved morphologies and device designs. OSCs remain lightweight and flexible, and ongoing research (solvent engineering, additives) continues to push efficiencies above **20%**[3][10].

Device Structure and Operation

An OSC typically consists of a transparent anode (e.g. ITO) on glass or flexible substrate, a hole transport layer (e.g. PEDOT:PSS), an **active layer** blend of donor and acceptor materials (forming a bulk heterojunction), and a cathode (e.g. Al)[1][11]. Organic solar cells (OSCs) operate by converting sunlight into electricity through a four-step process: photon absorption, exciton diffusion, charge separation at a donor-acceptor interface, and charge collection at electrodes.

Upon illumination, photons create bound electron–hole pairs (**excitons**) in the donor material. These excitons diffuse (~10 nm) to a donor/acceptor interface, where they split into free charges: electrons move into the acceptor and holes remain in the donor. An internal electric field (from built-in voltage at electrodes) drives electrons to the cathode and holes to the anode, generating photocurrent[11][12].

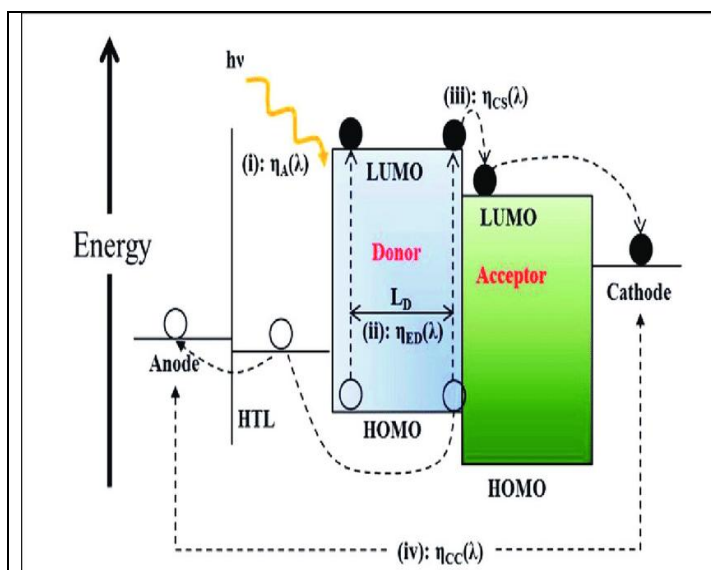


Figure 2. [10.5937/jaes14-10879](https://doi.org/10.5937/jaes14-10879)

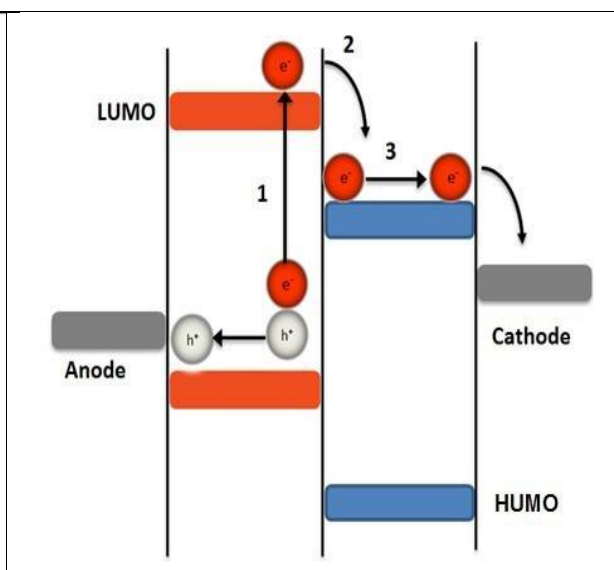


Figure 3.
DOI:[10.13140/RG.2.2.13501.41443](https://doi.org/10.13140/RG.2.2.13501.41443)

In a **regular** OSC, the stack is (anode/hole-blocker)–donor:acceptor–(electron-blocker/cathode). In an **inverted** architecture, the contact order is reversed, often improving stability. Compared to inorganic cells, OSCs have no classic p–n junction; instead the donor–acceptor energy offset drives exciton separation[11][13].

Materials and Variations

OSCs use diverse organic semiconductors. **Donor materials** are typically π -conjugated polymers or small molecules (e.g. P3HT, PTB7, D18, PTQ15) that absorb visible light. **Acceptor materials** include fullerene derivatives (PC₆₁BM, PC₇₁BM) and, more recently, non-fullerene acceptors (e.g. Y6, N3) which allow higher J_{SC} and stability. The choice of donor and acceptor sets the effective bandgap and thus the achievable V_{OC} (often ~0.7–1.1 V)[17].

Device architectures include single-junction BHJ cells and **tandem** or multijunction OSCs. Tandem OSCs stack two or more sub-cells (with different bandgaps) in series to capture more of the solar spectrum, analogous to inorganic tandem cells[2][9]. For example, Heliatek used vacuum-deposited small-molecule layers to build tandem (multi-stack) OSCs, yielding a 12.0% single-cell efficiency that they equated to ~15% silicon-equivalent performance[5]. In all cases, transparent conductive electrodes (ITO, PEDOT:PSS) and metal cathodes (Al, Ag) complete the stack.

Hybrid and Tandem Combinations

OSCs are often combined with other photovoltaics in tandem stacks. High-bandgap OSCs can serve as **top cells** over silicon, CIGS or perovskite bottoms[11]. Organic top-cells absorb high-energy (blue/UV) photons while transmitting lower-energy light to the bottom cell[11]. Recent advances include **perovskite–organic tandem cells**: for instance, Hou *et al.* (NUS, 2025) demonstrated a perovskite–organic tandem with 26.4% certified PCE by engineering a near-IR organic absorber[8][9]. Such hybrids leverage the low-cost, tunable nature of OSCs to push tandem efficiency toward 30% theoretical limits. Other combinations include all-organic multijunctions (multiple organic layers) and OSC–DSSC hybrids, reflecting ongoing innovation in mixed-technology stacks[9][11].

OSC–CIGS Tandem

In principle one can stack an organic front cell with a CIGS bottom cell(Figure 4). Scientists in the Middle East designed a flexible two-terminal organic/CIGS tandem solar cell for wearable applications. The device achieved an open-circuit voltage of 1.89 V, a short-circuit current density of 17.55 mA/cm², and a fill factor of 82.79%.

The latter includes a substrate made of indium tin oxide (ITO) and glass, the CIGS absorber, a cadmium sulfide (CdS) buffer layer, zinc oxide (ZnO), an aluminum-doped ZnO (ZnO-Al) optically transparent cathode, an interlayer based on transparent conductive oxides (TCO), a hole transport layer (HTL) made of molybdenum trioxide (MoO₃), an absorber made with an organic material known as PM6:m-DTC-2 F, and another ZnO layer.

The simulation under standard illumination conditions initially achieved a power conversion efficiency of 22.5%. By further increasing the doping of the CIGS absorber and by optimizing the absorbers' film thicknesses at 100 nm and 2.5 μm for the front and rear cells, respectively, the research group was able to raise the tandem device efficiency to 27.46%. It also achieved an open-circuit voltage of 1.89 V, a short-circuit current density of 17.55 mA/cm², and a fill factor of 82.79%.

The organic cell and the CIGS device achieved an efficiency of 12.20% and 20.10%, respectively.

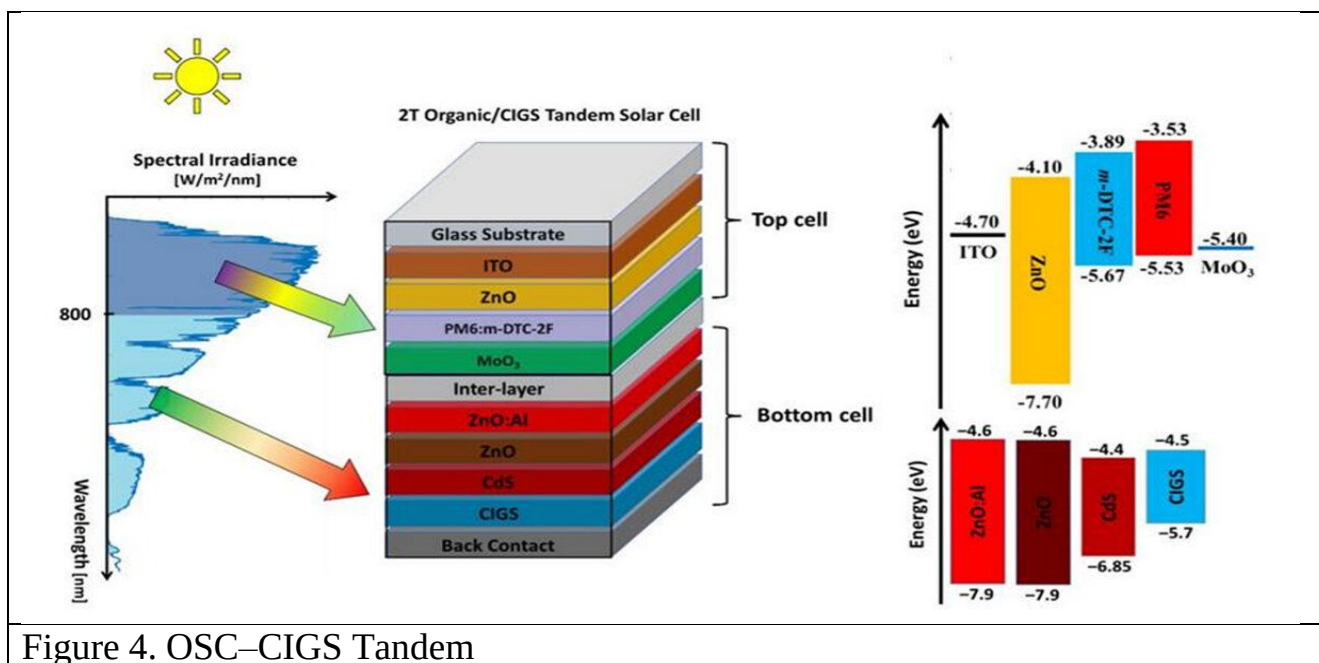


Figure 4. OSC–CIGS Tandem

Organic–DSSC Hybrids

Organic Solar Cells (OSC)–DSSC hybrids are tandem devices integrating OSC's low-cost organic polymers for broad absorption with DSSC's dye-sensitized TiO₂ for efficient charge generation, often in 2-terminal or 4-terminal setups to exceed single-junction limits via complementary spectra.

In an organic–DSSC hybrid, a conventional dye-sensitized cell (DSSC) is combined with an organic solar subcell. Two connection schemes are possible: series (two-terminal) or parallel (four-terminal) tandem. In a **series** hybrid, the DSSC and OSC share the same current; their voltages add. This can raise V_{oc} but requires matching currents. For example, connecting a DSSC to an inorganic cell raised the tandem V_{oc} by ≈ 0.3 V (with J_{sc} limited by the DSSC)[4]. In **parallel** coupling, the subcells operate at the same V_{oc} and currents add, which can improve low-light response but may be impractical due to mismatched impedances.

Reported performance of organic–DSSC hybrids is modest. One demonstration (a DSSC/CIGS analog) achieved only $\sim 6.1\%$ PCE[4]. In general, hybrid OSC–DSSC tandems suffer from spectral overlap and recombination losses, so typical efficiencies remain only a few percent. (No high-efficiency organic+DSSC tandem has been certified to date.) The hybrids do allow broader-spectrum absorption – e.g. visible light via the dye and longer wavelengths via the organic absorber – but detailed studies are sparse.

Structure: Top OSC (e.g., P3HT:PCBM blend) / Recombination layer (e.g., PEDOT:PSS/ITO) / Bottom DSSC (TiO₂ photoanode, organic/ruthenium dye, electrolyte, Pt cathode)(Figure 5).

Fabrication: Spin-coat OSC layers; deposit TiO_2 , sensitize with dye, assemble with electrolyte.

Efficiency: Up to 11.02% in tandem DSSCs with organic sensitizers; hybrid configurations reach ~10-12% PCE, with potential for 18% in optimized inorganic-organic variants.

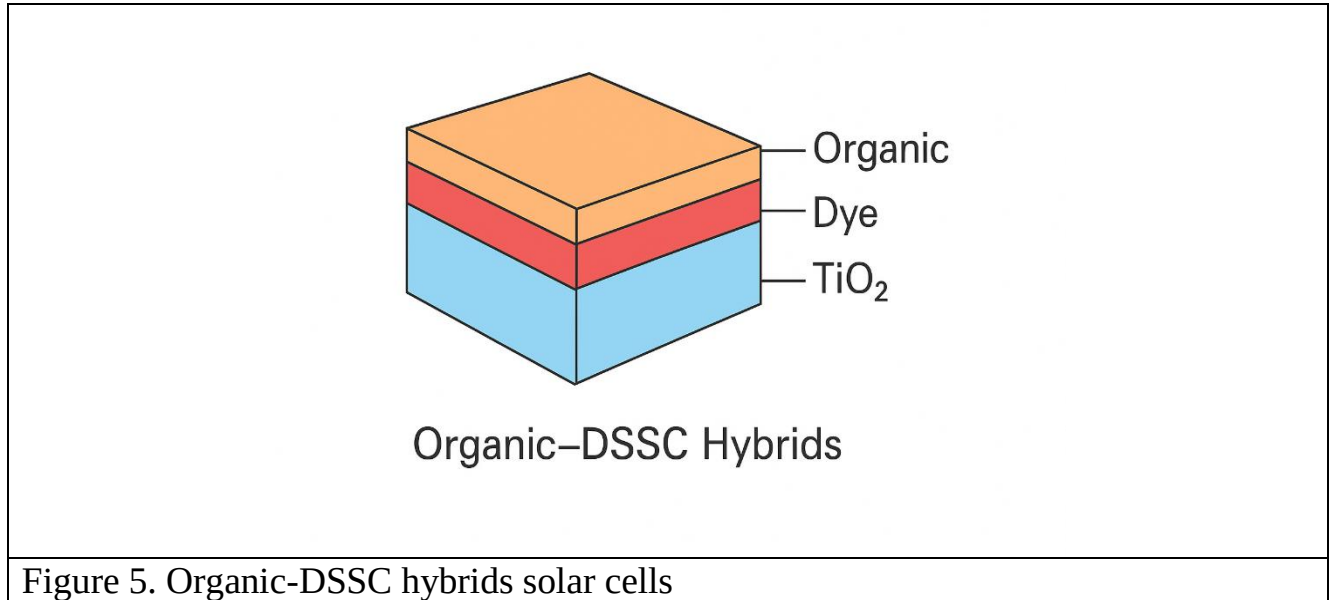
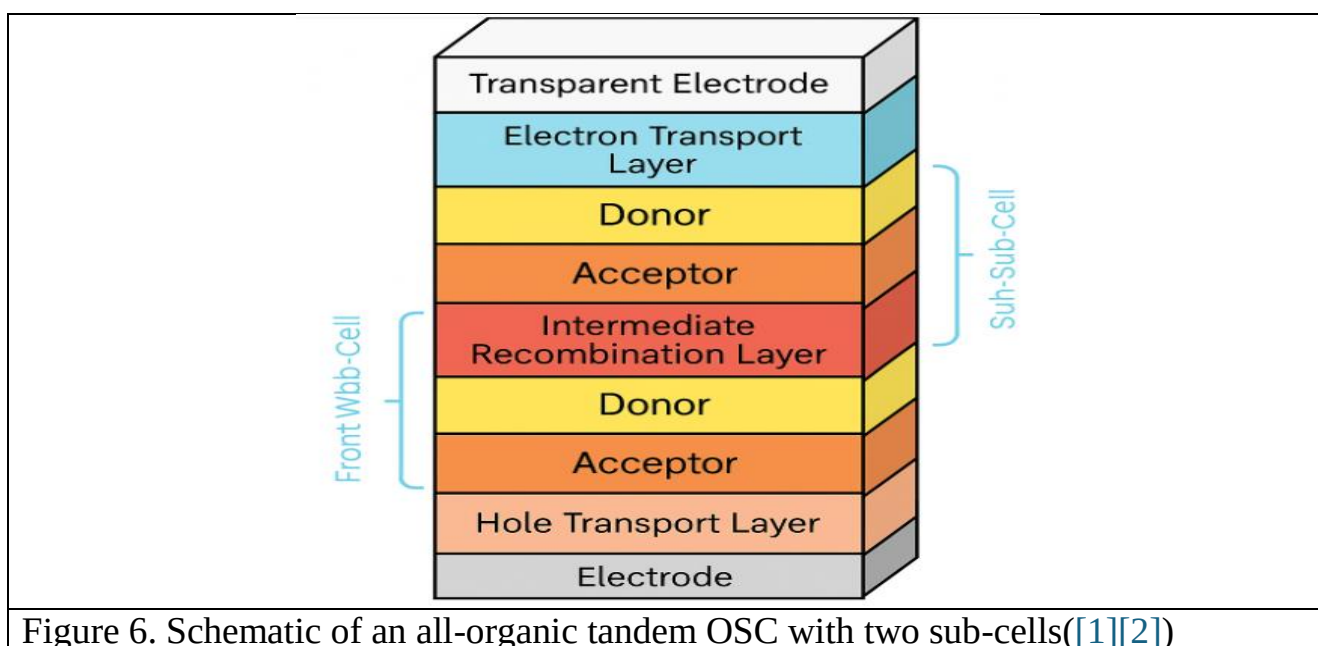


Figure 5. Organic-DSSC hybrids solar cells

All-Organic Tandem OSC-OSC

Figure 6: Schematic of an all-organic tandem OSC with two sub-cells (front wide-bandgap and rear narrow-bandgap) stacked monolithically[1][2]. In a series-connected OSC-OSC tandem, complementary absorption layers extend the spectral range and the open-circuit voltages of the two sub-cells add together[1]. Charge pairs generated in each donor-acceptor junction are collected through the intermediate recombination layer, yielding a combined voltage and a shared current. Optimal design requires current matching between sub-cells; otherwise, the smaller sub-cell current limits the tandem output. Recent demonstrations exploit high-performance donor-acceptor materials to push tandem efficiencies.



In practice, tandem OSCs have achieved record PCE values. For example, Wang *et al.* (2025) reported a two-terminal tandem based on novel nonfullerene acceptors reaching **21.5%** (certified 21.2%)[2]. Earlier, Jia *et al.* (2021) obtained **16.40%** (front cell 13.40%) with a series-connected tandem stack[3]. The current–voltage behavior of such a tandem (Fig. 7c in Jia *et al.*) shows a summed V_{oc} of 1.65 V, $J_{sc} \approx 14.5$ mA/cm² and fill factor 68.5%[3]. In general, all-organic tandems now surpass 15% PCE, with reports up to ~21%[2].

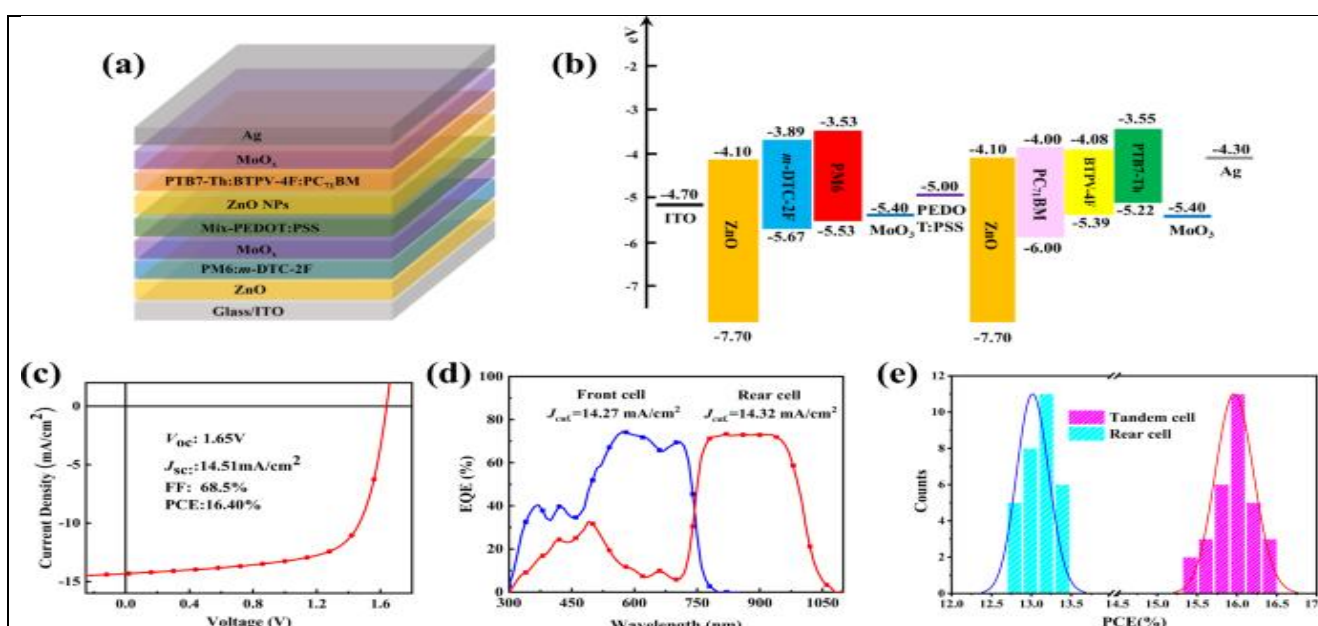


Fig. 7: Device structure and photovoltaic performance of tandem solar cells.

(<https://doi.org/10.1038/s41467-020-20431-6> |

www.nature.com/naturecommunications)

Figure 7: **a** Device architecture of the tandem OSCs. **b** Energy level diagram of the related materials in the tandem OSCs. **c** The J – V curves of the optimal tandem OSC under the illumination of AM 1.5 G, 100 mW cm^{-2} . **d** EQE spectra of the front and rear cells of the tandem OSC. **e** PCE distribution of the BTPV-4F based single-junction OSCs and tandem OSCs based on 30 individual devices.

To understand the current matching behavior between front and rear sub-cells in the tandem OSCs, EQE spectra of the sub-cells were measured, as shown in Fig. 7d. In monolithic tandem OSCs, the EQE spectra of one specific sub-cell are acquired by applying bias illumination to the other sub-cell to a level that the under-investigated sub-cell is current-limiting in its own absorption spectrum range. In this study, the light bias was obtained by a 550 nm short wave pass filter and a 850 nm long wave pass filter, for the measurements of the rear and front cell, respectively. The rear cell shows a broad EQE spectrum with a high response over 65% in the wavelength range of 760–970 nm. The integrated J_{sc} of front and rear sub-cells are 14.27 and 14.32 mA cm^{-2} , respectively, indicating the highly balanced current generation in each sub-cell. The high and well-balanced J_{sc} of the tandem OSCs is mainly attributed to the complementary absorption range of both sub-cells and the carefully tuned thickness of each active layer

Other OSC Hybrid Combinations (optional)

Perovskite–OSC Tandem: Perovskites’ tunable bandgap make them attractive paired with OSCs. The perovskite top cell (wide bandgap) absorbs the visible range, while an organic bottom cell (narrow bandgap acceptor) harvests NIR photons. Recent works have demonstrated high efficiencies. For instance, Brinkmann *et al.* (2022) achieved 24.0% (certified 23.1%) using an ultrathin indium-oxide interconnect[5]. Zhu *et al.* (2023) developed an inverted perovskite solar cell enhanced with an organometallic interfacial layer, achieving certified 24.3% efficiency and record operational stability. The design employed ferrocenyl-bis-thiophene-2-carboxylate (FcTc₂) between the electron transport layer (C60) and the perovskite absorber. This molecule significantly improved electron extraction and inhibited ion migration, leading to device stabilization(Figure 8a). Jia *et al.* (2025) further pushed the record to 26.7% by improving the infrared-absorbing organic subcell[6](Figure 8b). These devices show high V_{oc} ($\approx 2.15 \text{ V}$) and demonstrate the potential of organic/perovskite stacks.

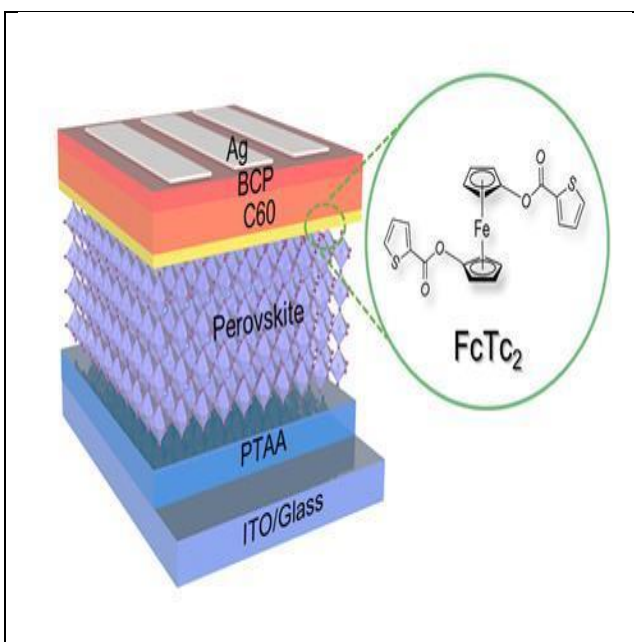


Figure 8a. The structure of the inverted perovskite solar cell supercharged with ferrocenyl-bis-thiophene-2-carboxylate that helped the cell set a new efficiency record for perovskite devices. Source: © Science/AAAS
Z Li *et al*, *Science*, 2022, **376**, 416 (DOI: [10.1126/science.abm8566](https://doi.org/10.1126/science.abm8566))

Figure 8b. The new perovskite-organic tandem cell (right) designed by NUS scientists can achieve a power conversion efficiency of 26.4%, outperforming the previous benchmark for similar devices.

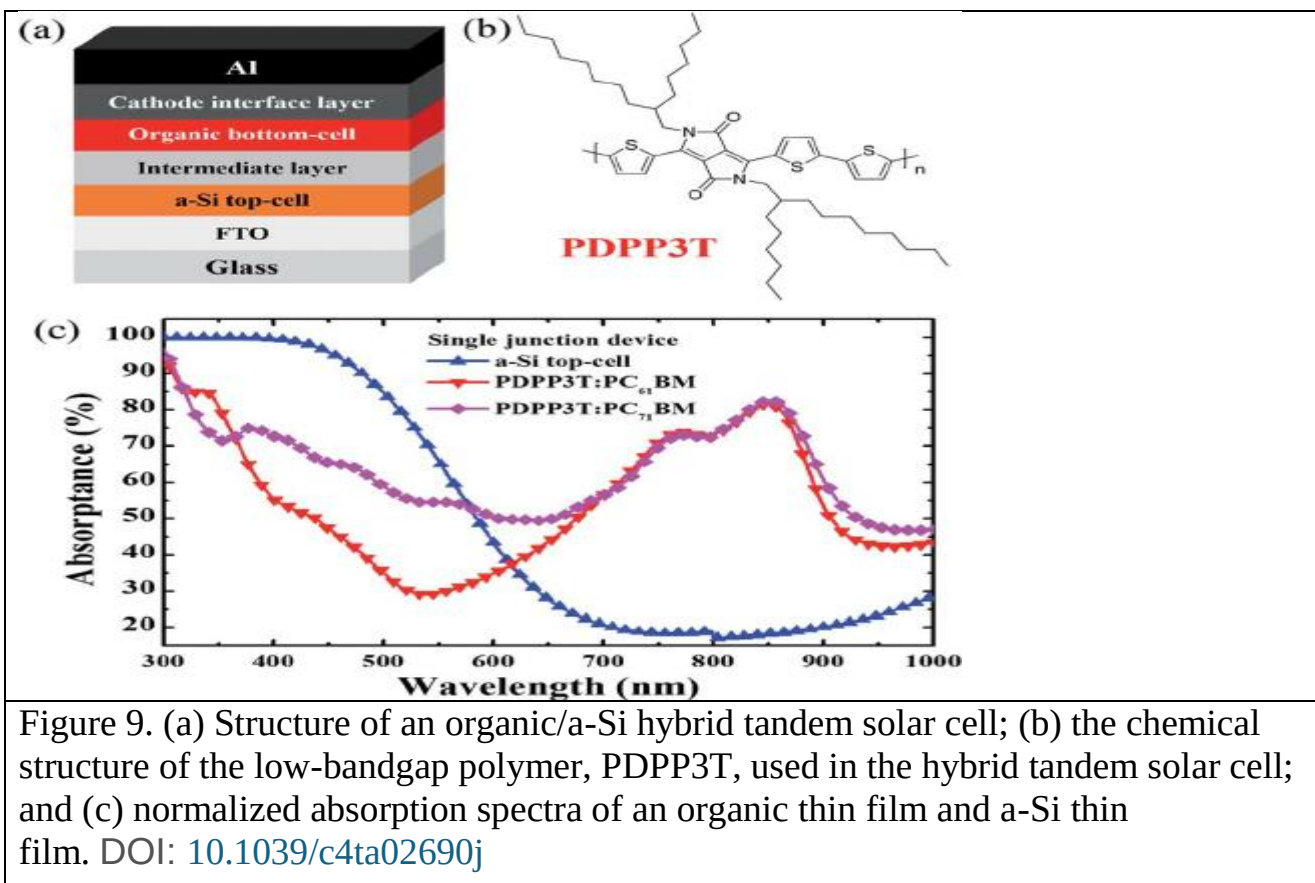
OSC–Si Tandem

Organic Solar Cells (OSC)–Si tandems are hybrid devices stacking an amorphous silicon (a-Si) top cell for short-wavelength light absorption (400–650 nm) with an organic bottom cell for longer wavelengths (650–950 nm), connected by an intermediate recombination layer to boost overall efficiency beyond single-junction limits.

Structure: Typically monolithic 2-terminal: FTO glass substrate / a-Si p-i-n stack / ITO(50 nm) + PEDOT:PSS (40 nm) intermediate layer / Organic active layer (e.g., PDPP3T:PC61BM blend, ~110 nm) / Cathode interface layer (e.g., PFO SO₃Na) / Al(aluminium)cathode. Energy bands align for efficient charge recombination(Figure 9).

Fabrication: a-Si deposited via PECVD; ITO by sputtering; PEDOT:PSS and organic layers spin-coated; cathode evaporated. Optimize a-Si thickness (72–125 nm) for current matching.

Efficiency: Achieved PCE up to 7.5%, with Voc ~1.51 V (sum of sub-cells), Jsc ~6.73 mA/cm², FF ~73%. Higher than single a-Si (4.15%) or OSC (5.89%). Potential for 14% with optimizations. Recent 4-terminal designs report up to 25.86% with organic layers like P3HT:PC70BM. Similarly, organic-on-silicon tandems remain largely theoretical. Some studies suggest that a ~1.7 eV organic top cell on 1.1 eV c-Si could boost efficiency, but practical demonstrations are lacking.



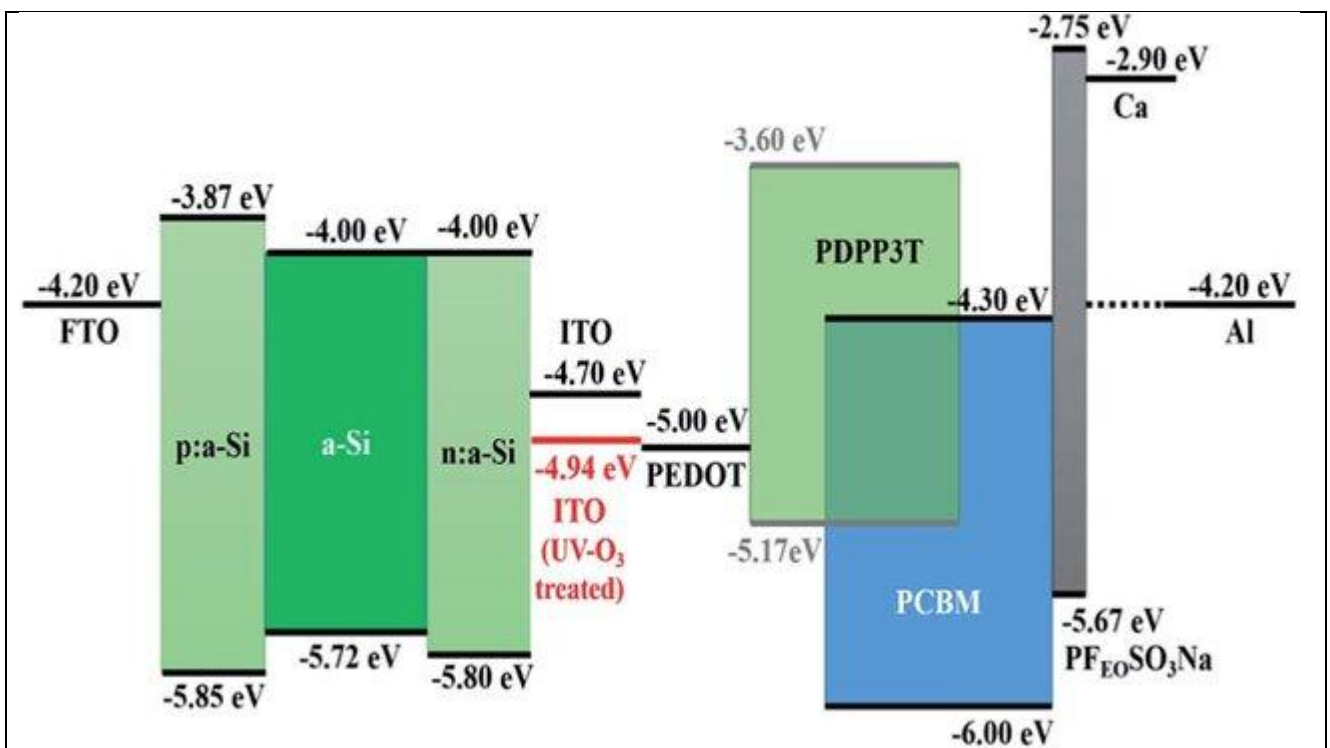
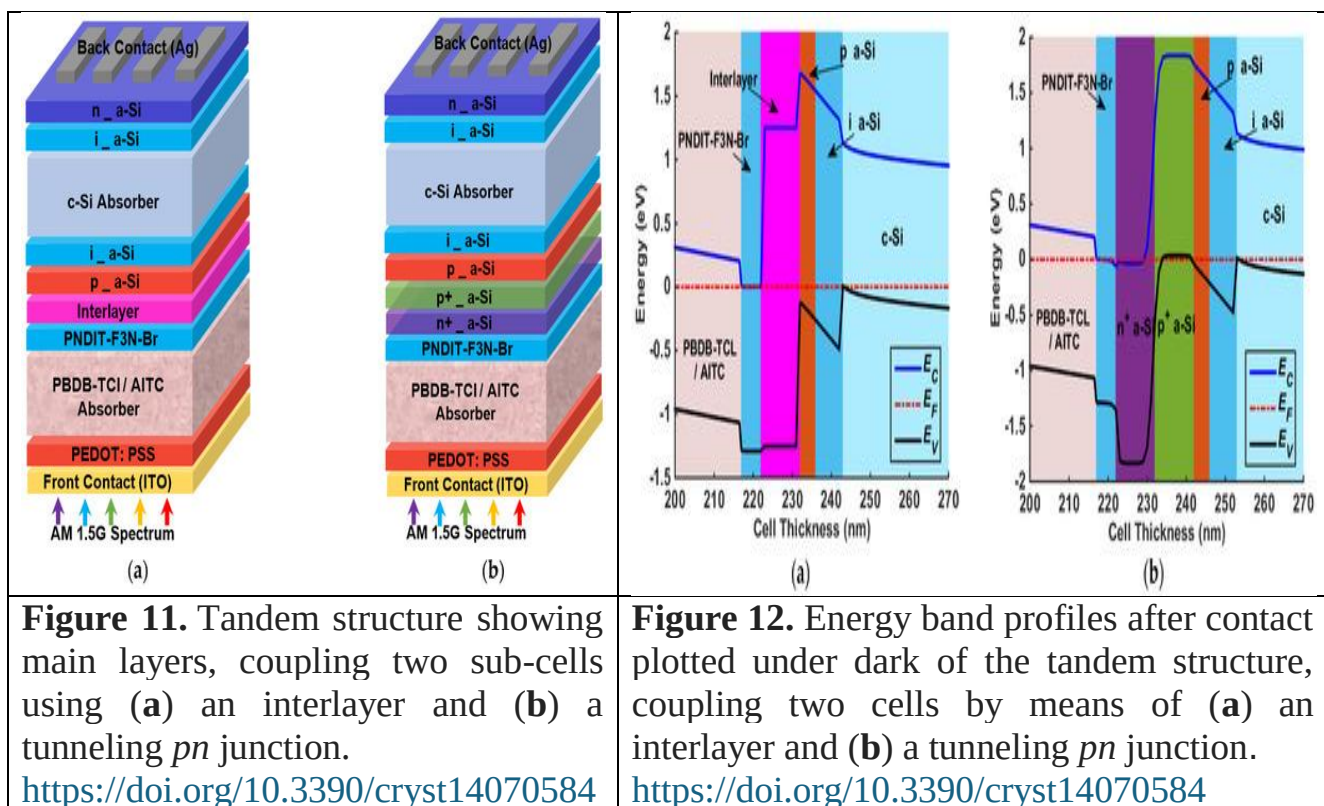


Figure 10. Approximate energy band diagram of the organic/a-Si hybrid tandem solar cell. The work function of the ITO layer was measured by SKPM(Scanning Kelvin Probe Microscopy). DOI: [10.1039/c4ta02690j](https://doi.org/10.1039/c4ta02690j)

Two sub-cells

The proposed structure of the organic/Si tandem is illustrated in **Figure 11**. The designed structure integrates a wide bandgap organic front cell with a narrow bandgap Si rear cell. In this tandem configuration, the constituting cells are interconnected via an interlayer (**Figure 11a**) or through a tunnel *pn* junction (**Figure 11b**). We investigated both interconnection techniques to demonstrate the difference between them. **Figure 12a,b** demonstrate the energy band profiles plotted at dark when coupling both top and bottom cells using an interlayer and a tunnel junction, respectively.



Besides, **Figure 13** displays the simulation results for the J - V curves (**Figure 13a**) of the top, rear, and tandem cells and their EQE curves (**Figure 13b**), while **Table 2** addresses all cell parameters. The tandem cell factors, in this case, are as follows: $J_{SC} = 14.2 \text{ mA/cm}^2$, $V_{OC} = 1.81 \text{ V}$, $FF = 77.54\%$, and $PCE = 20.03\%$.

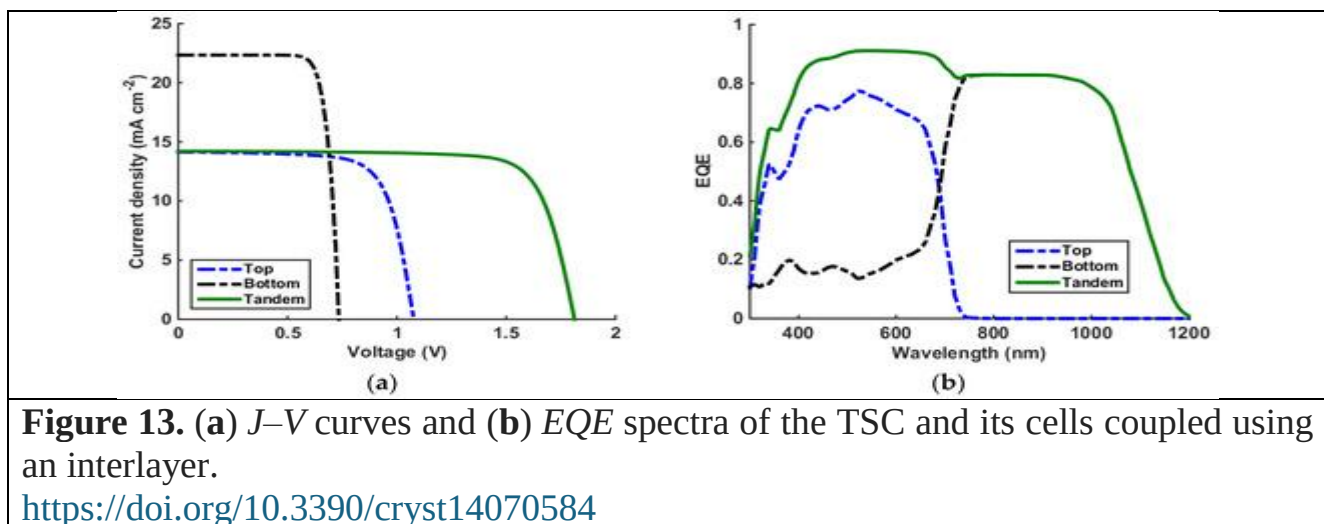


Table 2. Cell parameters of simulated organic/Si tandem cells with distinctive coupling methods. <https://doi.org/10.3390/cryst14070584>

PV Parameters		J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	PCE (%)
Interlayer	Top sub-cell	14.15	1.08	72.26	11.01
	Bottom sub-cell	22.34	0.73	80.48	13.20
	Tandem cell	14.22	1.81	77.75	20.03
Tunnel junction	Top sub-cell	14.32	1.08	72.23	11.14
	Bottom sub-cell	23.51	0.74	80.37	13.93
	Tandem cell	14.13	1.84	77.95	20.20

Record:

The record perovskite–Si tandem (~34.8%) hints at potential(Figure 14), but OSC–Si tandems have yet to be realized.

Fabrication and Processing

OSCs benefit from versatile manufacturing. **Solution processing** (e.g. spin-coating, blade or slot-die coating, inkjet printing) is common for polymer-based OSCs, enabling roll-to-roll production of flexible modules. In these methods, a donor/acceptor blend in solvent is coated onto the substrate; solvent choice and drying conditions are critical for optimal phase separation and crystallinity[10]. Alternatively, **vacuum thermal evaporation** is used for small-molecule OSCs: the material is heated in vacuum and condenses as a thin film on the substrate[18]. Heliatek’s devices, for example, use vacuum-deposited oligomer layers (~5 nm each) to form thin, uniform stacks with high reproducibility[19].

Common steps include deposition of an electron- or hole-blocking interlayer (to improve V_{oc}) and post-deposition annealing. Encapsulation is vital, since organic materials are sensitive to oxygen and moisture. In manufacturing, companies like Heliatek have developed pilot roll-to-roll lines: their first production line (launched 2012) started delivering organic solar films to industry partners[20]. Roll-to-roll printing promises low-cost, large-area OSC production, particularly for lightweight or semi-transparent applications (e.g. building-integrated PV)[20][11].

OSCs are fabricated in various structures to improve power conversion efficiency (PCE), as shown in Figure 14.

- **Single Active Layer (Figure 14A):** One active layer sandwiched between anode (on substrate) and cathode. Process: Deposit active layer on anode/substrate, then add cathode. Suffers from low PCE due to inefficient exciton dissociation.

- **Bilayer Heterojunction (Figure 14B):** Donor and acceptor layers stacked between anode (on substrate) and cathode. Process: Sequentially deposit donor on anode, then acceptor, and cathode. Improves exciton dissociation at interface but limited by short diffusion lengths, requiring ultrathin films.
- **Bulk Heterojunction (Figure 14C):** Blended donor-acceptor mix as active layer between anode (on substrate) and cathode. Process: Mix donor (e.g., P3HT) and acceptor (e.g., PCBM) materials, deposit blend on anode, then add cathode. Enhances interface area for better exciton diffusion and dissociation, achieving up to 18% PCE.
- **Tandem Heterojunction (Figure 14D):** Two sub-cells with complementary absorption spectra, separated by an interlayer, between anode (on substrate) and cathode. Process: Deposit first active layer on anode, add interlayer, deposit second active layer, then cathode. Aligns quasi-Fermi levels; enables broad-spectrum absorption via simple, low-cost manufacturing without lattice matching.

General heterojunction fabrication involves: (i) photon absorption generating excitons, (ii) exciton diffusion to interface, (iii) dissociation into free carriers, (iv) carrier transport/collection at electrodes.

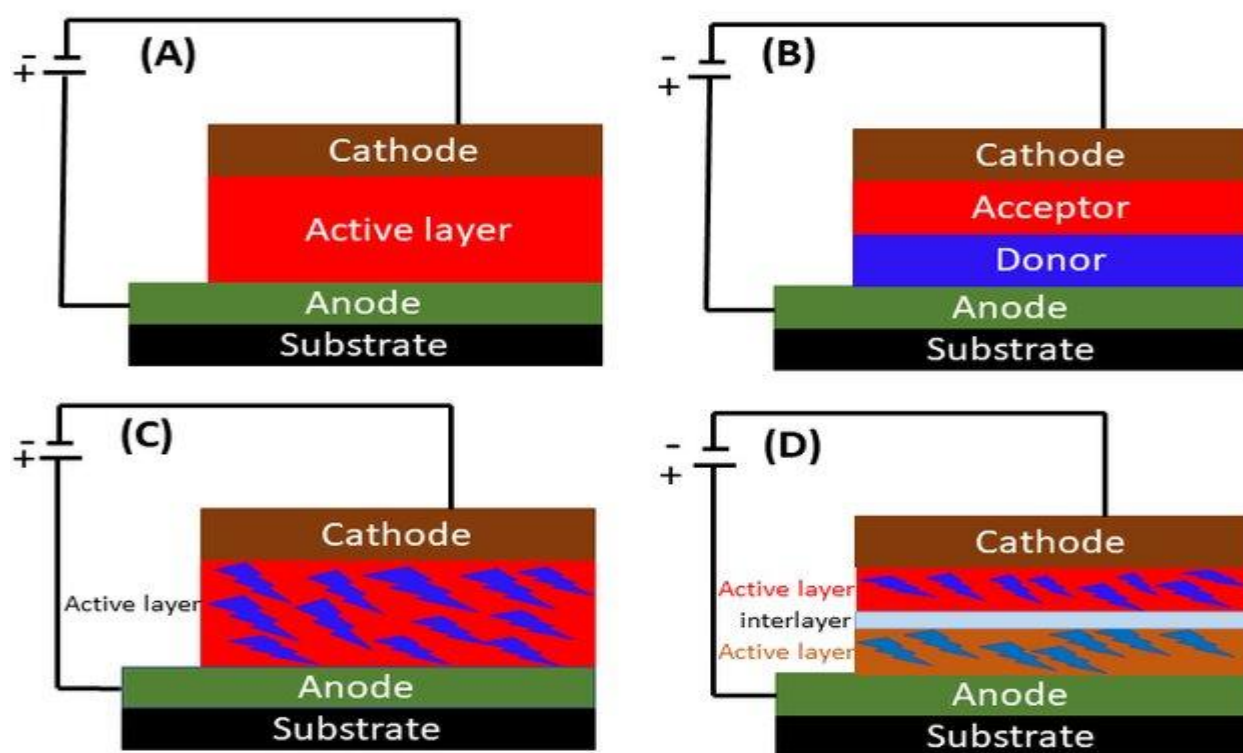


Figure 14. The fabrication of OSC: (A) single active layer, (B) bilayer heterojunction, (C) bulk heterojunction, (D) tandem heterojunction.
<https://doi.org/10.3390/app13042051>

I–V Characteristics and Efficiency

The current–voltage (J–V) curve under illumination determines OSC performance. Key parameters are the short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), and fill factor (FF).

The **power conversion efficiency** (PCE) is given by

$$\eta = \frac{V_{OC} \times J_{SC} \times FF}{P_{in}},$$

where P_{in} is the incident light power[14]. In practice, V_{OC} corresponds to the J–V curve’s x-intercept (voltage at zero current) and J_{SC} is the y-intercept (current at zero voltage)[12].

The **fill factor** (FF) measures the “squareness” of the curve and equals the ratio of the maximum power rectangle to the $V_{OC} \cdot J_{SC}$ area[15]. OSCs historically suffered from lower FF (often <70%), but values >75% have been achieved with inverted structures[16].

Experimentally, J–V curves are measured under standard test conditions (AM1.5G spectrum, 100 mW/cm²)(Figure 15). An OSC’s **external quantum efficiency** (EQE) is also used, giving the wavelength-dependent photocurrent yield. Combined, these metrics quantify performance[3][13]. Notably, researchers have reported OSCs with *certified* efficiencies above 19%: for example, Chen *et al.* (2025) achieved 20.82% in a single-junction OSC[4], while Sun *et al.* (2025) reached 19.96% using a new low-cost polymer[6].

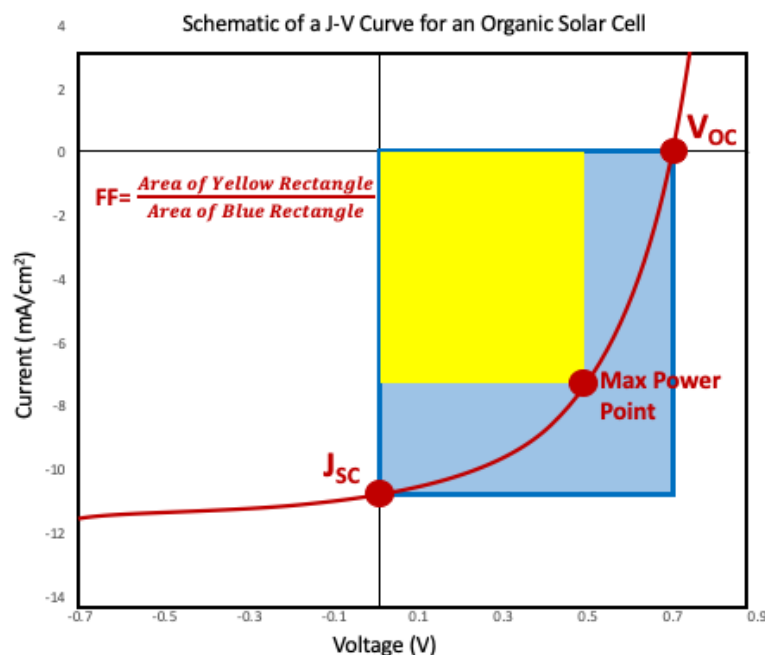
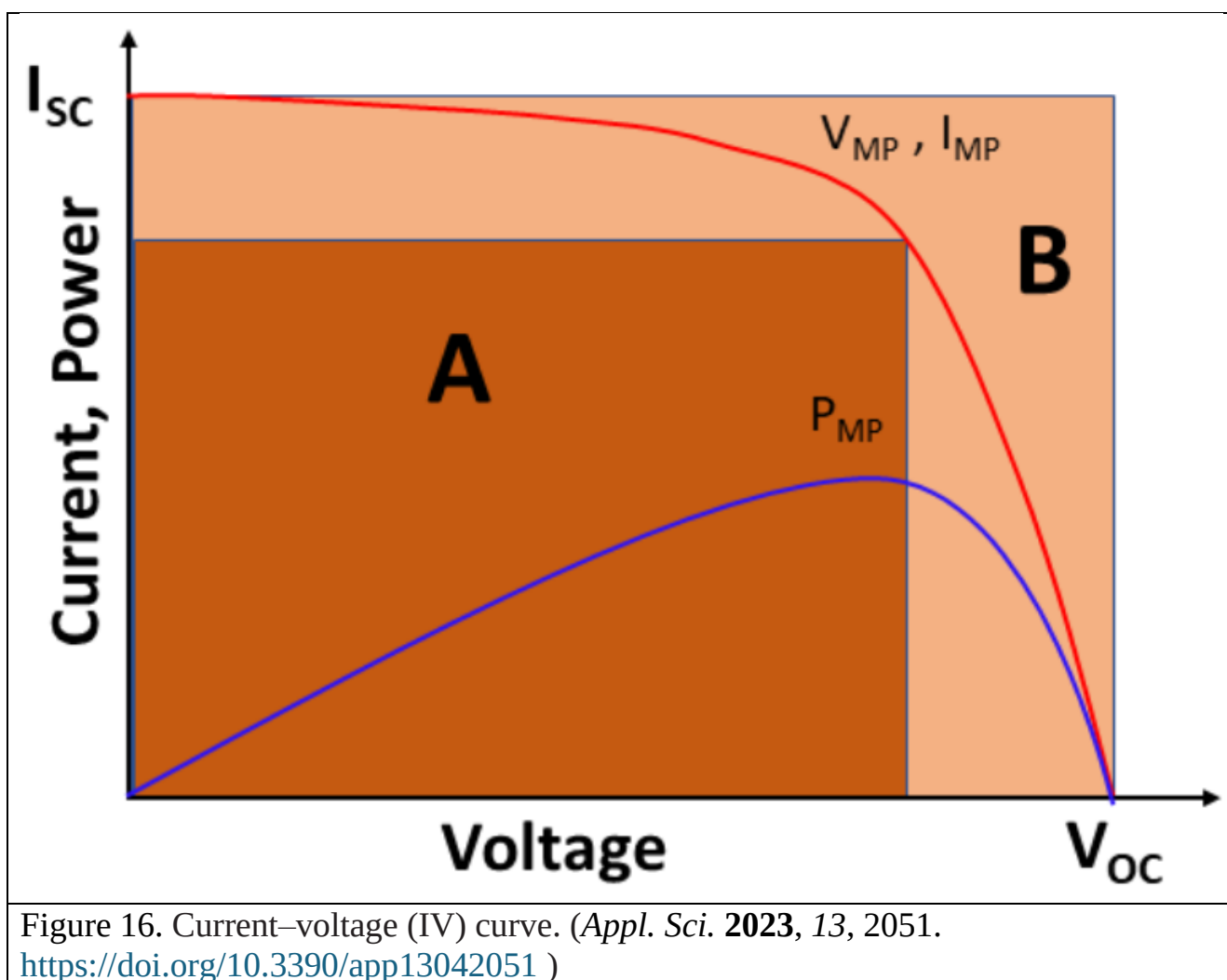


Figure 15: Typical J–V (current–voltage) characteristic of an OSC. J_{SC} and V_{OC} are indicated on the axes, and the yellow rectangle illustrates how FF is computed as the ratio of areas[14][15].

Efficiency Calculations and Comparison

The important electrical characteristics of OSC that are correlated to its performance are the open-circuit voltage, short-circuit current, maximum power point, fill factor, power conversion efficiency, and quantum efficiency. The expected values and interdependence of these parameters are demonstrated on a classical current–voltage (I–V) curve (Figure 16) The PCE calculation $\eta = (V_{OC} \cdot J_{SC} \cdot FF) / P_{in}$ [14] applies to OSCs as with any PV. For example, if $V_{OC}=0.9$ V, $J_{SC}=20$ mA/cm², $FF=0.70$, then $\eta \approx 12.6\%$ (under 100 mW/cm²). Typical state-of-art values (as of 2025) are $V_{OC} \sim 0.8$ – 1.0 V, $J_{SC} \sim 15$ – 25 mA/cm², and $FF \sim 0.75$ – 0.80 in champion cells[15][17]. Device **series** and **shunt resistances** also affect the I–V shape: poor film quality or interfaces can reduce FF and thus efficiency.

Performance comparisons must distinguish lab-scale devices vs larger modules/prototypes. While lab cells have hit $\sim 20\%$ PCE, commercial OSC modules have lagged: early prototypes (e.g. Konarka) were ~ 3 – 5% efficient and short-lived[21]. Heliatek’s lab cells of 12% have translated into ~ 7 – 10% module efficiencies in roll-coated films[20][22]. In general, commercial OSCs target niche markets (wearables, building elements) where flexibility and low light operation matter more than record efficiency. Both lab and pilot-scale results are quoted in the table above for context.



Recent Advances and Applications

The theoretical efficiency limit (Shockley–Queisser) for a ~ 1.5 eV bandgap OSC is $\sim 30\%$, but practical goals are lower. Researchers focus on widening absorption (e.g. using tandem or ternary blends) and reducing non-radiative losses. Novel non-fullerene acceptors and additive-engineered morphologies have doubled efficiencies in some systems[10]. For example, Chen *et al.* (Nat. Mater. 2025) used an organic crystallization regulator to achieve 20.82% PCE across 100–400 nm film thicknesses[4].

OSCs suit applications where lightweight, transparency or mechanical flexibility are needed. Their low-temperature processing enables incorporation on plastics and textiles[11]. Due to lower cost of materials, a PCE of $\sim 10\text{--}15\%$ is considered commercially viable for OSCs[23]. With ongoing improvements in stability (e.g. better encapsulation and materials), OSCs are moving from lab curiosities toward real products (e.g. solar charging wallpapers, integrated PV facade panels) [20][23].

Key Takeaways

- OSCs use organic donor–acceptor semiconductors; the first bilayer device (Tang 1987) had ~1% efficiency[1].
- Modern OSCs employ bulk heterojunction blends and advanced materials, now achieving >20% PCE[4][6].
- Efficiency is determined by the J–V curve: $\eta = (V_{OC} \cdot J_{SC} \cdot FF) / P_{in}$ [14], as illustrated above.
- Table (above) compares record OSCs by year, showing rapid efficiency gains.
- OSCs can form tandem cells with other PVs (perovskite, silicon) to boost overall output[8][11].
- Fabrication methods include solution printing and vacuum deposition; companies like Heliatek have demonstrated roll-to-roll manufactured OSC films[19][20].

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Chapter VIII

8. TRANSPARENT SOLAR CELLS

Introduction

Solar photovoltaic (PV) technology has evolved through several generations, each improving efficiency and broadening applications. **First-generation** solar cells were based on single-junction crystalline silicon (c-Si) wafers – a mature technology that dominates today’s market due to silicon’s abundance and well-understood manufacturing processes. **Second-generation** PV introduced thin-film materials (like amorphous silicon, CdTe, CIGS), which reduced material usage and enabled flexible form factors. **Third-generation** solar cells saw the rise of multijunction devices, where multiple semiconductor layers with different bandgaps are stacked to capture a broader solar spectrum. By using tandem junctions (e.g. GaInP/GaAs/Ge in space solar cells), these devices achieved record efficiencies around 47% under concentrated light[1][2]. The progression toward multi-bandgap absorption demonstrated that dividing the spectrum among specialized layers greatly boosts efficiency beyond the single-junction Shockley–Queisser limit (~33% for one bandgap). This historical pursuit of efficiency set the stage for **transparent solar technologies** as an innovative offshoot of third- and fourth-generation concepts.

Transparent solar cells (TSCs) represent a new frontier where the emphasis shifts from maximizing opaque efficiency to balancing energy conversion with optical transparency. The motivation for transparent PV emerged from the need to integrate solar generation into surfaces that must remain see-through – notably windows, glass facades, vehicle windshields, and electronic displays. Traditional solar panels are opaque and require dedicated installation area (rooftops or open fields), which limits their adoption in densely built environments. Researchers realized that if PV devices could be made *transparent*, essentially turning any sheet of glass into a power-generating surface, it would unlock vast areas (building windows, greenhouse roofs, automobile glass, device screens) for energy harvesting[2]. In the United States alone, an estimated 5–7 billion square meters of glass surface are available; covering a fraction of this with transparent solar coatings could supply a significant portion of national electricity demand[2]. Thus, the development of transparent solar cells is both a technological challenge and an opportunity to seamlessly embed clean energy generation into everyday surfaces without altering their primary function (providing visibility and light).

Historical Development

The concept of solar transparency builds on earlier advances. Dye-sensitized solar cells (DSSCs) introduced in the 1990s by O’Regan and Grätzel offered a semi-transparent, colorful PV option, albeit with moderate efficiency. Later, organic and

hybrid perovskite solar cells (often termed **fourth-generation** PV) demonstrated that extremely thin active layers could be partly transparent. Researchers at MIT and Michigan State University (MSU) in the 2010s took these ideas further by developing solar cells that selectively absorb ultraviolet (UV) and infrared (IR) photons while transmitting the visible portion of light, rendering the device nearly invisible to the human eye[4]. This approach was fundamentally different from earlier “see-through” PV attempts where crystalline silicon cells were merely spaced apart or thinned down to let light through – those methods inherently traded away active area (and efficiency) for transparency[4]. The new generation of transparent solar cells instead uses novel materials and designs to harvest *only* the non-visible parts of the spectrum, preserving transparency without sacrificing all photogeneration. In essence, it is an evolution from the multijunction strategy: rather than stacking cells to absorb *more* of the spectrum (for higher efficiency), transparent PV technologies selectively absorb *less* of the spectrum (the invisible parts) to allow visible light to pass. Both strategies divide the solar spectrum among specialized absorbers; in transparent cells the “visible” band is relinquished to maintain see-through clarity.

Working Principles of Transparent Solar Cells

The researchers have developed the transparent luminescent solar concentrator (TLSC) to achieve the transparent behavior of the cell rather than trying to develop the challenging transparent PV glass cell [4]. Transparent solar panels use transparent luminescent solar concentrators as glass, which is transparent in nature. It uses organic molecules to absorb invisible spectrum of sunlight. So, these organic molecules absorb the specific IR and UV light. The electrons of molecules are excited by the energy of radiation and jump to a higher-level orbit. When they settle at ground state, the energy is released in the form of IR radiation (luminescent or glowing) of the different non-visible spectrum. This emitted IR light is guided through the edge of the plastic, where the strips of traditional solar cells convert it into electrical energy. This technology is feasible on cars windows, buildings, mobile phones, and other devices with a transparent surface. The limiting factor of this technology for commercialization is its low efficiency of about 1%.

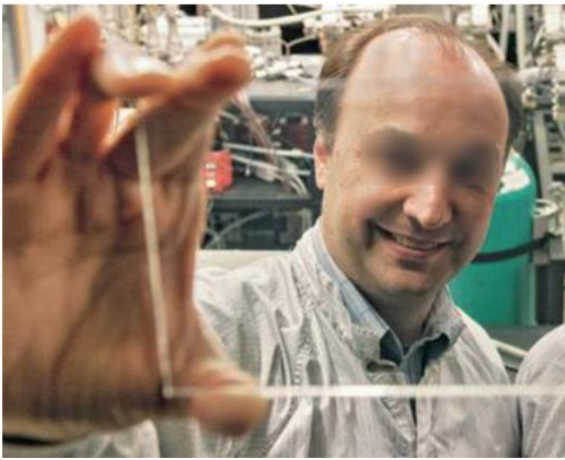


Figure 1. Transparent Solar PV Panels. DOI:
<http://dx.doi.org/10.5772/intechopen.110062>

The organic salts absorb IR and UV light and emit IR in case processes occur outside the visible spectrum. Thus it appears transparent. TLSC is composed of organic salts that absorb specific UV and IR light, which then luminesce (glow) as another invisible wavelength. This wavelength is then guided to the edge of the window-thin PV solar cell strips that convert it into electricity. The mass production of such transparent solar panels can give an efficiency of about 10%. This can help to generate power through every window of home or office buildings and may bring a transformative result [4].

Transparent solar panels are categorized into (i) partially transparent solar panels: Heliateg GmbH, a German manufacturer has developed this technology that can absorb 60% of the sunlight it receives. They have achieved an energy conversion efficiency of about 7.2%. However, the generation of solar power can be increased by adjusting the transmitted and absorbed sunlight, for example, south-facing glass buildings can reduce the transmitted light. (ii) fully transparent solar panels: The researchers at MSU, USA have achieved fully transparent PV glass panels that resemble regular glass. They have achieved energy conversion efficiency of about 10%. Bigger or more windows can generate more solar power [4].

Currently, researchers at Michigan State University and MIT as well as manufacturers such as Brite solar, Physee, and Ubiquitous energy are pioneers in transparent solar panel technology as shown in Figure 1. Ubiquitous energy has achieved energy conversion efficiency of 9.8% and working toward developing net-zero energy buildings [4].

By definition, a **transparent solar cell** must generate electricity from sunlight *without* significantly impeding the transmission of visible light. This requirement imposes a fundamental challenge: conventional solar cells work by absorbing photons to create electron-hole pairs, so a transparent cell must either forego absorbing the

visible photons or find a way to absorb and re-radiate light in a non-visible form. There are two primary strategies to achieve transparency:

- Transparent solar panels don't absorb all visible light like traditional solar panels. Instead, they selectively absorb ultraviolet (UV) and infrared (IR) light, which are invisible to the human eye, and convert them into electricity. Sunlight can pass through the medium in transparent solar glass and it defeats the conversion purpose. But in transparent solar panels, the absorption happens in a different way. The cell selectively harnesses a portion of the sunlight that is invisible to naked eye and allows the visible light to pass through the device. The visible light is allowed to pass through, making the panel appear transparent.
- **Luminescent Down-Conversion (or Re-Emission):** In this approach, incoming visible light is not directly absorbed for charge generation. Instead, a transparent medium (often a polymer or glass) is doped with luminescent centers (organic dyes, quantum dots, etc.) that absorb UV or high-energy visible light and re-emit it at a longer wavelength (typically in the infrared). The re-emitted light is guided by internal reflection to the edges of the device, where it is collected by photovoltaic strips (which can be traditional solar cells hidden in the window frame). This is the principle of the **transparent luminescent solar concentrator (TLSC)** [1]. Essentially, the window itself acts as a light-harvesting waveguide: it remains largely transparent because the luminescent process involves mostly non-visible wavelengths. The visible photons either pass straight through or are re-emitted still as visible light in some designs, maintaining a clear view. The trade-off here is that not all absorbed energy reaches the edge solar cells (some is lost in re-emission and waveguide inefficiencies), and the overall efficiency can be modest. Early TLSC prototypes achieved only around 1% efficiency with ~86% transparency[1]. However, because the approach is very compatible with large-area windows and can use inexpensive organic salts or dyes, it holds promise for low-cost power generation over huge surfaces. Researchers note that by tuning the luminophores and improving waveguiding, TLSC efficiencies up to ~10% might be achievable in mass production[1], which would be transformative given the expanses of glass in modern cities.

No matter the strategy, all transparent solar cells must incorporate **transparent electrodes** as well. A conventional silicon cell uses an opaque metal grid on the front; in a transparent device, both the front and back contacts should ideally be transparent conductors (like indium tin oxide or graphene-based layers)[4]. This allows light to enter and exit with minimal obstruction. In some designs, one electrode can be opaque if it's at the very edge or patterned in a way that minimally impacts the view (for instance, a narrow busbar around the window perimeter). A fully transparent cell,

however, often employs transparent conductive oxides or ultra-thin metal films as electrodes.

Another important metric is the **Average Visible Transmittance (AVT)**, which quantifies what percentage of visible light a device lets through (weighted by the eye's sensitivity across wavelengths). A perfectly clear window has AVT ~100%, while a tinted window might be 50%. Transparent PV typically aims for AVT of 50% or higher. There is an inherent **efficiency-transparency trade-off**: increasing transparency (approaching a clear window) means giving up more of the solar photons that could be absorbed for energy[19]. Thus, many devices are **semi-transparent**, finding a compromise where some fraction of visible light is absorbed (or the device has visible tint) to boost efficiency. Partially transparent solar cells – where, say, 50% of light is transmitted and 50% absorbed – can achieve much higher efficiency than fully transparent ones, though they appear tinted. We will later compare specific numbers for various technologies.

To summarize the working principle: transparent solar cells exploit materials and device architectures that **harvest invisible light** (UV and IR) and convert it to electricity, while **passing visible light** with minimal attenuation. Some use direct photovoltaic conversion with special semiconductors, others use luminescent conversion and waveguides. The end result is a device that, when placed on a window or display, generates power “invisibly” in the background. In the next sections, we classify the major types of transparent solar cells and examine how each type implements these principles in practice.

Classification of Transparent Solar Cell Technologies

Multiple approaches have been developed to realize transparent or translucent solar cells. They can be classified by the active materials and mechanisms they use. The major categories include: **transparent luminescent solar concentrators (TLSC)**, **dye-sensitized solar cells (DSSC)**, **perovskite-based transparent cells**, **polymer (organic) solar cells**, **quantum-dot-based cells**, and **crystalline silicon transparent cells**. Each type has distinct working principles, advantages, and limitations, which we compare below.

Transparent Luminescent Solar Concentrators (TLSC)

TLSCs are perhaps the most intuitively “transparent” solar devices because they resemble a clear pane of glass or plastic that has been infused with light-absorbing molecules. In a TLSC, the glass itself (or a polymer layer on it) contains luminescent centers that absorb UV and/or some high-energy visible light, then re-emit the energy at longer wavelengths (typically in the infrared). The re-emitted light is guided by total internal reflection to the edges of the pane, where narrow strips of traditional PV cells (e.g. silicon or thin-film cells) are mounted to capture it[1]. The main body of the

window looks transparent because the luminophores are designed not to absorb visible light (or only a specific non-dominant color, yielding a near-neutral tint).

Examples and Performance: Early demonstrations of TLSCs were pioneered by researchers like Richard Lunt and colleagues. In 2014, a team at MSU announced a fully transparent luminescent solar concentrator that could turn ordinary glass into a power source[1]. This device achieved near-100% transparency to the human eye, as all visible light passed through, but only about 1% conversion efficiency since it was harvesting primarily UV (which is a small fraction of solar energy)[14]. Subsequent improvements have raised the efficiency modestly. For instance, a large-area TLSC window developed by Ubiquitous Energy uses organic dyes to absorb UV/IR and reported ~3–5% efficiency at around 50% transparency in recent prototypes[5]. Another company, ClearVue in Australia, uses an inorganic nanoparticles approach (and some infrared-reflective coatings) in a clear glass unit that directs IR to edge-mounted cells; their second-generation panels achieved about 30 W/m² (roughly 3% efficiency) while maintaining ~70% visible light transmission[6]. ClearVue’s latest “Solar Vision” glass targets ~5% overall efficiency with similar high transparency[6].

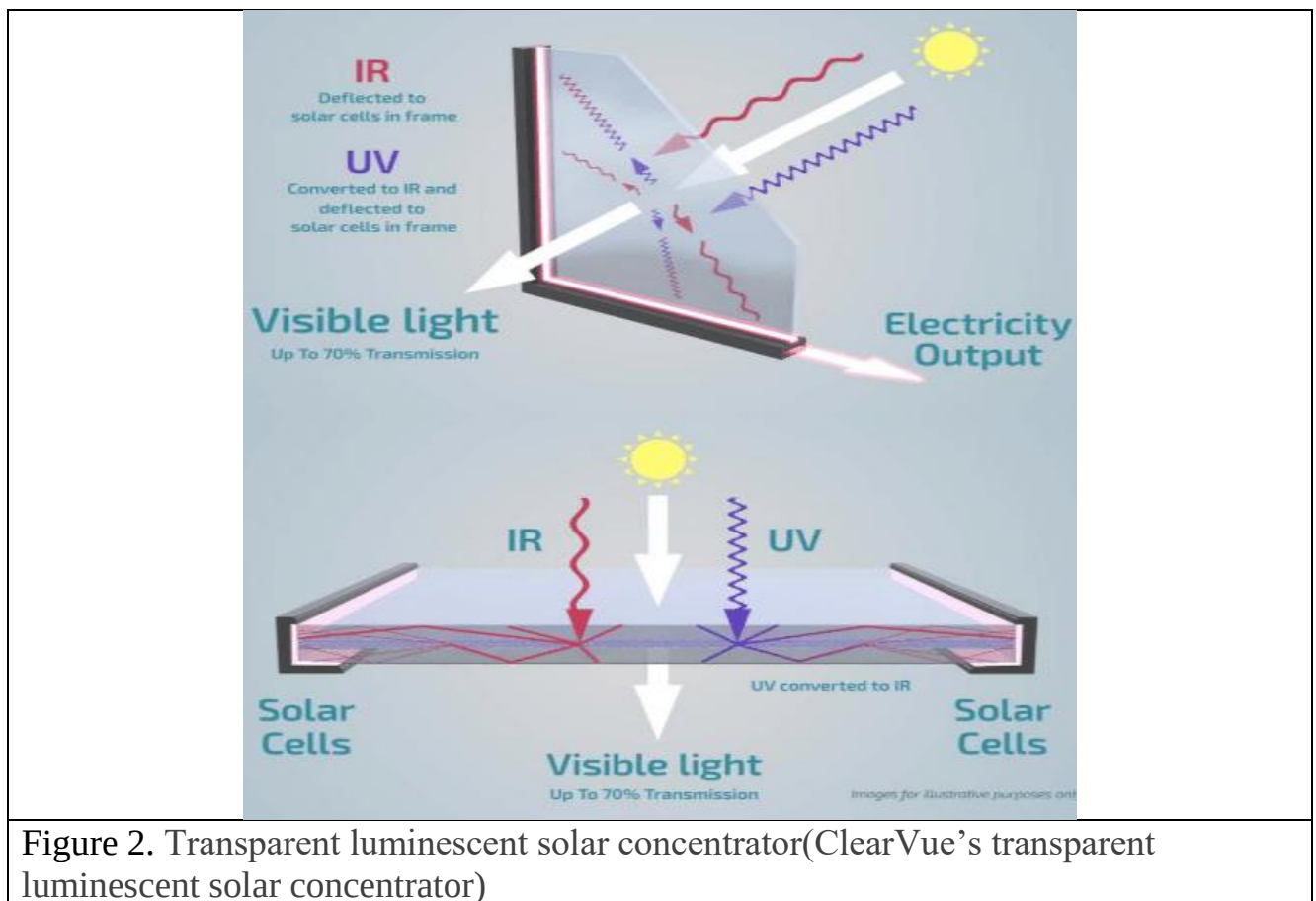


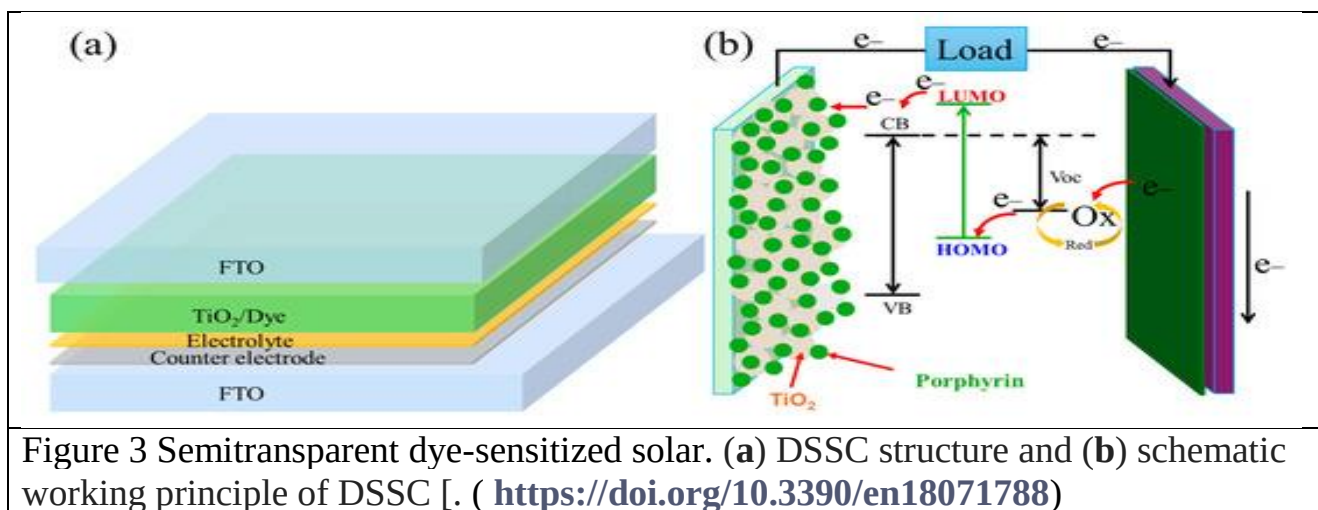
Figure 2. Transparent luminescent solar concentrator(ClearVue’s transparent luminescent solar concentrator)

One attractive aspect of TLSC(Figure 2) technology is scalability: since it primarily involves coating or embedding luminescent materials into large glass panels, it aligns well with existing glass manufacturing. It also offers flexibility in design – by adjusting the dye or QD concentrations, one can trade off transparency vs. power. **Partially transparent** implementations are possible by using a slight tint (absorbing a bit of visible light to boost energy yield). For example, Microsoft and others have tested tinted luminescent windows that double as privacy glass and power generators. However, a known limitation of TLSCs is their relatively low efficiency ceiling, imposed by the Stokes shift and re-emission losses (not all absorbed photons reach the edges) and the limited fraction of solar spectrum harnessed. The highest transparencies (80–90% AVT) inevitably yield efficiencies under 1–2%[\[1\]](#). There is ongoing research to discover new luminescent materials (e.g. phosphorescent nanocrystals or rare-earth dopants) that can capture a broader slice of the infrared while remaining visually undetectable, which could improve the performance.

Despite modest efficiencies, TLSCs hold great promise for **building-integrated photovoltaics (BIPV)** because their aesthetics are unparalleled – a building can have power-generating clear windows without looking any different from conventional glass. They can also be used in tandem: for instance, a TLSC window could concentrate light to small edge cells that are themselves high-efficiency multijunction devices, combining concentration and spectral splitting concepts. In summary, TLSCs exemplify one end of the transparent PV spectrum: maximum transparency and versatility, with efficiency currently secondary but expected to rise with material advances.

Dye-Sensitized Solar Cells (DSSC)

Dye-sensitized solar cells are a well-established third-generation PV technology that can be made semi-transparent and even colorful, making them naturally suited for certain transparent or translucent applications. A DSSC typically consists of a layer of porous titanium dioxide (TiO_2) nanoparticles coated with a light-absorbing dye, an electrolyte (or solid hole transport material), and a counter electrode. In conventional (opaque) DSSCs, a reflective backing is often used to capture transmitted light, but for transparent or bifacial DSSCs, both electrodes are transparent conductors (like fluorine-doped tin oxide glass) so that light can enter from either side[\[27\]](#).



To achieve transparency in DSSCs, several approaches are used: - Using **thin TiO₂ films** or nanostructures so that a portion of visible light is not absorbed by the dye. Essentially, limiting the dye loading can increase transparency at the cost of some absorption. Some transparent DSSCs incorporate a TiO₂ nanotube or nanowire structure that is sparse enough to allow light through between the nanostructures[28]. - Selecting **dyes that only absorb specific wavelengths**, possibly in the infrared or just a narrow band of visible (giving a colored tint). For example, dyes that absorb predominantly in the green will make the cell appear magenta (transmitting red and blue). By choosing appropriate dyes or combining multiple dyes, one can create DSSCs that appear grey or lightly tinted, balancing aesthetics and absorption. - **Transparent counter electrodes:** Replacing the usual platinum-coated glass counter electrode with a fully transparent material (like a thin carbon nanotube or graphene layer) avoids blocking light from the rear side.

Examples and Performance: Transparent and semi-transparent DSSCs have been reported with decent performance. One study reported a DSSC with ~60% light transmission and 9.2% power efficiency using a TiO₂ nanoparticle film applied by screen-printing. This result (60% AVT, 9.2% efficiency) is notable because it shows DSSC can, in principle, approach the efficiencies of traditional silicon panels while still transmitting a significant amount of light. However, that particular device likely had a noticeable tint. Another research effort used a bilayer of TiO₂ with different nanoparticle sizes to improve photocurrent while maintaining transparency, achieving around 7–8% efficiency at ~55% transparency. In practical terms, commercial DSSC-based transparent panels (often called “solar windows” or “solar glass”) have appeared with efficiencies in the 3–5% range and various tints. For example, *Exeger* and *Greatcell* (formerly *Dyesol*) have developed DSSC films for indoor light harvesting and building windows that come in different colors and transparency levels.

DSSCs perform relatively well in low-light conditions and at non-optimal angles, which is advantageous for windows that may not always face direct sun. They can also be fabricated using solution-processing (like doctor-blading or screen printing the TiO_2 and dye soaking), potentially offering lower-cost production. From an architectural standpoint, the ability to have **colored PV glass** is appealing – one could imagine stained-glass-like solar windows that generate electricity.

The challenges for DSSC in transparent mode include stability (many use liquid electrolytes which can leak or freeze, although solid-state versions exist) and achieving truly neutral color. Most DSSCs inherently tint the light because the dyes absorb in part of the visible. A completely colorless DSSC is difficult unless the dye is absorbing only UV or IR – which typically lowers efficiency significantly. Nonetheless, ongoing research into new sensitizer dyes and cobalt or iodine-free electrolytes may yield improvements.



Figure 4 Semitransparent dye-sensitized solar module for BIPV applications
University of Rome Tor Vergata

In summary, DSSCs can be made semi-transparent and are a viable transparent PV technology with moderate efficiency. They offer aesthetic versatility (various colors) and decent performance under diffuse light. Their role in transparent solar tech is often in applications where *partial* transparency is acceptable or even desired (e.g. tinted windows or decorative PV panels). As of now, they strike a middle ground:

higher efficiency than the fully transparent organic devices, but with lower transparency (usually 50–70% at best) and a visible tint.

Perovskite-Based Semi-Transparent Solar Cells

Metal-halide perovskite solar cells have garnered huge interest due to their rapid rise in efficiency (exceeding 25% opaque efficiency in lab cells) and their tunable bandgaps. Perovskite materials (typically hybrid organic-inorganic lead halides like $\text{CH}_3\text{NH}_3\text{PbI}_3$) strongly absorb visible light, but by adjusting composition or thickness, they can be made semi-transparent. The concept of a **semi-transparent perovskite solar cell** is especially powerful in tandem configurations and see-through applications.

One way to get a transparent perovskite cell is to use a **very thin perovskite layer** so that a fraction of light transmits. Another approach is to use a **wide-bandgap perovskite** (by mixing halides or using 2D perovskites) that only absorbs the UV and part of visible, letting longer visible wavelengths through. Additionally, using transparent electrodes (like ITO and ultrathin metal or conductive oxide rear contacts) avoids blocking transmitted light.

Examples and Performance: A notable demonstration in 2014 by researchers at the University of Antioquia (Spain) achieved a semi-transparent perovskite cell with 6.4% power conversion efficiency at 29% average visible transmittance (AVT), and another variant with 7.3% efficiency at 22% AVT. These devices were made by thermal evaporation of the perovskite in thin layers (<40 nm) and used an ultrathin 6 nm gold electrode (which is semi-transparent) capped with LiF to reduce reflectance. The resulting cells were like tinted glass: one had higher transparency (~29%) but lower efficiency, while the other traded some transparency for more efficiency. Later work improved on this: for instance, a semi-transparent perovskite cell with a peak transparency of 77% at near-infrared wavelengths and about 12.7% efficiency was reported. In that case, the device used a multilayer stack and an anti-reflective coating to maximize both transparency and efficiency.

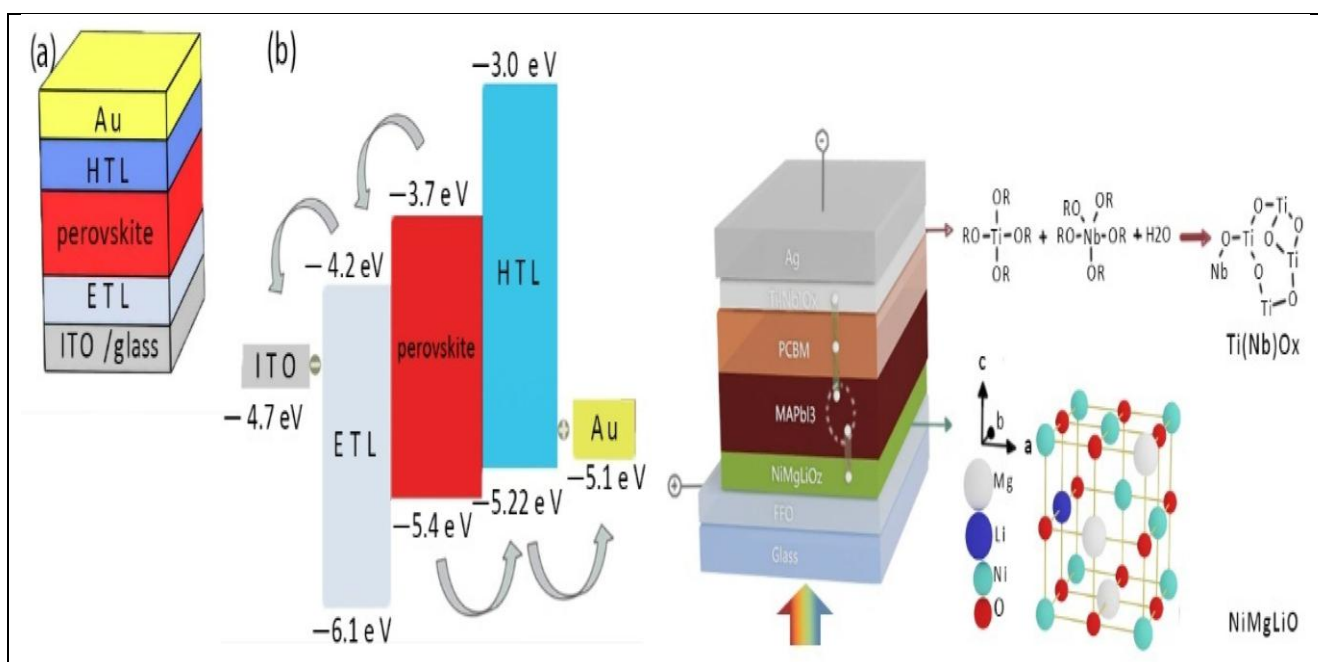


Figure 5 Perovskite-Based Semi-Transparent Solar Cells*
<https://doi.org/10.3390/jcs8110458>

Perovskite cells can also serve as the **top cell in a tandem**, where transparency is used to allow the unabsorbed light to reach a second cell behind. For example, a tandem of a semi-transparent perovskite (bandgap ~ 1.7 eV) over a silicon cell (bandgap 1.1 eV) is a very active area of research, as the perovskite can absorb the visible and some UV, while the silicon catches the red/IR that passes through. Researchers have demonstrated perovskite/silicon two-terminal tandems with the perovskite top cell having around 50% transparency in the red part of the spectrum; these tandem devices reached efficiencies well above 25%. In the context of transparent solar for windows, one could similarly combine a semi-transparent perovskite layer with another semi-transparent layer or a selectively absorbing layer to use more of the spectrum.

The advantages of perovskite transparent cells are **high potential efficiency** (thanks to perovskites' strong absorption and tuneable bandgap) and relative ease of fabrication (many are made by spin-coating or evaporation). They also can produce a neutral color transparency if designed carefully – for instance, mixing in a bit of dye or using multiple bandgaps can flatten the transmission spectrum for a more uniform tint. A key challenge, however, is stability: perovskites are sensitive to moisture and UV light, and in window applications longevity is critical. There is progress in encapsulation and in developing UV-stable perovskite compositions (e.g. adding bromide or using inorganic cations) that could improve durability. Additionally, many perovskites contain lead, raising environmental concerns for large-scale use in

consumer windows (research into lead-free perovskites or containment strategies is ongoing).

In summary, perovskite-based transparent cells stand out as a promising high-efficiency option for semi-transparent photovoltaics. They are likely to feature first not as standalone transparent windows, but in **tandem PV modules or multi-layer coatings** where one layer is semi-transparent. Nonetheless, as material stability improves, one can envision building windows with perovskite PV coatings that are lightly tinted yet generate significant power. Already, semi-transparent perovskite mini-modules have been tested in prototypes for power-generating window glass, indicating a near-future commercial potential.

Polymer and Organic Transparent Solar Cells

Organic photovoltaic (OPV) cells – which use carbon-based molecular or polymer semiconductors – can be made inherently semi-transparent because their absorbers can be extremely thin and their absorption spectrum can often be tuned. These are sometimes called **polymer solar cells** or **organic transparent PV**. Many organic semiconductors absorb primarily in specific wavelength ranges, and by selecting compounds that avoid much of the visible spectrum, researchers have created cells that are visibly transparent or tinted.

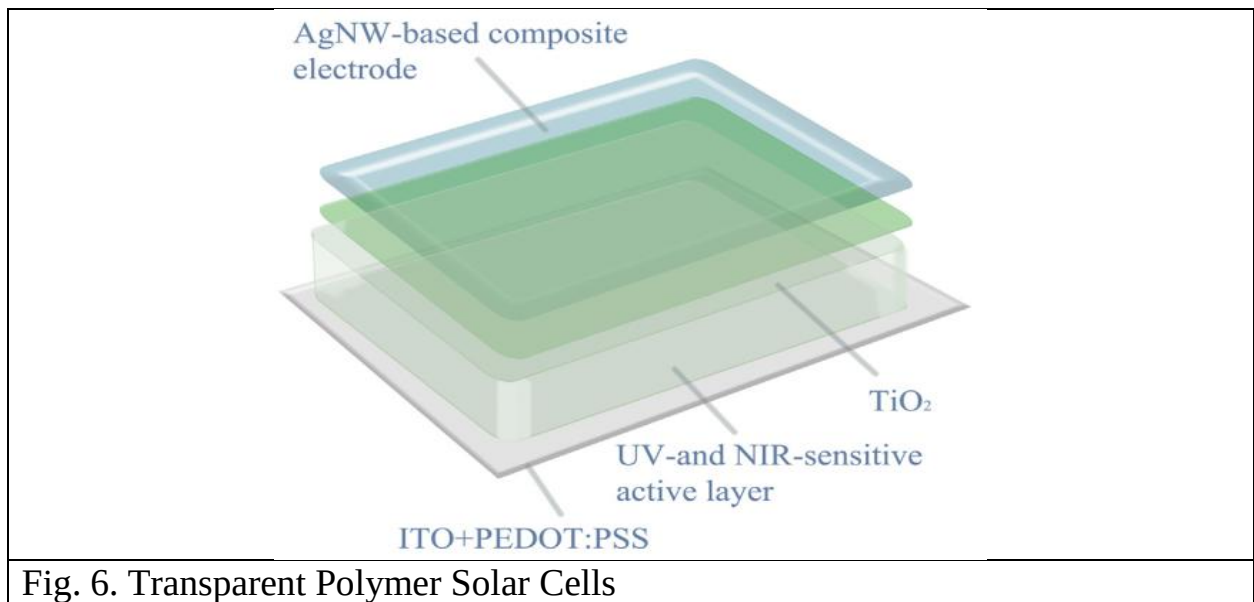


Fig. 6 shows the design of the transparent PSC. It includes 2 transparent electrodes that have active materials sandwiched between them, which are sensitive to UV and NIR light. The active material has a polymer heterojunction as an electron donor and PCBM as an electron acceptor; the combination makes PBDTT-DPP: PCBM.

Miles Barr, Vladimir Bulović and team at MIT (later co-founders of **Ubiquitous Energy**) demonstrated one of the first transparent organic solar cells that absorbed UV and IR using a pair of organic molecules (one being a donor, another an acceptor

like a fullerene), with both electrodes transparent[4]. The device had an active layer only a few tens of nanometers thick, sandwiched between transparent indium tin oxide and a transparent conductive oxide/metal thin film. This cell, as mentioned earlier, transmitted ~70% of visible light and initially had ~2% efficiency[39]. With further development, the team improved efficiency by stacking multiple cells in series (to better utilize the IR) and reached about 4–5% efficiency while still maintaining over 50% transparency[40]. By 2020, Ubiquitous Energy announced a certified world-record transparent cell efficiency of 9.8% (for a small-area cell) using their organic coating called ClearView Power™[5]. In practical terms, they anticipate their full-size production transparent windows will have 7–10% efficiency at around 50% visible transparency[5].

Other companies and labs have also achieved notable results with organic transparent PV. **Heliatek**, a German OPV manufacturer, produced partially transparent organic cells (using small-molecule oligomers) that achieved 7.2% efficiency at 40% transparency[7]. This was a record in 2014 for transparent OPV and demonstrated that even a 40% transparent film could still yield efficiencies comparable to older silicon panels (if it were fully opaque, Heliatek's cell would be ~12% efficient, but because only 60% of light is absorbed due to 40% transparency, the measured efficiency is 7.2%[7]). Those films were envisaged for car sunroofs and building glass, providing a grey-green tint. More recent polymer solar cell research, like colorful **organic stained-glass** solar panels, have shown ~5% efficiency with 50% transparency in various hues (by using different polymer:fullerene blends or non-fullerene acceptors tuned to certain wavelengths).

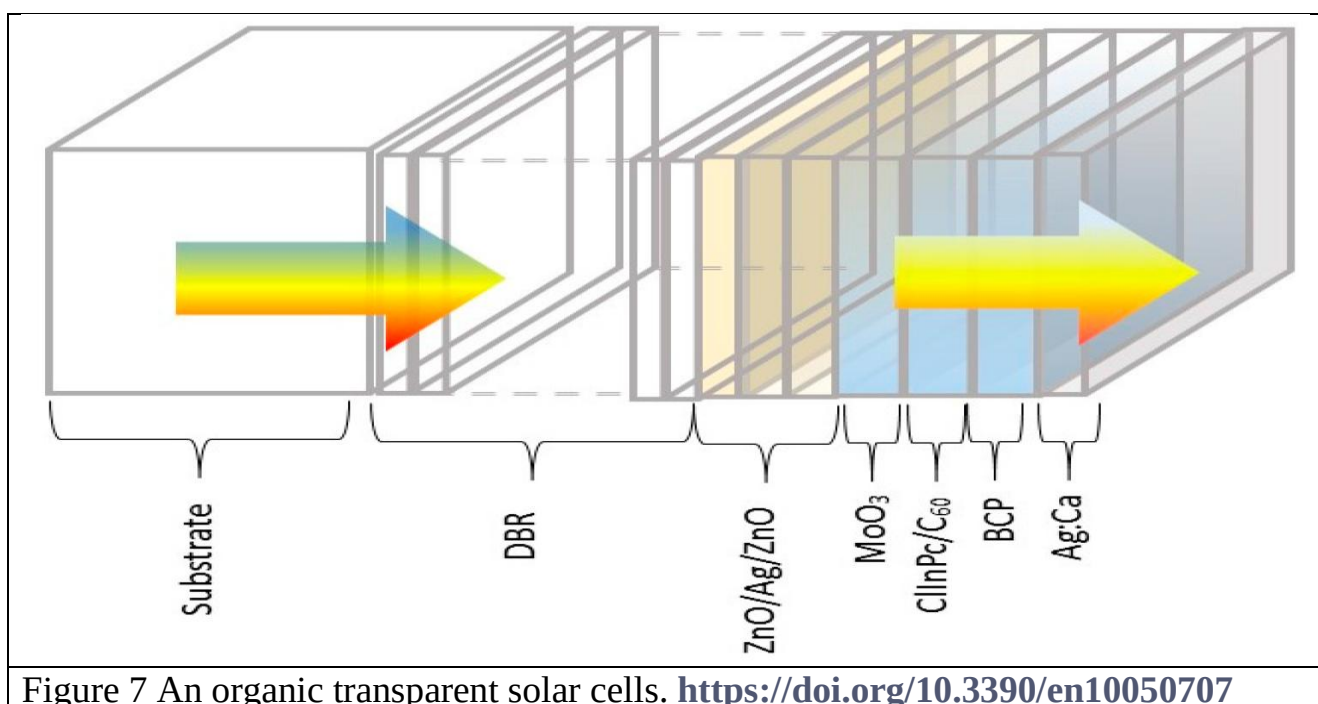


Figure 7 An organic transparent solar cells. <https://doi.org/10.3390/en10050707>

The benefits of organic transparent solar cells include mechanical flexibility (they can be made on plastic substrates for flexible or curved transparent panels), light weight, and potentially low-cost roll-to-roll manufacturing. They also tend to have a neutral appearance if designed with the right active layer – indeed, Ubiquitous Energy’s selling point is that their coating is “invisible” on glass, with no perceptible tint to the casual observer[8]. This is achieved by carefully filtering out any dye or polymer absorption in the visible range. Instead, the organic compounds harvest UV and the near-IR beyond human vision.



Figure 8 Mechanical flexibility organic transparent solar cells

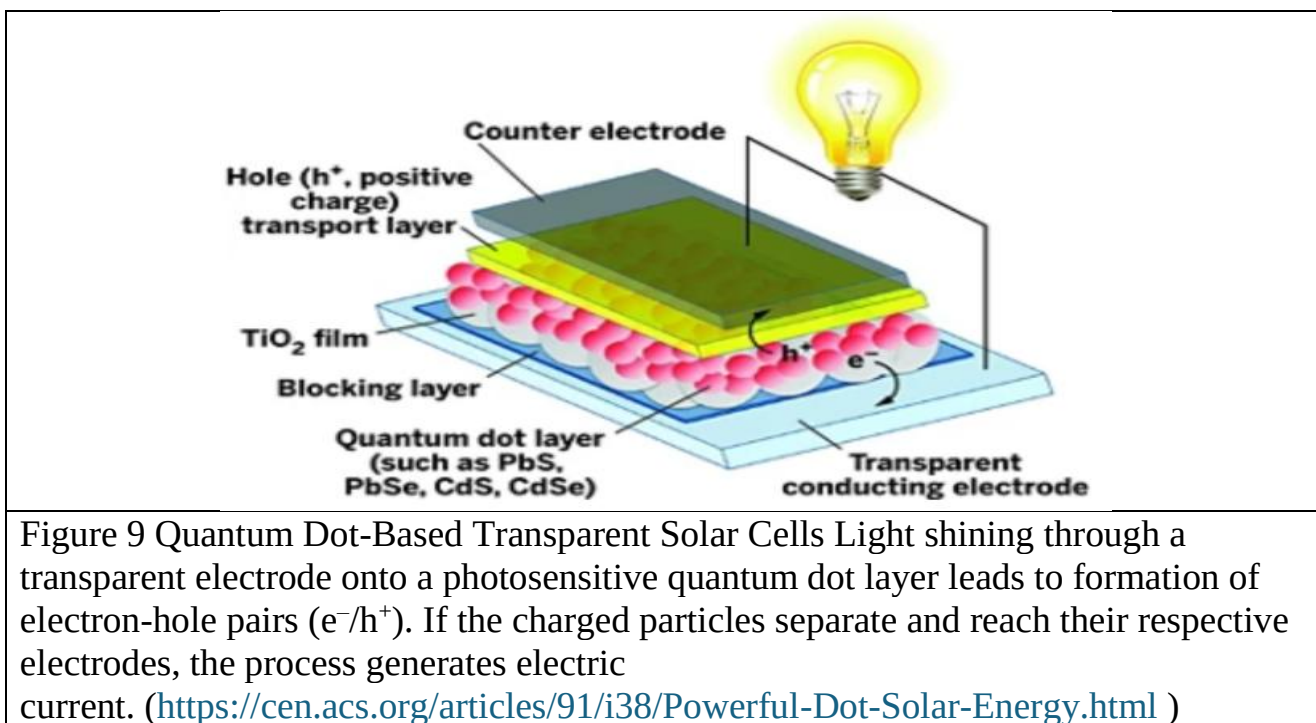
Challenges for OPV in transparent applications mirror those of other organics: **stability** (organic materials can degrade under UV exposure and oxygen/water ingress, requiring good encapsulation), and moderate efficiency. Although ~10% has been reached in lab cells, commercially one might see ~5–7% in initial products. Additionally, the transparent electrodes often rely on indium tin oxide which is brittle and expensive; alternatives like silver nanowires or conductive polymers are being explored to create fully flexible transparent OPVs. Another limitation is that organic absorbers typically have narrower spectral absorption bands, so even if two or three different absorbers are stacked, some parts of the solar spectrum might remain unused unless you sacrifice more visible light.

Overall, polymer/organic transparent solar cells are among the most mature “truly transparent” PV options. They are already being piloted in commercial settings: for example, installations of Ubiquitous Energy’s clear solar windows in commercial buildings have been reported, where tenants cannot distinguish them from normal glass yet the windows quietly generate a few watts per square meter of building-integrated power[46]. As lifetime and efficiency improve, organic transparent PV may become a standard glazing option for green architecture.

Quantum Dot-Based Transparent Solar Cells

Quantum dot (QD) solar cells use semiconductor nanocrystals as the light absorber. QDs have size-tunable bandgaps (via quantum confinement), which means one can engineer them to absorb specific portions of the spectrum. Two main approaches exist for QD-based transparent PV: **quantum dot luminescent concentrators** (a subset of TLSC where QDs serve as the luminophores), and **quantum dot heterojunction solar cells** that are made semi-transparent.

In luminescent concentrators, quantum dots (like CdSe/ZnS core-shell, or silicon QDs, etc.) can be embedded in a transparent matrix. Many QDs strongly absorb UV and blue light and re-emit at longer wavelengths (e.g. visible or IR). If one chooses QDs that re-emit in IR, the plate can remain visibly transparent. For instance, silicon quantum dots or certain carbon dots can absorb UV and emit around 800–900 nm (IR). These have been used to create LSC panes that are clear to the eye while guiding IR to the edges. A famous example is *UbiQD's "Wendow" product*, which uses fluorescent quantum dots in window glass for greenhouses and is aiming for commercialization in 2023[9]. They report that their prototypes maintain ~80% visible transparency with a subtle tint, producing a few watts per square meter.



Quantum dot solar cells (as a direct PV device) can also be semi-transparent by making the QD layer very thin. For example, a film of lead sulfide (PbS) QDs, which absorb in the visible and IR, can be tuned in thickness such that some visible light transmits. However, most QD PV research focuses on maximizing absorption for

efficiency, so fully transparent versions are less common. One interesting avenue is **colloidal quantum dot tandem cells**, where a wide-bandgap QD layer (transparent to visible, absorbing UV) is stacked with a narrow-bandgap QD layer (transparent to IR, absorbing visible). In principle, such a stack could yield a see-through device that still converts much of the UV and IR.

Examples and Performance: The literature reports some QD-based LSCs achieving high transparency and modest output. As mentioned, one review noted that a transparent luminescent solar concentrator (likely using either organic dyes or QDs) achieved 86% visible transparency but less than 1% efficiency[1]. If QDs were used, they might have been selected to avoid absorbing any visible light, hence the very high transparency. On the other hand, by accepting a bit more tint, a QD-LSC could raise efficiency: researchers have shown devices with CdSe/CdTe QDs embedded in polymer achieving ~3–4% efficiency at ~50% transparency (appearing lightly tinted)[13]. QD-based transparent PV panels have also been demonstrated in greenhouses. For example, a greenhouse using LSC panes doped with silicon QDs provided power for fans and sensors while letting most visible light through to the plants. These QD windows can even be tailored to pass the wavelengths optimal for plant growth (PAR spectrum) while using some of the rest for electricity[5][6].

The advantages of QD approaches include the **tunable absorption** (by choosing the size/type of dots) and potentially high stability for inorganic QDs (some QDs like silicon or carbon are quite robust and non-toxic, unlike organic dyes that can photobleach). Also, QDs can sometimes exhibit multi-exciton generation (one high-energy photon creating multiple electron-hole pairs) under certain conditions, which is an exotic way to boost current – though leveraging that in a transparent context is still theoretical. A challenge with QDs is that many effective QDs (Cd-based, Pb-based) are toxic or regulated substances, complicating their use in consumer windows unless sealed well. Additionally, self-absorption losses (the QD re-emission being re-absorbed by other QDs) can limit the size of LSC panels; new QD chemistries try to minimize the overlap between absorption and emission spectra to reduce this loss.

In summary, quantum dot transparent solar cells largely overlap with luminescent concentrators. They represent a materials-innovation route to transparent PV. By choosing the right nanocrystal, one can create a window that appears perhaps slightly tinted or even nearly colorless, while performing down-conversion of UV to IR for energy harvesting. As nanotechnology advances, we may see more efficient QD-based coatings that improve the power output of transparent PV windows.

Transparent Crystalline Silicon and All-Back-Contact Cells

Crystalline silicon (c-Si) is not an obvious candidate for transparency – a standard silicon wafer is opaque and absorbs most visible light. However, engineers have found ways to incorporate c-Si in partially transparent modules, and recent

breakthroughs have even demonstrated *neutral-colored, partially transparent silicon cells* with impressive efficiency. There are two main methods here: **geometric transparency** and **advanced cell design** (e.g. **all-back-contact microcell arrays**).

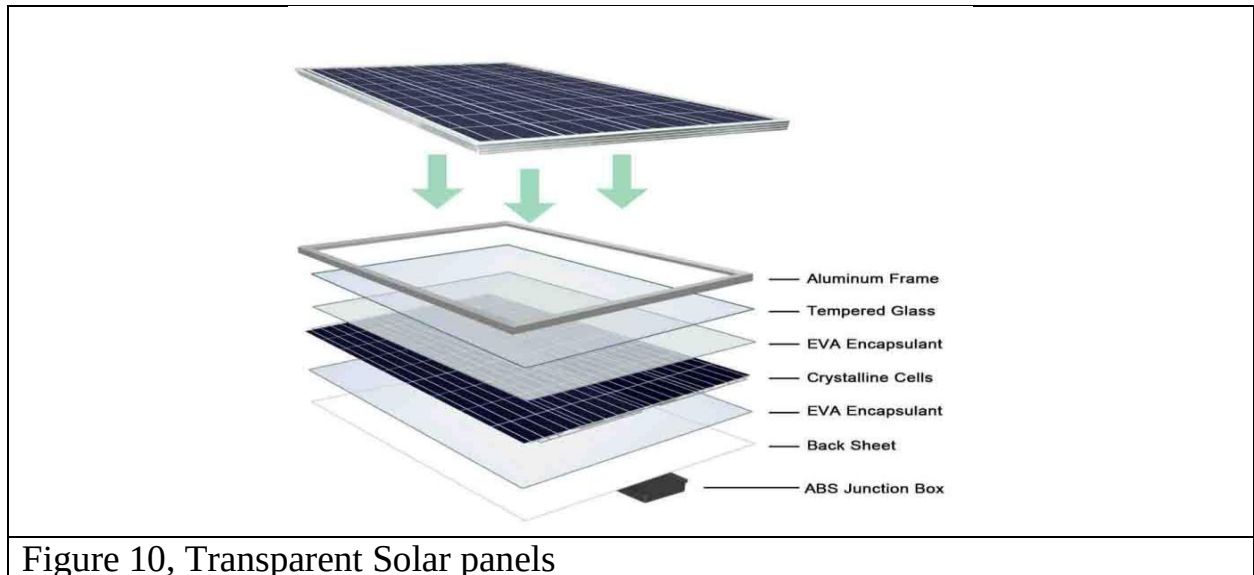


Figure 10, Transparent Solar panels

Geometric transparency involves using conventional silicon solar cells but arranging or processing them to allow light through. Examples include: - Slicing cells into very thin strips or small micro-cells and spacing them so that between the active silicon sections there are gaps where light passes. These are sometimes called “solar tiles” or “solar grids.” The overall module then looks like a mesh. Many BIPV products in the past used this approach: e.g. a façade panel with dozens of tiny monocrystalline cells laminated between glass, with spaces in between. If, say, 50% of the area is cells and 50% is empty glass, the module might have ~50% transparency. The efficiency of the module would be roughly half of an opaque module (since only half the area has active material). Indeed, one can achieve around 10% module efficiency at 50% transparency this way (if the silicon cells are 20% efficient over their area)[8]. The drawback is that such an array has a noticeable grid or stripe pattern; it’s not uniformly transparent. It can be suitable for skylights or façades where a pattern is acceptable or even aesthetically designed. - Drilling micro-holes in a thin silicon wafer in a dense pattern to let light through. Some researchers have explored perforated silicon solar cells – essentially making a sieve-like cell. The challenge is maintaining electrical continuity and avoiding too much recombination around the hole edges, but it can work to a degree. - Using ultra-thin wafers that absorb less. A standard 180 μm silicon wafer absorbs ~90% of visible light (hence is opaque), but a very thin silicon film (on the order of a few micrometers) might transmit more light. However, silicon’s absorption coefficient in visible is quite high, so even 10 μm of silicon absorbs most visible photons – thus, thickness reduction alone can’t give high transparency unless thickness is so small that efficiency plummets.

A more recent approach is the **All-Back-Contact (ABC) transparent crystalline silicon solar cell**. This cutting-edge design, reported in 2024 by a UNIST (Korea) research team, uses a crystalline silicon wafer with all metal contacts and busbars on the rear side, combined with a clever module assembly that eliminates the usual opaque inter-cell connections[10]. By putting all electrodes on the backside, the front side is just bare silicon and encapsulant – which is still not transparent by itself, but they likely use either very thin cells or some partial transparency technique in the cell. The key innovation was that the module, when assembled, appears *neutral-colored and transparent* like glass, without the grid lines or metal ribbons that typically mar BIPV aesthetics[53]. The UNIST team reported a **peak efficiency of 15.8% with an average visible transmittance of 20%** for their transparent c-Si cells[11][10]. A 16 cm² mini-module with four cells in series achieved 14.7% efficiency at the same ~20% transparency and was able to directly charge a smartphone under sunlight[56]. While 20% transparency is relatively low (the panel would look like a heavily tinted window, passing only one-fifth of ambient light), the significance is that this is done with crystalline silicon – offering stability and efficiency much higher than most other transparent technologies. Moreover, the use of all-back-contact (like interdigitated back contacts) means there are no front grid shadowing losses and the module can have a seamless appearance when tiled together[11]. The “neutral-colored” aspect suggests the cell does not strongly tint the transmitted light; presumably the silicon thin cells or perforations are arranged such that what light does pass through is spectrally balanced (perhaps using an AR coating to avoid colored reflections).

This ABC transparent c-Si approach essentially opens a new pathway: using the workhorse silicon technology but reimagined for partial transparency and high aesthetic appeal. While currently the transparency is only 20%, it’s likely enough for applications like *skylights or sections of curtain wall* where a tinted glass is acceptable. And at ~15% efficiency, such panels could deliver power densities of ~150 W/m² in full sun[11], which is about half of a conventional module’s output, but with the benefit of being see-through. The UNIST team also showed they could “tune” the output by connecting unit cells in series within the glass, reaching module voltages of 10 V from a transparent 16 cm² module[11] – indicating the concept is modular and scalable.

Aside from the UNIST design, other crystalline-based transparent products are in development. For example, some startups embed very thin silicon solar cells onto window glass in a sparse matrix. Another concept is using polysilicon or micro-crystalline transparent films (though those behave more like thin-film). **Heterojunction with intrinsic thin layer (HIT)** solar cells with transparent conductive oxide contacts on both sides can also be partially transparent if made thin enough.

In summary, crystalline silicon transparent solar cells are at the intersection of old and new: leveraging the efficiency and stability of silicon PV, but overcoming its opacity

by innovative structuring and packaging. This category currently focuses on *partially transparent* solutions (since fully transparent silicon is unachievable given silicon's bandgap covers visible light). These are ideal for applications where some tint is acceptable or structural support is needed (silicon provides mechanical strength too). The recent ABC neutral-color cell is a breakthrough example, achieving performance parity with standard panels in a see-through format[10]. We will dedicate the next section to describing this ABC technology in more detail, as it represents a state-of-the-art transparent solar cell.

All-Back-Contact (ABC) Transparent Solar Cells

One of the most exciting recent developments in transparent PV is the **all-back-contact transparent crystalline silicon solar cell**. As introduced above, this design tackles two major hurdles in making silicon transparent: the obstruction of metal contacts and the optical properties of silicon itself. By placing all electrical contacts on the rear side of the cell, the front surface looks like continuous glass with no metallization. This immediately improves the aesthetics and transparency since grid lines or busbars are removed from view[10]. However, a silicon wafer normally would still block light – so how do we get transparency? The exact details are quite technical (and proprietary to the research team's process), but the reported devices had an average visible transmittance (AVT) of 20%, meaning 1/5 of visible light passes. Likely, the silicon wafer is partially etched, thinned, or patterned with microscopic openings. The term “*neutral-colored*” suggests that the transmitted light is not strongly colored, so the cell might have a uniform distributed aperture (like many tiny window-like gaps or a very thin active layer that uniformly absorbs a certain fraction across the spectrum without spectral spikes).

The **seamless modularization** mentioned in the UNIST research is also key[11]. Typically, to connect multiple solar cells in series, you need metal interconnects (ribbons) between cells, and gaps to avoid shading neighbor cells, etc. In a transparent module, those wires and gaps would show up. The UNIST team devised a method to monolithically connect cells in series on the same glass without visible wires or spacing[11]. This likely involved laser patterning or novel busbar arrangements at the edges. The result was a “seamless” transparent solar module – effectively the entire glass looks uniform. In their demonstration, a 4-cell module output 10.0 V and 235 mW (under one-sun illumination) over 16 cm² area[11]. They even used it to charge a smartphone through its display glass, illustrating one of the envisioned use-cases: a phone or tablet screen that generates power while remaining clear[11].

From a theoretical standpoint, the ABC design maximizes what efficiency is possible for a given transparency by removing front losses and optimizing light trapping. All incident light either is absorbed in the thin silicon regions or passes through; none is blocked by contacts. Silicon's bandgap (1.12 eV) means it can absorb up to ~1100 nm (NIR), which covers the entire visible. So achieving any visible transparency means some photons that silicon *could* have absorbed are let through. The 15.8% efficiency

at 20% AVT indicates that the cell likely absorbs a good chunk of the visible (hence relatively low AVT), but effectively converts what it does absorb (since 15.8% is close to typical one-junction efficiency for a thin cell). If one tried to get, say, 50% AVT in the same approach, the efficiency might drop proportionally (maybe ~8–10%). Still, that would be quite useful for many applications.

The ABC cells require advanced fabrication: interdigitated back contacts (IBC) are already a high-end cell technology (used in premium panels like SunPower's, though those are opaque). Combining IBC with partial transparency likely involved micro-fabrication steps (like photolithography or laser ablation of tiny openings). There's also the challenge of extracting current efficiently when much of the surface is open – the current paths need to be carefully designed so that electrons generated in isolated regions can still reach the back contacts. The success of the 2024 study shows these engineering issues can be overcome, potentially opening a path to **commercial transparent silicon PV**.

In practical terms, an ABC transparent module could be used in building façades, offering a tinted-window appearance with significant power generation. Automakers could integrate them into sunroofs or side windows where a slight tint is fine. Because it's silicon, it will have long-term stability (30-year lifetimes like standard panels) and well-known environmental safety. Professor Seo's team at UNIST emphasized that this could expedite commercialization of transparent PV, as industry can leverage existing silicon production know-how[11].

It's worth noting that the term "ABC" here stands for *All-Back-Contact*, not to be confused with the ABC (Always Be Cool?) or any acronym – it specifically refers to the solar cell design. ABC is actually a common term in solar manufacturing for any cell with both contacts on the rear; the novelty here is applying it to transparency. In conclusion, ABC transparent solar cells represent a bridge between traditional solar efficiency and modern transparency needs. They are likely to be more expensive initially (due to complex fabrication), but their high performance may justify use in premium architectural projects or electronic devices. As research continues (the PNAS publication in 2024 is likely just the first step), we could see improvements that increase the AVT while retaining double-digit efficiencies[10]. A future 10% efficient, 50% transparent silicon panel would be a game-changer, and the ABC work suggests this is not a fantasy but an achievable goal with incremental innovations.



Figure 11: A small all-back-contact transparent solar cell (on top of a smartphone) developed by UNIST, South Korea. All the metallic electrodes are on the rear side, enabling a glass-like appearance. Such cells achieved ~15% efficiency with 20% visible transparency, and a module of them can directly charge electronic devices[65]. The image shows the clear solar cell module poised on a phone screen, illustrating potential integration into consumer electronics.

Integration with Tandem and Hybrid Solar Systems

Transparent solar cells are not only useful as stand-alone devices; they can also be integrated into **tandem configurations and hybrid energy systems** to maximize energy utilization. A tandem (multi-junction) solar cell typically stacks a higher-bandgap cell on top of a lower-bandgap cell so that each absorbs a different part of the spectrum. Transparent or semi-transparent cells are natural candidates for the **top cell in a tandem**, since they can absorb the short-wavelength light and allow the rest to pass through to the bottom cell.

One successful example is the perovskite/silicon tandem: a semi-transparent perovskite layer (bandgap ~1.7–1.8 eV) is placed above a silicon cell (1.12 eV). The perovskite converts the high-energy visible and UV photons, while the silicon (which is opaque) absorbs the red and IR that the perovskite lets through. Researchers Bi et al. demonstrated a two-terminal perovskite/Si tandem where the perovskite top cell had about 50% transparency in the red, resulting in an overall tandem efficiency around 29%. In that device, the perovskite itself was a thin layer with ~7% efficiency standalone (when semi-transparent), but its presence boosted the silicon cell performance by capturing photons the silicon alone cannot (blue and green wavelengths). This concept can be extended to other combinations: for instance, a semi-transparent CIGS cell over a perovskite, or a DSSC over a silicon cell.

For window and building applications, one could envision **hybrid solar windows** combining multiple layers: a transparent luminescent layer to handle UV (guiding it to edges or to a secondary cell) plus a semi-transparent thin-film cell for IR. There are designs for *photovoltaic double-glazing* where the outer pane has a transparent PV coating and the inner pane has a second PV layer, maybe capturing whatever the first missed. Because transparent cells often generate a lower voltage individually, tandem stacking can also raise the voltage into a more usable range (similar to putting cells in series).

Visual diagrams of layered structures help illustrate these integrations. For example, consider a layered stack: starting from the sun-facing side, you might have a transparent conducting oxide, then a transparent perovskite cell (absorbing UV and part of visible), then a transparent intermediate electrode, then a silicon heterojunction cell beneath. A schematic cross-section of such a tandem is shown below.

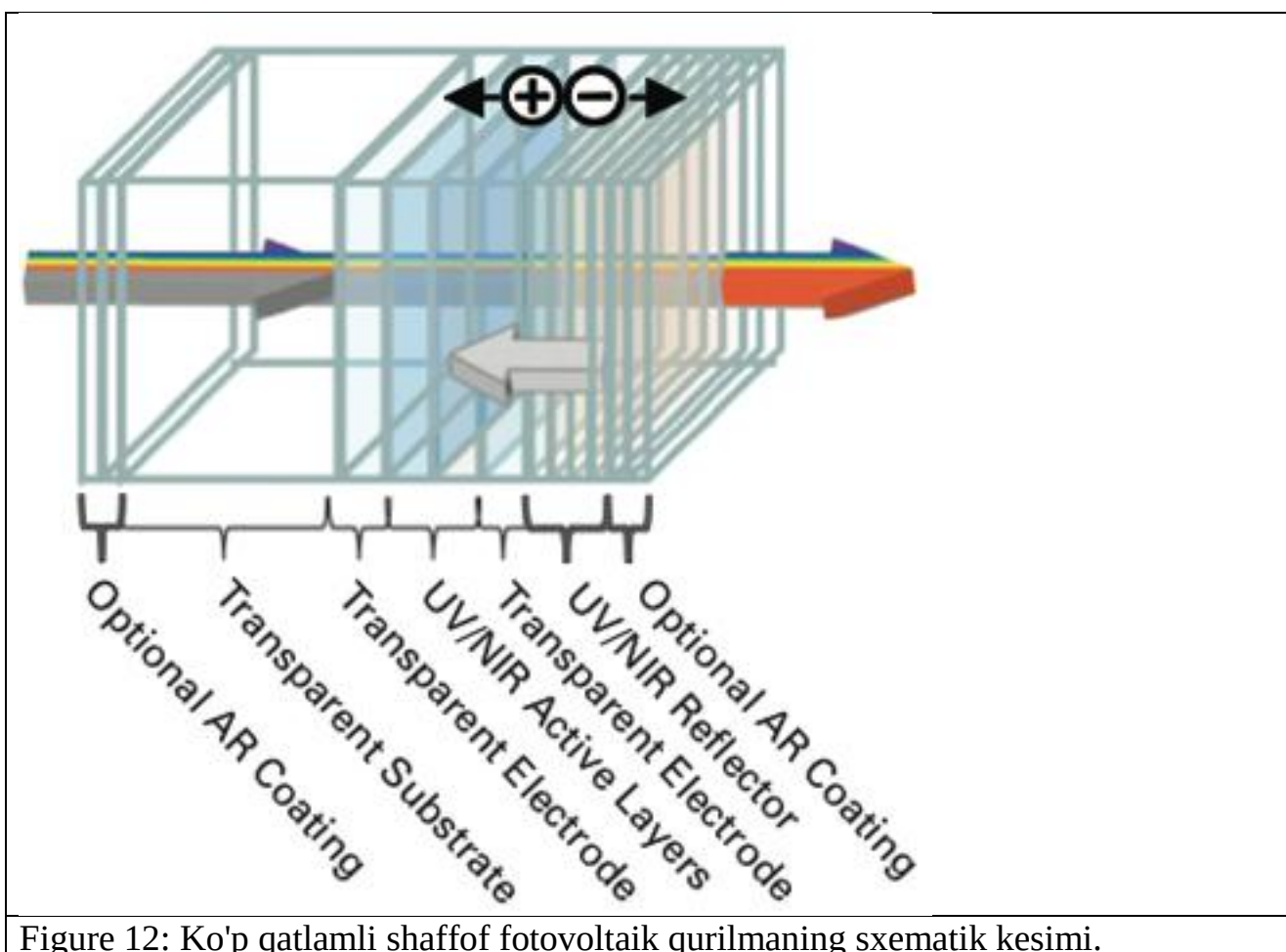


Figure 12: Ko'p qatlamli shaffof fotovoltaik qurilmaning sxematik kesimi.

The thick substrate on the left is a piece of glass (or flexible transparent substrate). On it, multiple thin-film layers form the solar cell stack. In this illustrated example, the device transmits visible light (shown by the straight arrow passing through) while capturing ultraviolet (UV) and near-infrared (NIR) light. Key

components include transparent electrodes at the front and back, UV/NIR-absorbing active layers (such as a wide-bandgap perovskite or organic semiconductor for UV, and a low-bandgap layer for NIR), and optionally a reflector for NIR on the back side to bounce unabsorbed IR photons for a second pass[9][10]. Anti-reflective (AR) coatings on the outer surfaces maximize light input by reducing glare. Such a device could function as a tandem: the top active layer might absorb UV and some visible, while a lower layer (or a separate cell behind) absorbs NIR, thereby utilizing a broad spectrum while still letting most mid-visible light through to maintain transparency.

Beyond tandems, **hybrid systems** might refer to combining transparent PV with other functionalities. For instance, integrating transparent solar cells with **electrochromic (smart window) technology** is a hot research topic. A smart window can change its tint on demand; pairing it with a transparent PV that powers the tinting circuit makes a self-powered smart solar window. Some experimental devices use perovskites that have a phase transition from transparent to colored under certain conditions, effectively acting as their own tinting mechanism while generating power (often called “solar switchable windows”).

Another hybrid concept is transparent PV plus **thermal energy harvesting**. Windows let in light which becomes heat indoors. A transparent PV could reduce that heat load by absorbing IR (thus acting somewhat like a low-E coating) and converting some of it to electricity. In a hybrid photovoltaic-thermal (PVT) window, fluid channels might even be embedded to carry away excess heat. Though complex, this could simultaneously provide electricity and improve building energy efficiency by controlling solar heat gain.

For agrivoltaics (greenhouse use), integrating transparent PV is a form of hybrid solar-agriculture system. Here the “hybrid” is not two different generators but rather combining solar power production with plant cultivation. Transparent panels (like the ClearVue glass or tinted DSSC panels) act as greenhouse roofs that generate power while selectively filtering the sunlight for crops[6]. For example, some transparent panels remove UV (which isn’t useful for plants and can be harmful) to generate power, while letting through most PAR (photosynthetically active radiation) for the plants. This dual use of land increases overall efficiency of resource use.

In summary, transparent solar technologies are very versatile in system integration. They can complement traditional solar cells in tandems, serve multi-functional roles in smart windows, and pair with other systems (like agriculture or thermal regulation) to enhance total energy utilization. As the technology matures, we expect to see creative combinations – for instance, a window that not only generates electricity, but also dynamically controls light transmission (for comfort) and even perhaps stores energy in an integrated thin-film battery. Transparent PV is inherently a **cross-disciplinary** innovation, sitting at the nexus of materials science, optics, and architectural engineering.

Efficiency and I–V Characteristics of TSCs

To analyze and compare transparent solar cells, we use the same fundamental photovoltaic equations and metrics as for conventional cells, with a few additional considerations for transparency. Key performance parameters include the open-circuit voltage (V_{OC}), short-circuit current density (J_{SC}), fill factor (FF), and power conversion efficiency (PCE). The **current–voltage (I–V) characteristics** of a solar cell under illumination are typically described by the Shockley diode equation (with photogenerated current):

$$I(V) = I_{ph} - I_0 \left[\exp \left(\frac{qV}{nkT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

Where I_{ph} is the photo-generated current (which equals I_{SC} at $V=0$), I_0 is the dark saturation current of the diode, n is the ideality factor, R_s and R_{sh} are series and shunt resistances, and other symbols have their usual meaning (q is electron charge, k Boltzmann's constant, T temperature). For an ideal cell with negligible resistive effects, the I–V curve is primarily governed by the first two terms. The **open-circuit voltage** V_{OC} occurs when $I=0$, given by:

$$V_{OC} \approx \frac{nkT}{q} \ln \left(\frac{I_{ph}}{I_0} + 1 \right)$$

In transparent cells, V_{OC} is often comparable to opaque cells made of the same material, since V_{OC} depends on the **voltage generated per absorbed photon**, not on how many photons are absorbed. For example, a DSSC or perovskite cell might have V_{OC} in the range 0.8–1.0 V whether it's transparent or opaque – transparency mostly reduces I_{ph} (the photocurrent) because fewer photons are absorbed[5]. In fact, one strategy to keep V_{OC} high in transparent designs is spectral selectivity: absorbing higher-energy photons (UV) tends to generate higher V_{OC} (since V_{OC} roughly scales with the effective bandgap or energy of absorbed photons). Thus, a transparent cell that only takes UV might have a higher bandgap absorber and potentially a higher voltage than a full-spectrum cell.

The **short-circuit current density** J_{SC} (current per area under zero voltage) will be directly proportional to how much of the solar spectrum is absorbed. A transparent cell that transmits $X\%$ of the light in the visible range effectively only absorbs $(100-X)\%$ of that portion (plus whatever it absorbs in UV/IR). One can estimate J_{SC} by integrating the product of the EQE (external quantum efficiency) with the solar spectrum over wavelength. For instance, if a cell absorbs all photons below 400 nm and above 700 nm, and nothing in between, its EQE in those regions might be, say, 80%, and zero in visible. Integrating that against the AM1.5 spectrum yields a certain J_{SC} . This J_{SC} will be much lower than an opaque cell's (~ 40 mA/cm² for silicon) – perhaps only a few mA/cm² depending on how narrow the absorption bands are. That

is why many transparent cells have lower current outputs and often need to be in series (to add voltage) for practical use.

The **fill factor (FF)** is mostly a function of device resistances and the diode quality. It's not directly related to transparency, except insofar as very low currents can make certain parasitic effects more noticeable. A well-made transparent cell can have FF similar to conventional cells (e.g. 70–80%). For example, Ubiquitous Energy's organic cells achieved a decent FF while hitting 9.8% efficiency[5], implying their diode quality and contacts were good.

The **power conversion efficiency (PCE)** is given by:

$$\text{PCE} = \frac{P_{\max}}{P_{\text{in}}} = \frac{V_{\text{OC}} \cdot I_{\text{SC}} \cdot \text{FF}}{P_{\text{in}}}$$

Where P_{in} is the incident solar power ($\sim 1000 \text{ W/m}^2$ under standard test conditions). In context of transparent cells, it's important to clarify whether PCE is reported relative to total area and total incident light. Most literature reports PCE as the fraction of *total* sunlight power converted, even if much of that sunlight is transmitted. Some have suggested defining a “visible-light power efficiency” excluding the transmitted portion, but generally we stick to the standard definition (which inherently penalizes a device for not using transmitted light). Thus, a 10%-efficient transparent cell produces 100 W/m^2 from 1000 W/m^2 sunlight, even though a large part of that 1000 W might be passing through.

Another theoretical aspect is the **balance between transparency and efficiency**. If $T(\lambda)$ is the transmission spectrum and $A(\lambda)$ the absorption (with R reflection, typically small if AR coated), then for each wavelength λ in the visible range there's a trade: increasing absorption $A(\lambda)$ will increase current but decrease transmittance at that λ . One can integrate the photopic response (the eye's sensitivity) times $T(\lambda)$ to get AVT, and similarly integrate $A(\lambda)\text{solar}(\lambda)$ to get current. *Designing a transparent cell often involves optimizing this spectral selectivity. Some papers define a figure of merit called light-utilization efficiency (LUE)* which multiplies transparency by efficiency to gauge the overall value (for building windows, both are important).* For example, a cell with 8% efficiency and 50% transparency might have an LUE comparable to one with 4% efficiency and 80% transparency. Depending on application, one might aim to maximize LUE rather than raw efficiency.

Additionally, in multi-junction or luminescent systems, the standard single-diode equation may not capture all behavior (e.g. luminescent concentrators have an optical concentration effect on the edge cells). But for simplicity, each PV junction still follows the general I–V form.

Standard equations such as the above are used to model transparent cells with appropriate modifications for the fraction of light absorbed. For practical device characterization, one often measures the *spectral transmittance* and *spectral EQE* (*quantum efficiency*) of the cell. The IV curve under illumination yields V_{OC} , I_{SC} , FF,

PCE as usual. It's also common to report the **average visible transmittance (AVT)** formally as:

$$\text{AVT (400–700 nm)} = \frac{\int_{400}^{700} \Phi_{\text{vis}}(\lambda) T(\lambda) d\lambda}{\int_{400}^{700} \Phi_{\text{vis}}(\lambda) d\lambda}$$

where $\Phi_{\text{vis}}(\lambda)$ is the luminosity function (light sensitivity of the human eye) weighting the transmittance $T(\lambda)$ across the visible band. This weighted average accounts for the fact that the human eye is more sensitive to green (~555 nm) than to red or violet. So a cell that blocks a bit of red might have a higher AVT (perceived transparency) than one that blocks the same amount of green.

In summary, the theoretical framework for TSC performance uses the same photovoltaic equations, with careful attention to the *spectral* distribution of absorption vs transmission. A transparent cell's efficiency is fundamentally limited by how much of the solar spectrum it harvests. If it only takes X% of the total photon energy, then its max efficiency is roughly X% times the Shockley–Queisser limit for that bandgap. This is why fully transparent (visible-pass) cells tend to max out around 10–15% in theory[4], whereas conventional cells can exceed 20%. Equations (1)–(3) still hold, but the values plugged in (I_{SC} , etc.) are a result of that selective absorption.

One can also mention the Shockley–Queisser limit adaptation: for a given bandgap and portion of spectrum, the limit changes. For instance, a cell only absorbing <400 nm (bandgap ~3.1 eV) has a theoretical efficiency around 5–6% under AM1.5, whereas one absorbing <700 nm (~1.8 eV) might reach ~20%. Transparent cells often effectively act like high-bandgap cells (if they avoid visible), hence lower theoretical maxima. Multi-layer transparent designs (like stacking two transparent cells for UV and IR separately) could approach the combined efficiency of those sub-bands.

To design and predict performance, researchers use the above equations along with optical models. Tools like the transfer matrix method can simulate a **transparent multilayer cell's quantum efficiency**, as recently done in studies using PVA/NaI layers and amorphous silicon to calculate how doping affects transparent cell quantum efficiency[12]. These theoretical models guide how adding transparency (e.g. by thinning a layer) will reduce current or how adding a reflector can boost a second pass.

In conclusion, transparent solar cells obey the same diode I–V relationships, but with reduced photocurrent due to intentional transparency. Equations for V_{OC} , I_{SC} , FF, and efficiency are used just as with normal cells, and the added metric AVT quantifies the transparency. These provide a framework to compare different technologies on an equal footing, and to optimize designs for the best trade-off between power output and light transmission.

Comparative Performance of Different TSC Technologies

Transparent solar technologies vary widely in their achievable efficiency and transparency. Below, we present a comparative overview in table form, summarizing typical performance metrics for the major TSC types discussed. This includes the power conversion efficiency (PCE), average visible transparency (AVT), and typical voltage/current characteristics for representative examples of each technology.

Table 1. Comparison of Transparent Solar Cell Technologies – Efficiency, Transparency, and Notable Parameters.

Technology & Example	PCE (Efficiency)	Average Visible Transmittance (AVT)	Typical V_{OC} (V)	Notes (J_{SC} density, etc.)
Transparent Luminescent Solar Concentrator (TLSC) – e.g. MSU 2014 prototype[1]	~1%	~86% (fully transparent)	– (uses edge silicon)	Absorbs UV & IR, re-emits IR to edges. Very high transparency; current collected by edge cells. Improved designs aiming for ~5–10% PCE at 50%–70% AVT[1][5].
Dye-Sensitized Solar Cell (DSSC) – lab cell with TiO_2 screen-printed[30]	9.2%	~60% (semi-transparent tinted)	~0.8 V	Uses Ru-based dye (orange tint). J_{SC} ~15–20 mA/cm ² in example. Commercial DSSC windows typically 3–5% PCE at 50% AVT with various colors. Bifacial designs can utilize light from both sides.
Perovskite Semi-Transparent Cell – Univ. Antioquia 2014[35]	6.4% – 7.3%	29% – 22% (two variants)	~0.9–1.0 V	$CH_3NH_3PbI_3$ perovskite with ultrathin metal electrode. Higher transparency version had lower PCE. Newer perovskite tandems: ~12% (top cell alone) at ~50% AVT, used in 25%+ tandem efficiency.
Organic/Polymer Transparent PV	9.8% (small-area)	~50% (estimated,	~1.0 V	Organic absorbers for UV+IR. Certified by

Technology & Example	PCE (Efficiency)	Average Visible Transmittance (AVT)	Typical V_{OC} (V)	Notes (J_{SC} density, etc.)
– Ubiquitous Energy record cell 2020[22]	cell)	high transparency)		Newport lab[5]. Anticipated product: ~7% module efficiency at 50%+ AVT[5]. Earlier MIT cell: 2% at 70% AVT[4]. J_{SC} typically ~5 mA/cm ² at 70% AVT.
Quantum Dot LSC (QD-TSC) – e.g. ClearVue Gen2 Glass[5]	~3% (module, ~30 W/m ²)	~70% (high transparency)	–	Si/QD nanoparticles in glass, IR to edge c-Si strips. Each 1.2×1.1 m window produced ~30–33 W (~3% eff)[5]. Next-gen approaching 5% PCE at similar transparency. V_{OC} depends on edge cells (e.g. 18 V if 36 cells in series).
Crystalline Si Partial (spaced cells) – e.g. BIPV façade panel with 50% coverage	~10% (module)	~50% (translucent)	~0.6 V per cell	Uses standard c-Si cells (20% eff) covering half area. Series connections yield module V (like 20 V for 36 cells). Visible grid pattern, tinted appearance. Proven durable, but aesthetics are a limitation[4].
Crystalline Si ABC (All-Back-Contact) – UNIST 2024[55]	15.8% (cell), 14.7% (module)	20% (neutral tint)	0.64 V per cell	Interdigitated back contact c-Si with micro-structured transparency. High efficiency at low transparency[10]. Module of 16 cm ² (4 cells series) gave 10 V, 235 mW[11]. Potential for larger modules with higher transparency in future.

Sources: Performance data compiled from recent literature and reports: IntechOpen chapter[1], PV Magazine reports[42][55], company press releases and academic publications[5][6]. These represent best-case or noteworthy results; typical commercial products may have lower performance.

From Table 1, we see clear trends. Technologies like TLSCs and QD-LSCs achieve the highest transparency (over 70–80%) but presently have the lowest efficiencies (a few percent). On the other hand, approaches leveraging crystalline semiconductors (silicon, or perovskite in tandem) can push efficiency into double digits but at the cost of noticeable tint (20–50% AVT). DSSCs and organics lie in between, offering moderate efficiencies in the 5–10% range at moderate transparency. It's worth mentioning voltage and current characteristics: in fully transparent concentrator systems (TLSC, QD-LSC), the voltage is actually generated by the edge cells which are often silicon – so a large TLSC window might output, say, 5 V (if 10 small Si cells in series at ~0.5 V each) at a current proportional to the window area and luminophore efficiency. In contrast, thin-film based transparent cells (DSSC, perovskite, OPV) typically produce lower current density and thus often are connected in series in modules to raise voltage for practical use. For instance, Ubiquitous Energy's transparent window panels are made by tiling many small transparent cell segments in series to get a higher voltage output per panel[72]. This modular design is evident in prototypes where buslines along the glass edge connect series strings of transparent cell strips, ensuring the window delivers perhaps tens of volts.

One important comparison metric is the efficiency-transparency trade-off. Some researchers have plotted efficiency versus AVT for various technologies: one finds an inverse relationship – as $AVT \rightarrow 100\%$, $PCE \rightarrow 0\%$. The goal is to find an “elbow” in that curve where meaningful efficiency is obtained at acceptable transparency for a given use-case. For building windows, often ~50% AVT is a minimum (many architectural glass have 50% or less anyway due to tinting or coatings). At that point, perovskites and organics can indeed hit ~5–10% efficiency, as shown in the table, which is promising. If a window can do 50% transparency at 10% efficiency, that's extremely attractive (some companies claim they are nearing that realm). In vehicles or small devices, one might tolerate lower transparency (a phone screen might only need ~30–40% if it's reflective LCD, for example). There, a crystalline solution like the ABC cell with 20% AVT might be viable because you can still see through a 20% transparent HUD or sunroof while generating significant power.

In **voltage-current (I–V) curves** of these technologies, transparent cells often exhibit similar shape to standard cells, but with lower short-circuit current. For example, a clear DSSC might have I–V that intersects the current axis at a lower value than a standard DSSC. The fill factor and slope near V_{OC} remain comparable if quality is good. Figures of I–V curves in literature show DSSC curves for different fabrication methods, etc. For brevity, we won't include a plot here, but generally: DSSC typically

$V_{OC} \sim 0.7$ V, I_{SC} a few mA/cm² when partly transparent; OPV $V_{OC} \sim 0.9$ – 1.2 V (depending on donors) and I_{SC} also a few mA/cm² at high AVT; perovskite $V_{OC} \sim 1$ V (for 1.6–1.7 eV bandgaps) and higher current if not too transparent; silicon $V_{OC} \sim 0.6$ V per cell and current depends on how much area is active.

It's also instructive to compare **stability** and **scalability** along with performance. Silicon-based and inorganic thin-film approaches (e.g. ClearVue's glass or ABC-Si) likely have multi-decade lifetimes akin to conventional PV. DSSC and organics historically have shorter lifetimes (due to dye degradation or oxygen ingress), though improvements in sealing have extended some to 5-10 years or more in real conditions. Perovskites currently have stability issues under UV and heat, which is ironic for a transparent cell that specifically is hit by UV – encapsulation and filters can mitigate that (some designs include a UV-blocking layer that both protects the perovskite and perhaps gives that UV to a luminescent layer to still use it).

In conclusion, while no single technology currently excels at both high efficiency and high transparency, the variety of approaches allows selection based on application priorities. Table 1 encapsulates the current landscape: if you need maximum transparency (a clear view), you might use TLSC/LSC with modest power. If you need higher power and can allow tint, a silicon or perovskite solution might be preferable. The numbers will surely improve in coming years, but as of now one can achieve roughly 5% efficiency at 50% transparency (several ways to do so: organic, DSSC, perovskite) or $\sim 10\%$ at 30% transparency (perovskite or crystalline), or ~ 1 – 3% at near 100% transparency (LSC). These benchmarks guide developers and architects in what to expect from today's transparent solar cells.

Applications and Deployment Potential

Transparent solar cells open up a wide array of applications by virtue of integrating energy generation into surfaces that were previously passive. Here we discuss several key domains where TSCs are being applied or considered, along with the advantages they bring:

- **Building-Integrated Photovoltaics (Windows and Facades):** Perhaps the most impactful application is in architectural glass. Modern buildings have extensive glazed areas (windows, curtain walls, skylights). Replacing or retrofitting these with power-generating transparent panels can turn skyscrapers into vertical solar farms without altering their appearance. Transparent PV windows can supply a portion of a building's electricity (some estimates suggest up to 40% of building energy in highly glazed structures[2]). They also reduce building cooling load by filtering infrared. Companies like Ubiquitous Energy and ClearVue are targeting commercial and residential windows that meet standard building codes (safety glass, insulation) while adding PV functionality. *Net-zero energy buildings* could employ these windows alongside rooftop PV to reach energy self-sufficiency. Aesthetic flexibility is another

benefit: DSSC or organic PV windows can come in various tints (amber, blue, green) to complement design, effectively functioning as electricity-generating stained glass. For historical or artistic buildings, transparent PV coatings could be applied to preserve appearance (for example, a clear coating on a glass skylight in a museum).

- **Automotive and Transportation:** Vehicles have significant glass surface area – windshields, sunroofs, side windows – which typically just let heat in. Transparent solar panels on cars can trickle-charge the battery or power auxiliary systems. Toyota, for instance, experimented with transparent solar roof panels. A fully transparent windshield with solar capability is challenging (due to strict clarity and safety requirements), but semi-transparent sunroofs are feasible. Audi and Hyundai have showcased concept cars with solar cell sunroofs (though those used crystalline strips or opaque thin-film embedded in glass). With truly transparent PV, any car window could become a generator without blocking driver visibility. This could extend to buses, trains (imagine train windows generating power for onboard electronics), and even aircraft windows or spacecraft panels (where transparency isn't needed for viewing but weight and dual-use might matter). Another transport-related use is in *greenhouses for agriculture* – while not exactly vehicles, greenhouses are transparent structures. Installing PV in them must ensure plants still get light. Here, transparent solar panels (especially those that pass the visible and use UV/IR) are ideal: they create **agrivoltaic greenhouses** that produce power and maintain plant growth[68][24]. ClearVue's field trials in Australia demonstrated greenhouse windows generating ~40% of the greenhouse's energy needs while plants grew under them normally[76].
- **Consumer Electronics:** Another exciting area is integrating transparent cells into device screens and displays. Smartphones, tablets, e-readers, and laptops all have displays that could potentially incorporate a transparent PV layer. This could enable the device to **self-charge from ambient light** (or at least extend battery life). For example, a phone with a transparent solar coating on its OLED screen could trickle-charge whenever exposed to sunlight or even indoor lighting. Some Kindle e-reader prototypes have included solar charging capability in the screen bezels; a fully transparent implementation could use the whole screen. There are challenges: display technologies must allow adding PV without affecting image quality. One promising synergy is with *reflective displays* or *dual-layer LCDs* where a transparent PV could sit behind a transmissive LCD and harvest light that passes through when the screen is off or from backlight leakage. Another is with *wearables*: imagine a smart watch whose face is a transparent solar cell over the display, or AR (augmented reality) glasses with solar coatings on the lenses powering the electronics.

These use-cases demand high transparency (nearly 90% for see-through lenses) so initial power will be low, but even a small cell can power ultra-low-power electronics in wearables.

- **Outdoor and Infrastructure:** Transparent PV can be applied in less obvious places too. Bus stops and shelter panels could incorporate see-through solar panels to power lighting or displays. Glass railings, noise barriers along highways (some prototypes in Europe used semi-transparent a-Si panels in noise barriers), and even transparent road signs or billboards with solar film are possible. An example is *streetlights with transparent PV* – the pole or the lamp cover could have a clear PV that charges a battery by day to run LEDs by night. Also, *greenhouses and urban farming*: we covered greenhouses, but even vertical farming facilities with artificial lighting could use transparent PV on windows to offset power use.
- **Aesthetic and Multi-functional Building Elements:** Transparent PV need not be limited to windows. It can be used in atrium roofs, glass floor panels, or even interior design elements like room dividers that double as power sources. *Smart glass facades* can incorporate transparent PV plus sensors and displays (for instance, a building facade that generates power and also has an integrated LED display for signage, all powered by the PV itself). Companies like Physee are working on “smart windows” that include not just PV but also environmental sensors, feeding data to building management systems[1].

One key benefit across these applications is **space efficiency**: Transparent PV uses surfaces that are already present and serving another function. This means additional power generation can be achieved without extra space or dedicated real estate. In urban settings, roof space is limited, but vertical facades are abundant – albeit not optimally angled, they still receive substantial light (especially glass skyscrapers that often reflect a lot of sun which could instead be captured).

However, there are also deployment considerations: - **Retrofit vs New Build:** Installing transparent PV in new constructions is easier, since one can plan for wiring, inverters, and possibly slightly higher upfront cost offset by long-term energy production. Retrofitting existing windows is trickier but not impossible; thin transparent PV laminates or films could be applied to existing glass. Some startups offer adhesive PV films that can be stuck on windows (these might be organic or a-Si based, semi-transparent). - **Grid Integration and Storage:** The intermittent nature of solar means if many building windows produce power, managing that (storing or feeding back to grid) will be crucial for realizing the benefit. For devices like phones, integration with battery charging circuits is needed – but that’s straightforward. - **Durability and Maintenance:** In applications like architecture and automotive, transparent PV must withstand weather, UV, temperature cycles, etc. Many transparent PV technologies (like organics and perovskites) are still being tested for

long-term durability. Encapsulation in laminated glass can protect them. Cleaning is another factor: windows get dirty, which can reduce both transparency and PV output. Self-cleaning coatings might be integrated. - **Regulations and safety:** Any modifications to structural glass require regulatory approval (for strength, fire safety, etc.). Transparent PV modules must meet these same standards. Additionally, electrical safety must be maintained (proper insulation of the PV layers so that touching the window doesn't pose a shock hazard, etc.). Many products place the active PV inside a double-glazed unit, fully encapsulated and unreachable to occupants.

Despite these challenges, pilot projects are already validating the concept. For example, in 2017, the **University of Michigan** retrofitted some building windows with transparent luminescent solar concentrators developed by MSU, to test their performance in real-world conditions (they were almost unnoticeable to building occupants). In the Netherlands, *Physee* installed PowerWindows (which are transparent panel with edge solar cells) in an office building, providing a few watts per square meter and powering sensors that control ventilation in response to sunlight. These early deployments show that even small contributions (say a building gets 50 kW from its windows) can meaningfully offset lighting and HVAC loads over a year. Looking at vehicles, in 2019 Toyota offered a Prius model in Japan with an optional solar roof (that could charge the 12V battery). While that roof used opaque cells, one can foresee next-gen versions with see-through solar glass roofs, so that passengers still enjoy a skylight. Some experimental solar cars (like Lightyear) actually considered semi-transparent panels for the windshield top section (where you don't need to see through). *Transportation infrastructure*, such as bus shelters in London and Dubai, already use semi-transparent PV panels to run lighting or displays.

A unique application worth mentioning is **spacecraft and satellites**: they often use solar panels for power, but sometimes need optical instruments or sensors that require clear fields of view. A transparent solar cell could potentially cover a telescope or sensor housing, generating power while letting most light through to the instrument – effectively doubling up functionality on limited spacecraft surface area. Also, for aesthetic projects like the **International Space Station's cupola** (which is an observation window), a transparent PV coating on it could generate a bit of extra power (though the ISS has huge arrays already, so maybe not needed).

In summary, transparent solar cells enable *ubiquitous solar energy harvesting* – from the windows of skyscrapers to the screen of your smartphone. They allow designers to overcome the traditional trade-off between having natural light / visibility and generating electricity from those same surfaces. As the efficiency and cost improve, we can expect to see an increasing deployment of these technologies. In the future, it might be commonplace that every new building has PV windows, every car charges itself when parked outside, and our personal gadgets sip power from the environment without ugly panels or chargers – all thanks to invisible photovoltaics.



Figure 13: A greenhouse installation using ClearVue transparent solar windows. The glass panels (seen in the walls and roof) look nearly identical to conventional glass, maintaining about 70% transparency, yet they contain an integrated photovoltaic function that generates electricity from sunlight[24]. In this two-year trial at Murdoch University, Australia, the solar windows produced $\sim 30 \text{ W/m}^2$ and powered fans and environmental controls, while allowing sufficient light for plant growth. This showcases the application of transparent PV in agriculture, where it provides both shelter and energy without significantly impeding the sunlight needed by crops.

Challenges, Limitations, and Future Directions

While transparent solar cells offer exciting possibilities, there remain several challenges that must be addressed as the technology moves toward wider commercialization. We outline the major limitations and ongoing research directions aimed at overcoming them:

- **Efficiency vs. Transparency Trade-off:** As discussed, there is an inherent compromise between achieving high transparency and high power output. Most transparent PV technologies today cannot match the efficiency of traditional opaque panels. For market adoption, especially in energy-intensive applications, transparent cells need to improve in efficiency. Future directions include multi-junction transparent cells (stacking different transparent layers to use more of the spectrum) and advanced light-management techniques (like photonic structures that trap IR light for absorption while letting visible

through). Researchers are exploring **spectrally-selective mirrors and filters** that could be integrated to reflect otherwise unused IR back into the cell for a second pass, or to reflect UV to a different layer (e.g. a luminescent layer)[4]. The concept of “**quantum cutting**” is also intriguing: converting one high-energy UV photon into two lower-energy IR photons, thereby potentially doubling the current from UV without absorbing visible light (this would use special phosphors or quantum dots).

- **Materials Stability and Longevity:** Many of the promising transparent PV materials (organics, perovskites, dyes) suffer from degradation when exposed to environmental factors like oxygen, moisture, and UV light. For instance, organic polymer cells can photo-degrade and perovskites can decompose or leach lead. Ensuring a 20+ year lifespan (standard for solar products) is a big challenge. This is compounded by the fact that transparent cells by design let UV through to the absorber (since they often rely on UV absorption), which can accelerate degradation. **Encapsulation** will be critical: using multilayer barrier films, UV-filtering top coats (which paradoxically might reduce some power by filtering UV – a trade-off between efficiency and stability might be needed). Alternatively, more stable materials are needed. For dyes in DSSC, newer metal complexes and organic dyes are being developed that resist photobleaching. In organics, non-fullerene acceptors have improved stability and certain polymers are engineered for UV robustness. Perovskite research is heavily focused on stability – using **2D/3D hybrid perovskites**, additive engineering (e.g. cesium, rubidium doping) to stabilize the crystal, and self-healing encapsulants.

Another stability aspect is thermal. Windows can get hot under sun; the solar cell must endure thermal cycling. Some transparent cells (like perovskite or DSSC liquid electrolyte) might have issues with extreme heat or cold (electrolytes can freeze or expand). Future transparent PV for varied climates may need temperature-resilient designs (e.g. solid-state DSSC, wide-temp electrolytes, robust sealing).

- **Manufacturing and Scalability:** Many of the current high-performing transparent cells are produced in laboratory settings using spin-coating, thermal evaporation, or other small-area techniques. Scaling these to large-area manufacturing (especially for window-sized panels) is challenging. Techniques like **roll-to-roll printing** for organic and perovskite PV, **large-area spray coating** or **slot-die coating** for inks, and high-throughput **sputtering** for transparent electrodes need to be optimized. Uniformity is crucial – even slight non-uniformity in a transparent panel could cause visible blemishes (which is unacceptable for a window). For devices like the ABC silicon cell, scaling up requires precision micromachining on large silicon wafers or even on module-sized glass – possibly leveraging the semiconductor industry’s tools. This could

be expensive initially. However, progress is being made: companies like Saule Technologies are deploying inkjet-printed perovskite solar films (not transparent ones yet, but the printing tech could apply to transparent designs). Heliatek has built roll-to-roll lines for organic films, albeit at lower throughput. In the future, **continuous processing** of transparent PV coatings on glass (similar to how low-E coatings are applied via vapor deposition on architectural glass today) could be implemented. The cost must also be considered: using rare materials like indium (for ITO) or tellurium (in some perovskites) can be a bottleneck if deployed at large scale. R&D into alternative transparent conductors (like carbon nanotube films, graphene, or conductive polymers) is underway to reduce reliance on indium.

- **Electrical Integration and Wiring:** Collecting power from transparent modules in a window frame requires wiring that doesn't spoil the aesthetics. Usually, transparent panels are framed, and connections are hidden in the window mullions. In some designs like Physee's PowerWindow, the edge of the glass has small solar strips and micro-inverters or DC converters embedded in the frame. For retrofits (stick-on films), very thin wires or transparent conductive adhesives have to carry current to the edges. Large-area transparent PV also faces the challenge of **series resistance** in transparent electrodes: ITO has higher resistivity than metals, so spreading current across a big area without metal grid lines is tough. Some transparent cells incorporate barely-visible mesh lines or use a metal grid so fine (or in a pattern that matches window borders) that it's not noticed. Others rely on segmenting into smaller sub-cells in series to mitigate resistive losses. The UNIST seamless module indicates that clever patterning can solve this[11]. In future, perhaps **wireless power transfer** techniques might even be used (e.g. a transparent panel could inductively couple to a frame without direct wiring – speculative, but conceptually possible with conducting coatings acting as antennas).
- **Optical Clarity and Aesthetics:** Ensuring that transparent PV installations meet visual expectations is crucial for adoption. Any haze, discoloration, or mirror-like reflection can be problematic. For example, some transparent solar coatings might produce a slight tint (say magenta or amber). While some architects might like a subtle tint, generally a neutral appearance is desired (hence the “neutral-colored” silicon cell being emphasized[11]). Anti-reflective coatings are also needed; stacking many layers in a transparent device can increase reflections if not managed, leading to a mirror effect. Future research includes **index-matching layers** and **nano-textures** to maintain clarity. Also, inconsistency (like one part of a window aging to a different tint than another) would be unacceptable. Thus, durability of color over time is a challenge. Real-world factors like dust or moisture condensation between panes could also

affect appearance and performance; designs must minimize these via proper sealing and perhaps self-cleaning hydrophobic coatings.

- **Energy Yield and Economics:** Transparent panels often have lower yield per area, so the economic return might be slower compared to conventional PV. If adding transparent PV increases window cost significantly, customers will weigh the benefit. However, there is value stacking: transparent PV can offset the cost of other window coatings (like low-E or tint films) by providing similar function (reducing IR entry) plus generating electricity. Still, more field data is needed on how much energy, say, a south-facing facade with 50% transparent PV can produce annually in various climates, and how that offsets building energy use. Early studies show that highly glazed buildings with transparent PV could approach the energy generation of traditional PV on the limited roof area[2]. In combination, they can reach net-zero. Government policies on building efficiency might drive adoption if, for instance, building codes give credit for power-producing facades.
- **Regulatory and Market Acceptance:** As with any new building technology, codes and standards must be established. Currently, IEC and UL are developing standards for building-integrated PV (BIPV), which include PV glass. Transparent PV modules will have to pass safety tests (hurricane impact for windows in some regions, fire ratings, etc.). There might also be concerns about **light pollution or aesthetics** from exterior viewpoints – e.g. if a building's transparent panels reflect differently or have slight coloration, city planners or owners might hesitate. Public acceptance will rely on demonstration projects that show these windows look and perform just like normal ones. Education is needed to ensure that property developers see transparent PV as a value-add rather than a risky novelty.

Despite these challenges, the trajectory for transparent solar cells is very promising. In terms of **future directions:**

- **Material Innovation:** We can expect new materials specifically for transparent PV. For example, new perovskite compositions without lead (to address toxicity) and with wider bandgaps for greater transparency, or entirely new classes like **organic-inorganic hybrids** that combine stability of inorganic with tunability of organic. Also, luminescent materials like **quantum dots** that are heavy-metal-free (there are carbon dots, perovskite nanocrystals with encapsulation to lock in lead, etc.). Phosphor research (like those used in LED bulbs) could yield stable UV-to-IR converters for TLSCs.
- **Tandem and Stacked Devices:** One likely future design is a *tandem transparent cell* – e.g. a transparent DSSC or perovskite that takes part of the spectrum and behind it an organic cell for another part, both layers letting some light through. Multi-layer coatings on glass could each capture a slice of spectrum, boosting total efficiency. Already, tandem of semi-transparent perovskite + silicon is being developed for >30% opaque efficiency; a

variant where the bottom cell is also somewhat transparent (say a silicon with holes or a CIGS on transparent substrate) could yield a partially transparent tandem with perhaps >15–20% efficiency. - **Adaptive Transparency (Dynamic PV):** A futuristic concept is solar cells that can switch modes – acting either as a solar cell or as a transparent window on demand. For instance, **electrochromic PV hybrids:** when power is needed or sun is strong, the window darkens (like electrochromic glass) and in that state it absorbs more light and produces more electricity. When transparency is needed (overcast or for interior daylighting), it switches to a high-transparency, lower-power mode. Some research has been done on perovskites that can **thermochromically** turn opaque (by a phase change) and simultaneously generate power. Another idea is **floating PV displays:** using microfluidics or electrophoretic techniques to move PV nano-particles in or out of the optical path (far-out research idea). - **Integration with Storage:** To fully utilize transparent PV in devices and buildings, integration with batteries or supercapacitors can be important. We might see window units that include a transparent battery film around the edges or in the frame, storing solar energy for lighting at night. Some have even looked at **transparent batteries** (using clear electrodes like ITO and organic electrolytes) that could be paired with transparent PV in a single stack – resulting in a self-charging window with an integrated energy storage layer.

In summary, the road ahead for transparent solar cells involves multidisciplinary efforts in materials science, device engineering, and architectural integration. The main limitations – lower efficiency and stability – are actively being tackled, and incremental improvements are steadily coming. As a perspective, consider that silicon solar cells in the 1950s had ~6% efficiency; now they exceed 26%. Transparent solar tech is relatively young (most progress in the last ~10–15 years), and some types are already near 10%. With continued R&D, it's plausible to reach 15–20% efficiency at moderate transparency in the next decade, which would make transparent PV truly ubiquitous in new construction and consumer devices.

The future vision is compelling: buildings where every window and facade panel quietly generates power; vehicles that charge themselves as sunlight streams through the glass; gadgets that live longer between charges by sipping ambient light; all achieved without altering the visual experience we expect from clear glass. Overcoming the current challenges will be the key to unlocking this vision. The progress so far – from 1% efficient demo cells to nearly 10% efficient devices and successful pilot installations – gives confidence that transparent solar cells will play a significant role in the renewable energy ecosystem moving forward, enabling a seamless integration of solar power into the fabric of our daily lives.

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Chapter IX

9. WIND ENERGY

Introduction

Wind turbines are electromechanical systems that convert kinetic energy of moving air (wind) into mechanical energy, and finally into electrical energy through a generator.

They are the key components of modern wind energy conversion systems (WECS). The working principle is based on aerodynamics and electromagnetic induction. Wind is created due to uneven heating of the Earth's surface by the Sun, causing pressure differences and air movement. Capturing part of this natural motion allows humans to generate sustainable electricity without burning fuel.

History

Wind energy has evolved from simple windmills to multi-megawatt turbines. Early windmills (used for milling and pumping) date back millennia, but electrical generation began in the late 19th century. The first electricity-generating wind turbine (12 kW) was built by C. F. Brush in 1888, followed by Poul la Cour's generator in Denmark in 1889[1]. These pioneers used primitive blades (often wooden or metal), but reliability was low (e.g. a 1941 1.25 MW turbine with steel blades failed within hours). A breakthrough came with the 1957 Gedser turbine (3-blade, 200 kW) in Denmark: it used glass-fiber composite blades and ran 11 years without maintenance[1]. After the 1970s oil shocks, wind development accelerated: by the 2000s turbines had grown to multi-megawatt size (e.g. >3 MW onshore) and even larger offshore[2]. Today wind power is a major renewable source – for example, global wind capacity reached ~1,136 GW by 2024[3]. Countries like Denmark already supply over half of their electricity from wind[3], and major projects exist worldwide (e.g. China leads with ~520 GW installed[4], the US ~155 GW[4]).

Evolution of Wind Energy

1. Ancient Windmills (7th Century)

- **Persian Windmills:** The earliest recorded windmills appeared in Seistan (modern-day Iran) around 700 A.D. These vertical-axis windmills were primarily used for grinding grain and pumping water.

2. European Windmills (11th Century)

- **Horizontal-Axis Windmills:** Introduced in Europe, these windmills featured improved designs with rotating heads, allowing them to face the wind direction, enhancing efficiency.

3. American Multi-Bladed Windmills (19th Century)

- **Water Pumping:** In the mid-19th century, the American Midwest saw the proliferation of multi-bladed windmills, primarily used for pumping water from underground wells.

Pioneering Electricity-Generating Wind Turbines

4. James Blyth's Turbine (1887)

- **Location:** Marykirk, Scotland(Figure 1)
- **Innovation:** Constructed the first wind turbine to generate electricity, powering ten light bulbs and a small lathe.

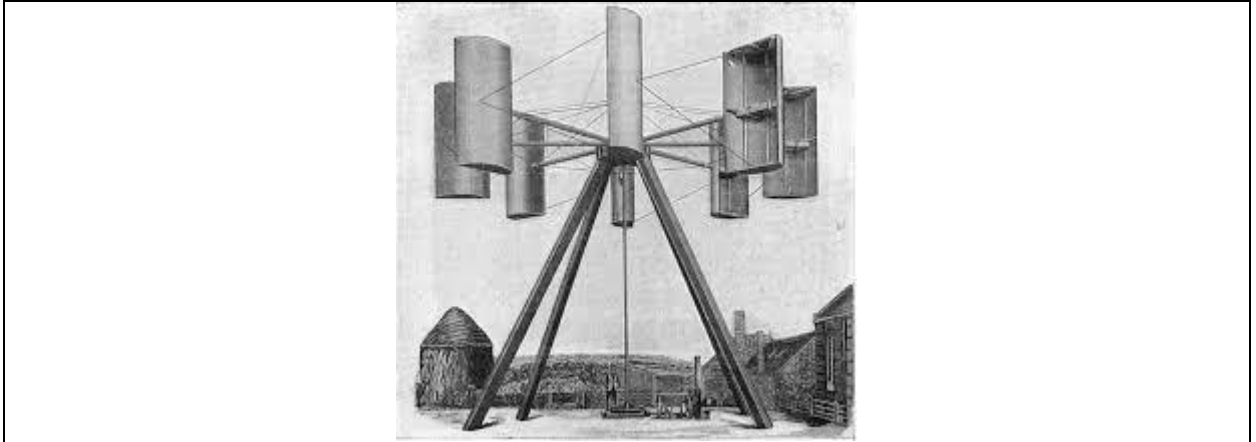


Figure 1. James Blyth's Turbine (1887)

5. Charles Brush's Turbine (1888)

- **Location:** Cleveland, Ohio, USA(Figure 2)
- **Design:** Built a large 17-meter diameter windmill with 144 blades, producing approximately 12 kW of power, used to charge batteries in his mansion().

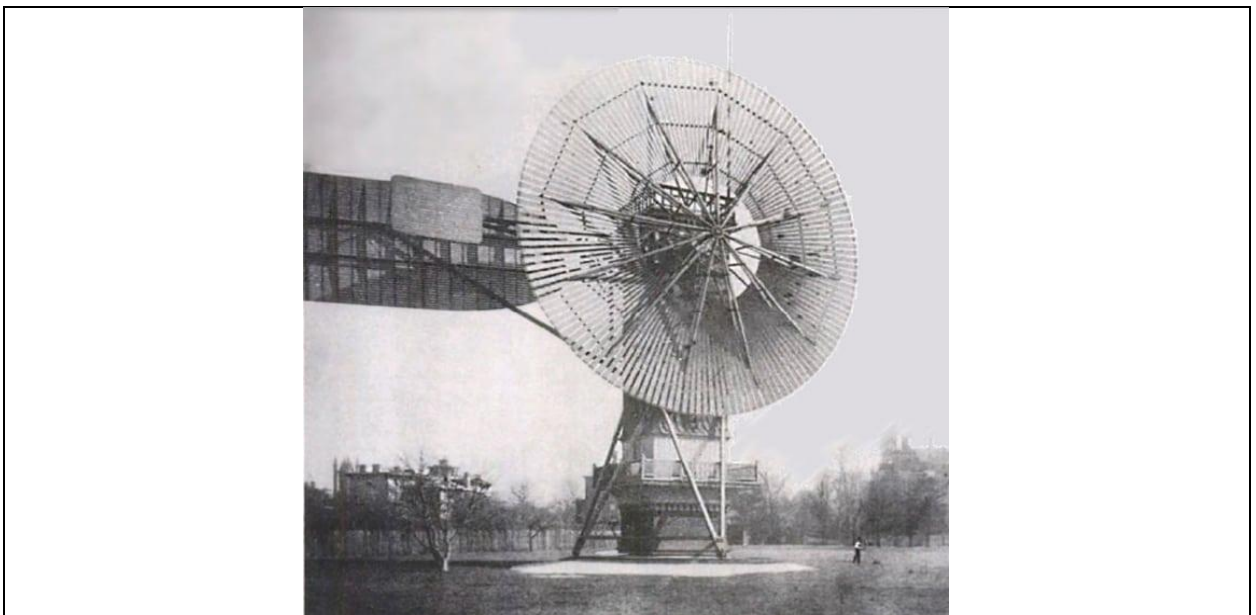
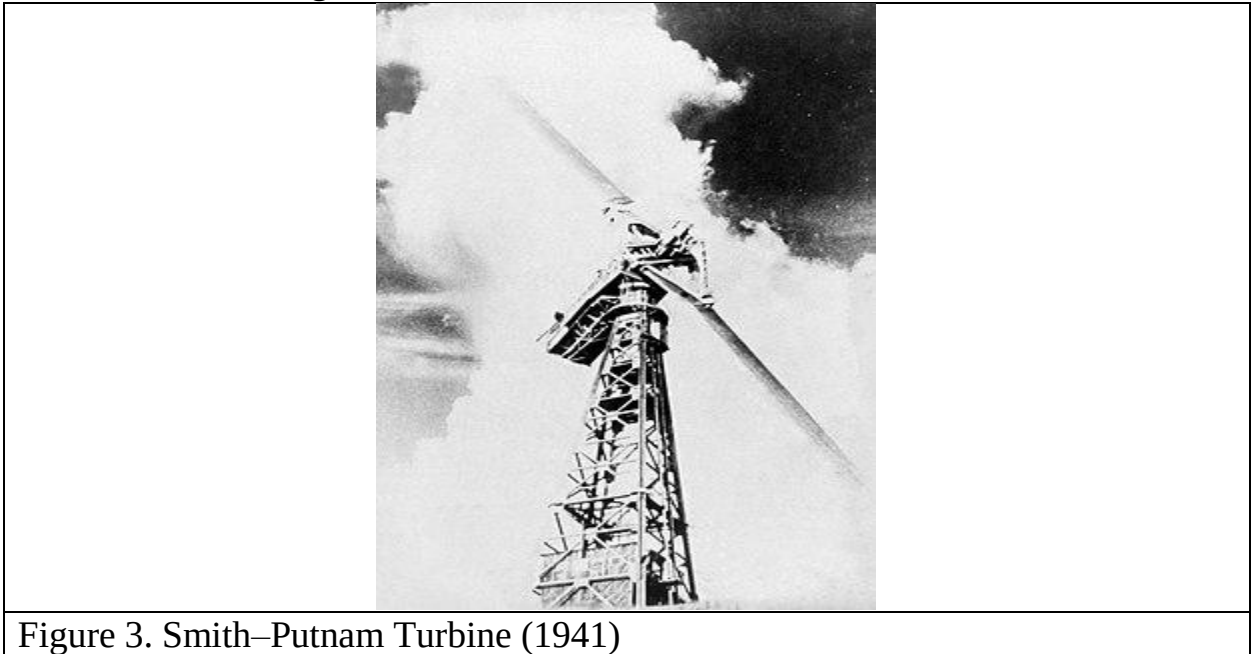


Figure 2. Charles Brush's Turbine (1888)

6. Smith-Putnam Turbine (1941)

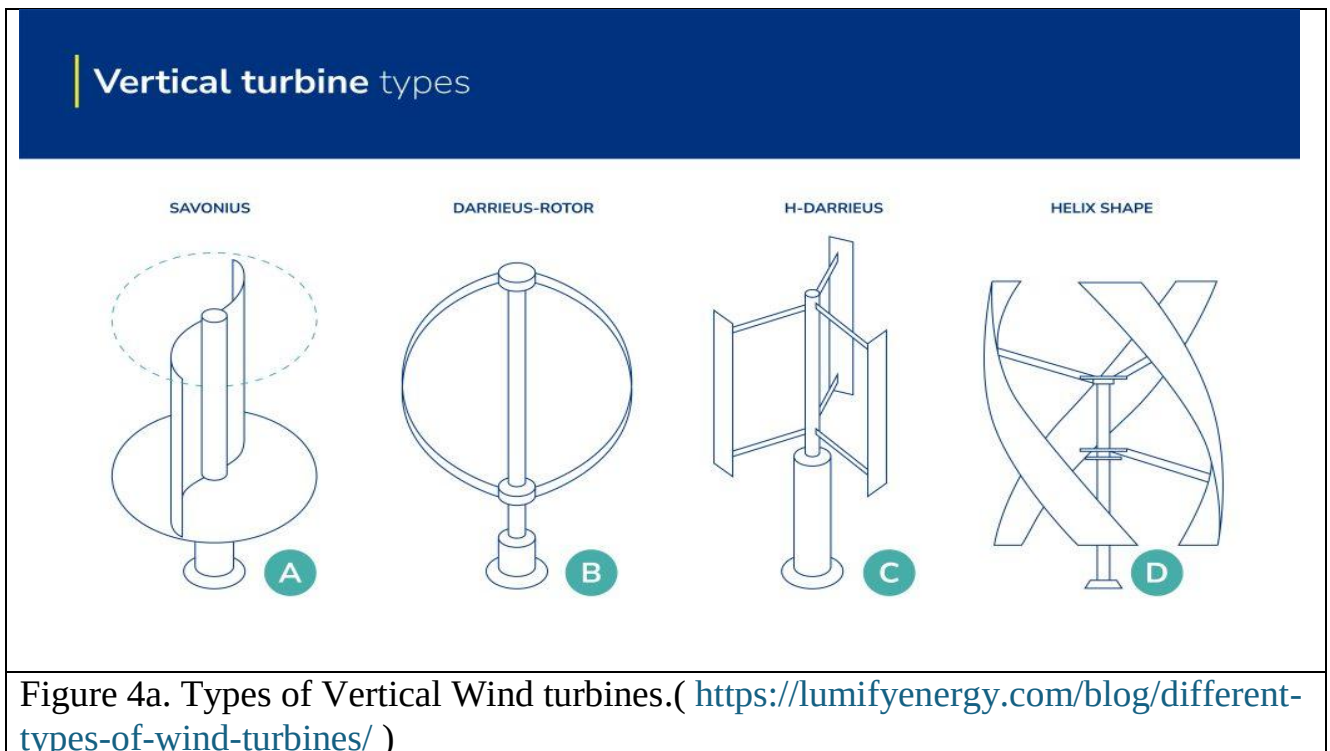
- **Location:** Castleton, Vermont, USA(Figure 3)

- **Significance:** First megawatt-scale wind turbine (1.25 MW) connected to the electrical grid. Operated for 1,100 hours before a blade failure led to its decommissioning.



Types of Wind turbines

In figure 4a,b it is shown all types Wind trubines:



The Figure 4a shows several types of **vertical-axis wind turbines (VAWTs)**, labelled A–D:

- **A – Savonius:** A drag-type VAWT. Typically consists of two or more “scoops” or half-cylinders that catch the wind; very simple design. [Википедия+2pdfs.semanticscholar.org+2](#)
- **B – Darrieus-rotor:** A lift-type VAWT where curved air-foil-shaped blades are mounted on a vertical shaft; sometimes called “egg-beater” type. [ResearchGate+1](#)
- **C – H-Darrieus (H-shape):** A variant of the Darrieus with straight-vertical blades connected to top and bottom of the rotor with horizontal arms (H-frame).
- **D – Helix shape:** A helical blade variant of VAWT (sometimes of Darrieus family) in which blades are twisted in a helix shape to smooth torque ripple and improve performance. [Википедия+1](#)
- Because of the vertical shaft, some components (generator, gearbox) are often located closer to ground level, which simplifies maintenance in some applications. [Википедия+1](#)
- They are typically less efficient than the most common horizontal-axis versions, and so less widely used commercially.

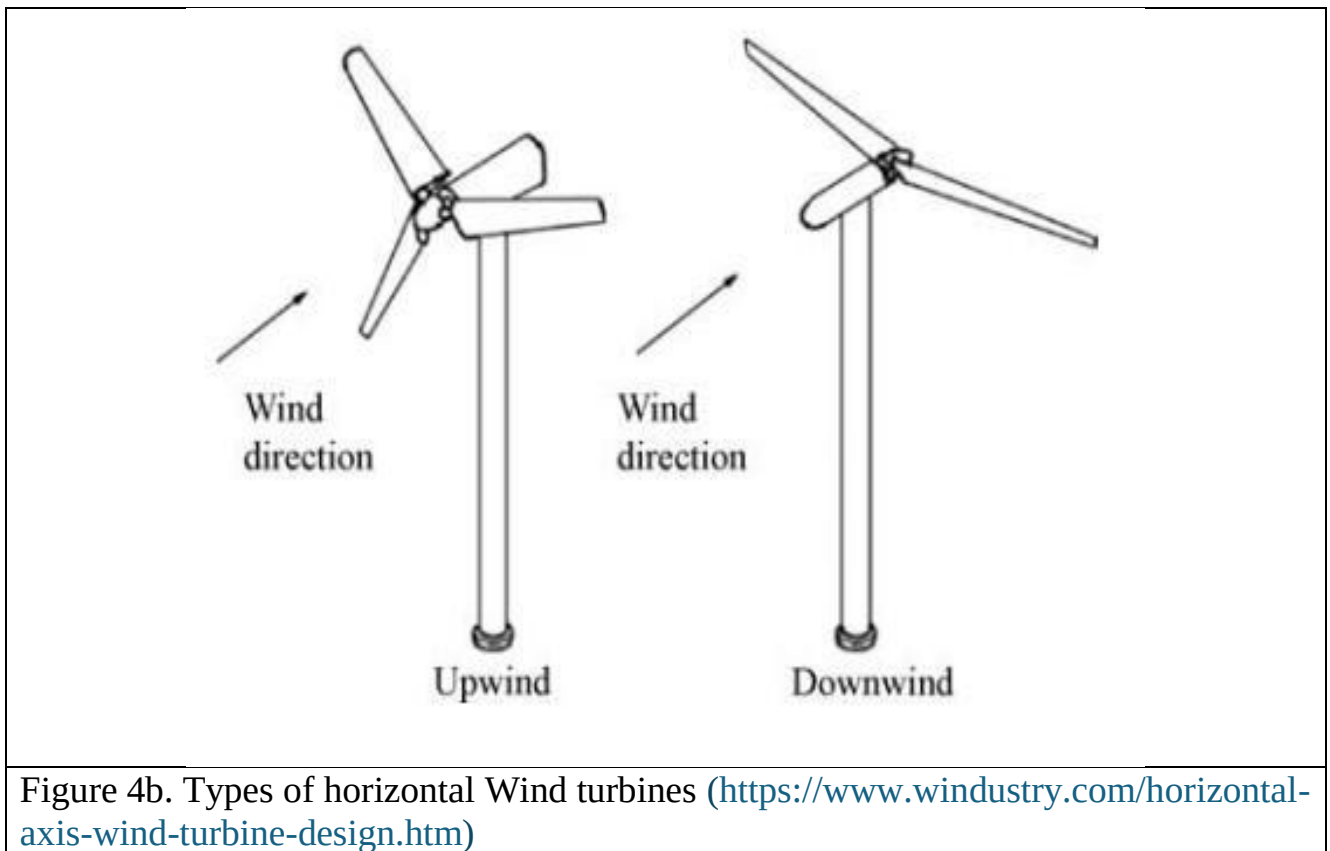


Figure 4b. Types of horizontal Wind turbines (<https://www.windustry.com/horizontal-axis-wind-turbine-design.htm>)

A. Upwind vs Downwind Orientation

- **Upwind HAWT:** The rotor (blades) faces into the wind (i.e., is “upwind” of the tower). Most large commercial machines follow this design. web.kpi.kharkov.ua+2elprocus.com+2
- **Downwind HAWT:** The rotor is on the leeward side of the tower, so the wind passes the tower before the rotor. These are less common in large scale today but have some distinct structural/maintenance trade-offs. uomustansiriyah.edu.iq+1

Key differences:

- Upwind avoids tower shadowing of the rotor and reduces fluctuating loads from tower wake. web.kpi.kharkov.ua
- Downwind automatically aligns with the wind (less yaw control complexity), but suffers from tower-caused turbulence and higher fatigue loads. uomustansiriyah.edu.iq

B. Blade Number / Rotor Variants

- **Three-bladed HAWT:** This is the dominant design in modern utility-scale wind farms. It provides good balance of aerodynamic performance, structural loading, and noise. [eia.gov+1](#)
- **Two-bladed HAWT:** Less common but used in some earlier or special designs. It often reduces cost or weight, but may incur more control/structural complexity (e.g., teetering hubs). [Википедия+1](#)
- **Single-bladed HAWT:** Rare, mainly experimental; often uses a counter-balance to maintain rotor equilibrium. (Less relevant for current commercial deployment) [Википедия](#)

C. Other Distinguishing Features

- **Rotor diameter / blade length:** Larger diameters capture more wind; modern HAWTs push blade lengths and hub heights higher to access stronger winds. [eia.gov+1](#)
- **Yaw control & blade pitch control:** To optimize power capture and protect the machine, large HAWTs include mechanisms to yaw (turn into the wind) and to pitch blades (adjust blade angle) depending on wind speed. [Википедия+1](#)
- **Gearbox vs direct drive:** Many large HAWTs use gearboxes to convert slower rotor speeds to higher generator speeds, but direct-drive designs (no gearbox) are also used. [Википедия](#)

Modern Wind Turbine Developments

7. Gedser Wind Turbine (1957)(Figure 5)

- **Location:** Gedser, Denmark
- **Design:** Three-bladed, 200 kW turbine with electromechanical yawing and stall control. Operated for 11 years without maintenance, influencing future turbine designs(11).

The Gedser Wind Turbine, built in 1957 by engineer Johannes Juul, was a pioneering achievement considered the "mother of all modern wind turbines". It was the first large, successful wind turbine to feed alternating current directly into the public grid and introduced several key design principles still in use today.



Figure 5. Gedser wind turbine today at the Energy Museum Bjerringbro

8. WTS-4 Turbine (1982)(Figure 6)

- **Location:** Medicine Bow, Wyoming, USA
- **Innovation:** First 4 MW wind turbine, featuring a two-bladed design with a teetering hub and pitch power control.

The "WTS-4" is called that because it is a four-megawatt wind turbine generator with a horizontal-axis design. The "WTS" stands for "Wind Turbine System," and the "4" indicates its power rating of 4 megawatts. The WTS-4 was a 4-megawatt (MW) horizontal-axis wind turbine that Hamilton Standard installed in Medicine Bow, Wyoming, in 1982. It was a System Verification Unit (SVU) for a U.S. Bureau of Reclamation project to study the integration of wind power with hydroelectric power systems. The WTS-4 was the world's first 4 MW wind turbine and was a two-bladed design.



Figure 6. WTS-4 Turbine (1982)(
<https://cowboystatedaily.com/2022/11/10/wyomings-first-wind-turbines-were-novelties-then-sold-for-scrap/>)

9. Vindeby Offshore Wind Farm (1991)(Figure 7)

- **Location:** Off the coast of Vindeby, Denmark
- **Milestone:** World's first offshore wind farm, comprising 11 turbines with a total capacity of 4.95 MW.



Figure 7. Vindeby Offshore Wind
Farm(https://en.wikipedia.org/wiki/Vindeby_Offshore_Wind_Farm)

The Vindeby Offshore Wind Farm was the first offshore wind farm in the world, erected in 1991 off the coast of the town of Vindeby on the Danish island of Lolland. It was later decommissioned in 2017 after 25 years of operation.

Floating Wind Turbine Innovations

10. Hywind Prototype (2009)(Figure 8)

- **Location:** Off the coast of Karmøy, Norway
- **Details:** First full-scale floating wind turbine (2.3 MW), demonstrating the feasibility of deep-water wind energy generation.

The 2009 Hywind Prototype was the world's first full-scale floating offshore wind turbine, developed by Statoil (now Equinor) off the coast of Karmøy, Norway. This 2.3 MW turbine, built on a SPAR floater, demonstrated that floating wind turbines could be a viable technology by enduring harsh conditions and successfully connecting to the power grid. Its success paved the way for later floating wind farm projects like Hywind Scotland.



Figure 8. First full-scale floating wind turbine (2.3 MW)(Hywind Prototype (2009))

11. Hywind Scotland (2017)(Figure 9)

- **Location:** Off the coast of Peterhead, Scotland
- **Achievement:** World's first commercial floating wind farm, consisting of five 6 MW turbines, totaling 30 MW capacity.

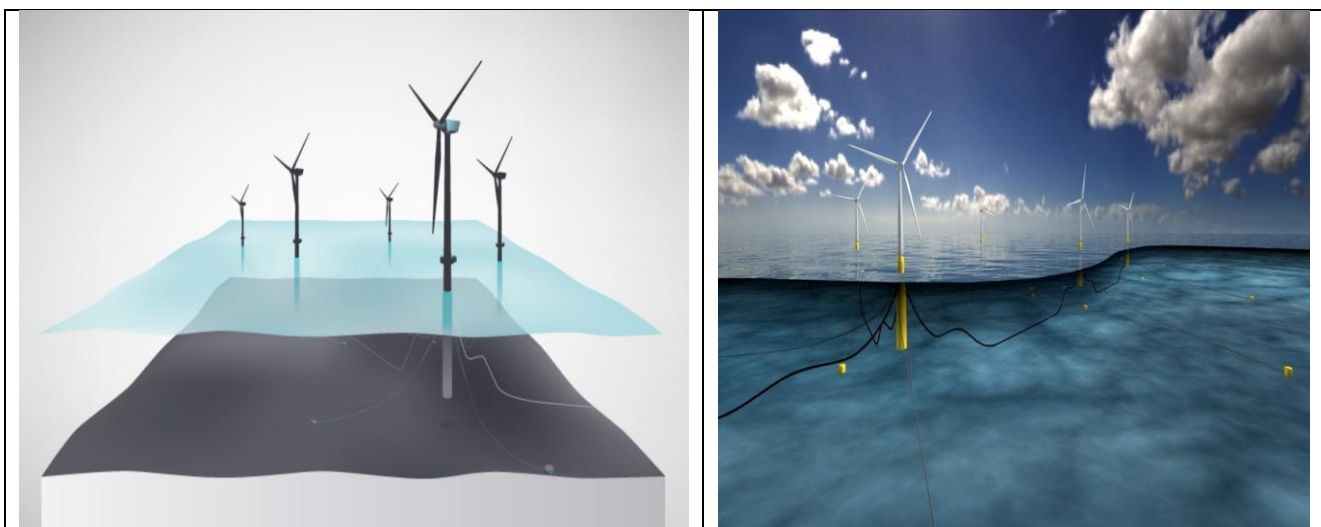


Figure 9. The world's first floating wind farm

The world's first commercial floating wind farm is Hywind Scotland, located 25 kilometers off the coast of Peterhead, Scotland. It consists of five 6 MW turbines with a total capacity of 30 MW and became operational in 2017. The farm is a joint venture between Equinor and Masdar.

On the X-Axis: Unconventional HAWTs(Figure 10)

WindFloat. Danish wind turbine maker Vestas in February teamed with U.S.-based Principle Power and Portugal's EDP to test a 2-MW floating wind turbine off the Portuguese coast, beginning this fall. The WindFloat reportedly decreases wave- and turbine-induced motion and can harness wind energy in waters more than 50 meters deep.



Figure 10. 2-MW floating wind turbine off the Portuguese coast

The Wind Lens. Japanese scientists, meanwhile, are touting another variation—the Wind Lens, a shrouded six-bladed HAWT 112 meters in diameter, which would be arranged in a honeycomb-like pattern (Figure 11). The concept has received much acclaim because it is thought capable of producing four to five times more power than conventional offshore turbines—though its designer, Kyushu University Professor Yuji Ohya, who unveiled the turbine at the Yokohama Renewable Energy International Exhibition in 2010, admitted he was uncertain whether the Wind Lens would ever actually be commercially produced, especially outside Japan.



Figure 11. **The Wind Lens.** The shrouded horizontal-axis wind turbine for offshore use

The latest reincarnation of this unconventional HAWT—also called a diffuser augmented wind turbine—is FloDesign Wind Turbine Corp.’s “jet engine” prototype (Figure 12). Integrating aerospace technology known as a mixer ejector, the prototype is much smaller than earlier designs, making it easier to align blades to the direction of the wind.



Figure 12. The jet engine prototype. Massachusetts-based aerospace technology company FloDesign is developing a shrouded turbine that, based on jet engine technology, directs air into patterns to create a rapid-mixing vortex.

On the Y-Axis: The Darrieus and the Savonius

Generally, VAWTs derive from one of two principle designs: the lift-based VAWT patented by Georges Darrieus in 1931, which uses two or three curved or straight blades joined together at the top and bottom and bowed outward in the middle in a troposkein (Figure 13), and the drag-based VAWT, created by Finnish engineer S.J. Savonius in 1922, which uses two S-shaped blades for the rotor.



Figure 13. The Darrieus. French engineer Georges Darrieus' 1931 vertical-axis wind turbine design—shaped like an eggbeater—has resurfaced in modern times.

Another popular variation of the Darrieus design, the H-rotor design or Giromill, is also being tested offshore. Technip—a French firm that worked with Siemens and Statoil to launch the Hywind floating turbines in Norway—launched the Vertiwind project to test a pre-industrial prototype along with French partners Nénuphar, Converteam, and EDF Energies Nouvelles (Figure 14).



Figure 14. Vertiwind. French company Technip and partners Nénuphar and EDF Energies Nouvelles, among others, have launched a project that would test the Darrieus H-rotor design offshore.

The UK's Energy Technologies Institute (ETI) also recently blessed the use of VAWTs as a viable alternative to traditional offshore turbines. ETI vouched that they can flourish technically, economically, and environmentally, even when sized as large as the 10-MW VAWT Aerogenerator. The Aerogenerator is half the height of an equivalent HAWT, and its weight is concentrated at the base of the structure (Figure 15).



Figure 15 Aerogenerator. British turbine-maker Wind Power is developing a 10-MW floating vertical-axis wind turbine.

The almost-floating vertical blades (Figure 16) spin with little resistance, even in light breezes (as low as 1.5 m/s). That increases power output and device lifetimes, said researchers from Guangzhou Energy Research Institute (which is under China's Academy of Sciences) and stakeholders Guangzhou Zhongke Hengyuan Energy Science & Technology Co., Ltd. when they introduced the turbine in 2006.



Figure 16 Maglev. When Chinese developers unveiled the magnetic levitation wind turbine at the 2006 Wind Power Asia Exhibition, it was hailed as a breakthrough in the evolution of wind technology. The technology is today used to power streetlights in Shenzhen and is available in ranges from 300 W to 1 kW.

VAWTs are gaining ground in the small wind market, too. One example, a Giromill, is Windspire Energy's 30-foot-tall, 4-foot-wide Windspire (Figure 17), which is said to generate some 2,000 kWh per year at 11 mph annual average winds. The Windspire was part of the National Renewable Energy Laboratory's (NREL's) independent testing project, but NREL terminated testing in January 2009, barely a year after the VAWT had been commissioned, because of "turbine component failures." Windspire says the test model was one of its "earliest production units," and it has since improved the turbine. Through a grant from NREL, the company plans to test and certify the new turbine according to standards promulgated by the Small Wind Certification Council—an independent body that began to accept performance and safety certification applications from small wind turbine makers just last year.

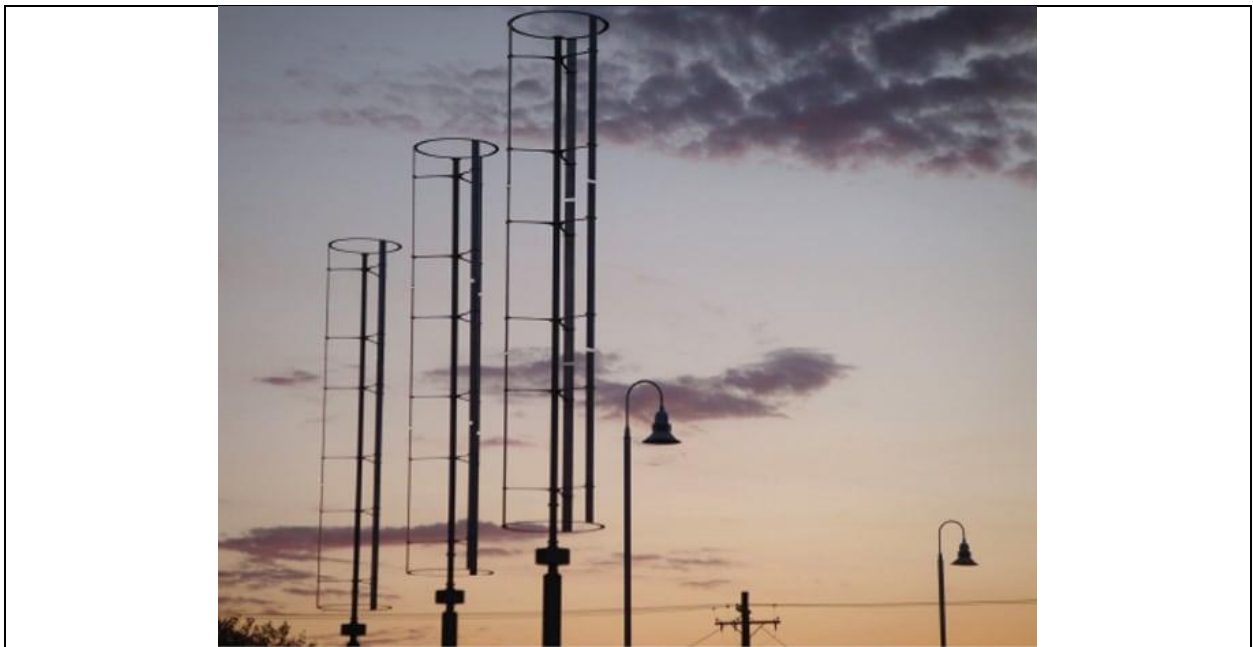


Figure 17 Windspire. Nevada-based Windspire's Giromill generates power when the wind blows against the vertical airfoils, causing them to spin.

The second type of VAWT—the Savonius—uses a rotor, formed by cutting a cylinder into two halves along the central plane and then moving the two semi-cylindrical surfaces sideways along the cutting plane so that the cross-section resembles the letter “S.” One much-cited modern-day example of a Savonius turbine is the Helix system from Helix Wind (Figure 18). As the wind blows (at speeds as low as 10 mph), the long helical blades catch wind from all directions, forcing it through the turbine. The turbine and generator assembly are currently being tested for UL listing, with which the turbine would be eligible for rebates under all state renewable energy programs.



Figure 18. The Helix. California firm Helix Wind's system is a Savonius, drag-based vertical-axis wind turbine.

To gain traction in the competitive market, other VAWT makers have chosen to address HAWT shortcomings. UK firm quietrevolution claims its qr5, a helical VAWT designed to increase demand for wind turbines in environments close to people and buildings, is said to virtually eliminate noise and vibration while generating 7,500 kWh per year (Figure 19). So far, more than 100 turbines have reportedly been installed across the UK, Austria, and Germany.



Figure 19. The quietrevolution. London-based quietrevolution's qr5 VAWT is designed to eliminate noise and vibration.

Airborne Turbines

Meanwhile, wind turbine design is also taking off in an entirely new direction—skyward. Prompted by suggestions that there is an estimated 870 TW of

power potential in high-altitude tropospheric winds, and that the four-decades-old idea is finally technically feasible, several developers around world (including research labs and private industry) are testing prototypes that use kite-like attributes to harness wind energy. The concept is so close to reality that the Federal Aviation Administration has administered limits restricting airborne turbines to flight at altitudes below 600 meters.

One prominent example is the KiteGen power plant (Figure 20), which comprises several “Kite Steering Units” that pilot an array of “power kites” over a predefined flight path. KiteGen is typically arranged in a “carousel” or “stem” configuration. Modular approaches could allow developers to build plants up to 100 MW with costs of energy produced lower than €0.03/kWh, KiteGen says.



Figure 20. KiteGen. Arranged in a “carousel” or “stem” configuration, Italian company KiteGen’s power kites are tethered to a power plant and flown over a predefined flight path.

Joby Energy takes another approach. It is testing a 30-kW system (Figure 21) that looks like a multiwinged kite supporting an array of turbines. Thrust for the kite’s vertical takeoff is supplied by motor generators connected to the turbines, and the orientation is controlled by a computer system that differentially adjusts rotor speeds to keep it flying in a circular path.

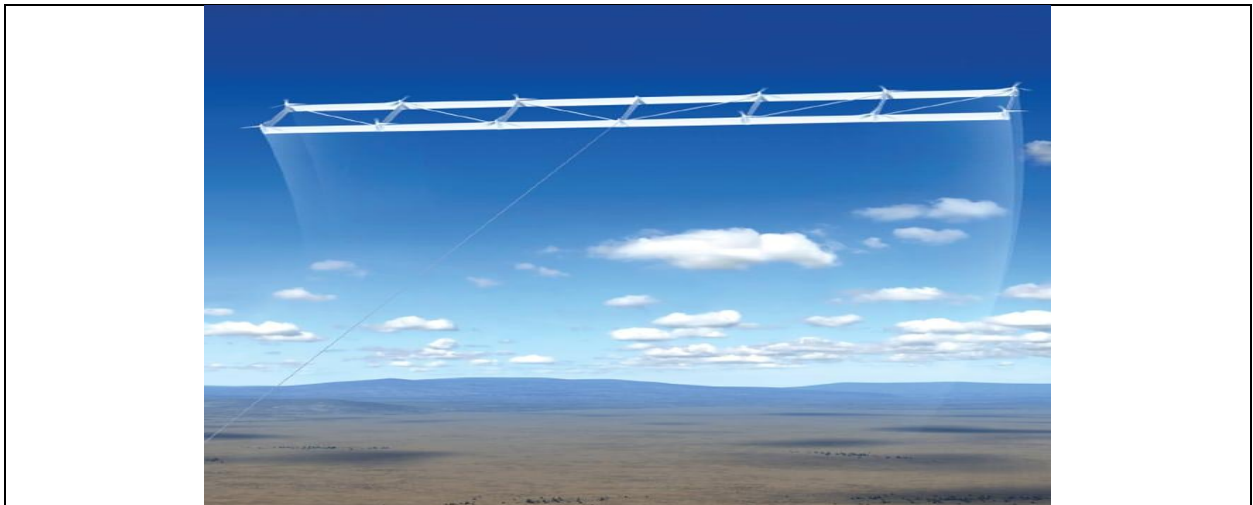


Figure 21. The Joby. California firm Joby Energy is evaluating a 30-kW multiwinged kite, while simultaneously designing and building 100- and 300-kW systems. Plans are to fly initial commercial systems between 500 and 2,000 feet high and to begin manufacturing commercial systems in 2012.

In Germany, Festo (maker of pneumatic and electrical automation technology) is exploring the Aerois Enerkite system, which is an autonomously controlled kite wing of up to 24 square meters.

In the Netherlands, a system prototype of the Ampyx Power Plane, a glider plane that unwinds a winch during flight to propel a generator on the ground, has actually met its rating of 10 kW. The system is a spinoff of the TU Delft University's Laddermill project. Peak power reached during a test of the Laddermill system in April 2010 was 20 kW.

In Switzerland, a coalition of academic researchers (including the University of Applied Sciences Northwestern Switzerland, the Swiss Federal Institute of Technology Zurich, and the Swiss Federal Laboratories for Materials Testing and Research) is evaluating high-altitude wind power.

Even China is stepping in, establishing a high-altitude wind energy research center in Guangdong Province, where plans are in place to build a 1-MW airborne wind power system in Foshan City.

Designs aren't limited to kites and airplanes, however. A California company, Magenn Power, has developed an airborne wind energy system, MARS (Figure 22), consisting of a helium-filled tethered wind turbine that rotates on a horizontal axis at altitudes of 600 to 1,000 feet. MARS rotation also generates the "Magnus effect," which provides additional lift, keeping the MARS stabilized.



Figure 22. MARS. Magenn Power’s MARS helium-filled wind turbine can be deflated and redeployed. It is capable of operating in wind speeds from 4 mph to more than 50 mph.

Other Turbines

An assortment of other turbines, typically a hybrid of HAWT and VAWT systems, exist—and are thriving. On the market, for example, is the Loopwind Wind Turbine, a high-torque, six-bladed turbine that captures wind with both front and rear blades. Japanese developers say that the design allows the Loopwing to be free of torque-imbalance suffered by VAWTs while being less affected by centrifugal force as compared with the propeller type. They also claim not only that the turbine rotates at wind speeds as low as 1.6 m/s but that it has a power coefficient of more than 40% in wind tunnel tests (with wind speeds of 8 m/s).

Among the “wackier” concepts are the larger, more ambitious architectural wind turbines. Several proposals have been made to integrate wind turbines into skyscrapers. The 600-meter-tall Anara tower in Dubai, for example, was designed to look like a massive wind turbine. Those plans were cancelled in 2009, but others are becoming reality. Last year, London saw completion of the £113.5 million Strata Tower (Figure 23), which generates a tenth of the power used by the building (a total of 50 MWh annually) via three five-bladed built-in turbines.



Figure 23. Tower of London. The Strata Tower in London’s Elephant and Castle neighborhood is a 43-story, 147-meter-high building that features three five-bladed built-in wind turbines.

Other concepts involve “biological” exteriors for buildings. Agustin Otegui, inventor of the “NanoVentSkin,” would incorporate tiny, biological self-repairing wind turbines into the outer layer of a building (Figure 24). “The outer skin of the structure absorbs sunlight through an organic photovoltaic skin and transfers it to the nano-fibers inside the nano-wires which then is sent to storage units at the end of each panel. Each turbine on the panel generates energy by chemical reactions on each end where it makes contact with the structure. Polarized organisms are responsible for this process on every turbine’s turn.”

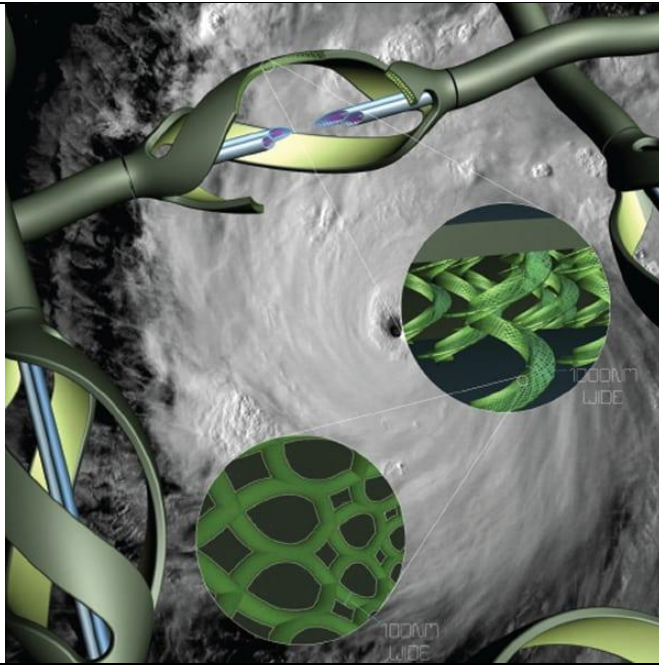


Figure 24. Turbine skin. The NanoVent Skin concept from designer Agustin Otegui features miniscule bio-turbines that could clad buildings to generate power.

Turbine Types

Wind turbines are mainly classified by rotor orientation and installation location. The two fundamental designs are **horizontal-axis** (HAWT) and **vertical-axis** (VAWT) turbines, and each can be deployed onshore or offshore.



Figure 25. HAWT – Horizontal Axis Wind Turbines

Modern large turbines overwhelmingly use a **horizontal-axis** design[5]. In a HAWT, the rotor axis is horizontal and faces into the wind (see Figure 25). Operates on lift principle. Commercial HAWTs usually have two or three blades (three-blade designs are most common for balance and efficiency). Key characteristics include: - **High efficiency:** HAWTs operate on the aerodynamic lift principle and can capture ~40–50% of wind power[3][5] (approaching the Betz limit of 59.3%[10]). They run at high tip-speed ratios with small blades relative to speed, yielding high power output. - **Yaw control needed:** Because the rotor must face the wind, HAWTs require a yaw mechanism to rotate the nacelle on the tower into the wind. - **Maintenance challenges:** The drivetrain (gearbox, generator) is at the top of a tall tower, so servicing often needs cranes. Modern towers can be 100+ m high[2]. - **Placement:** HAWTs are usually located on high towers to access stronger winds (e.g. average hub heights >100 m onshore[2])(Figure 26), which increases cost but boosts wind speeds.

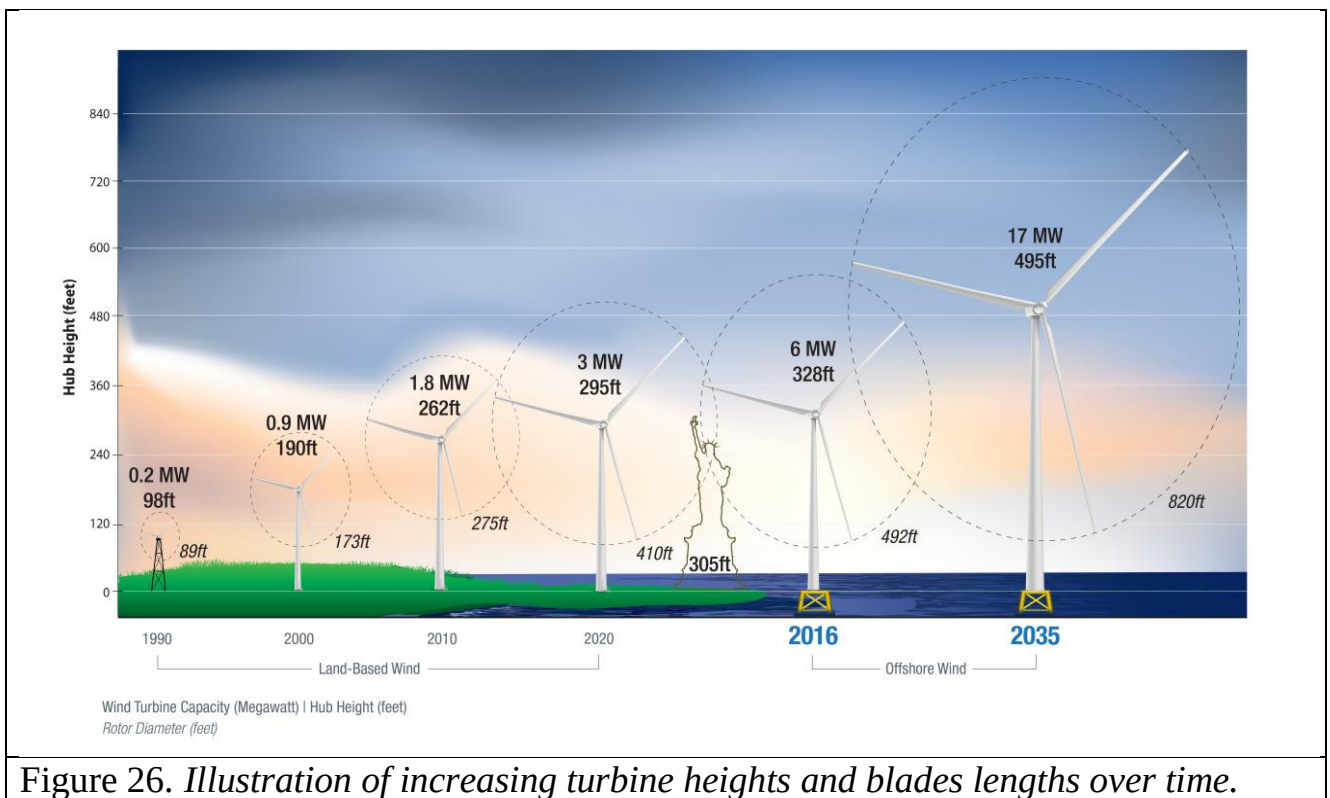


Figure 26. Illustration of increasing turbine heights and blades lengths over time.

In contrast, **vertical-axis** turbines have the rotor shaft vertical. Famous types include the Savonius (drag-based) and Darrieus (lift-based) designs. These have distinct features:

- **Savonius (drag VAWT)**(Figure 27): Consists of two or more scoops (half-cylinders). It self-starts easily (wind direction irrelevant) but has low efficiency (power coefficient $C_p \approx 0.15\text{--}0.20$) [5][7]. It is often used for small-scale or special applications (e.g. ventile cooling) where simplicity and reliability outweigh efficiency loss[12].
- **Darrieus (lift VAWT)**: Often “eggbeater” shaped (troposkein). It operates on lift like HAWTs and can reach higher C_p ($\sim 0.35\text{--}0.4$) [5][7], but it typically cannot self-start and experiences large fluctuating loads. The generator is ground-mounted (easier maintenance), and omnidirectional wind capture removes the need for yaw[5]. However, VAWTs generally capture less power than comparably sized HAWTs[8][5].



Figure 27. VAWT – Vertical Axis Wind Turbines. Savonius is another type of VAWT

Scale: VAWTs are rarely used at utility scale (Figure 28). Most commercial turbines are HAWT. VAWTs are more common for small urban installations or experimental systems. Their lower efficiency and engineering challenges (e.g. stress reversals in Darrieus blades[9]) limit widespread use[9].



Figure 28. VAWT – Vertical Axis Wind Turbines. This is an image of a Darrieus wind turbine.

Wind Turbine Components

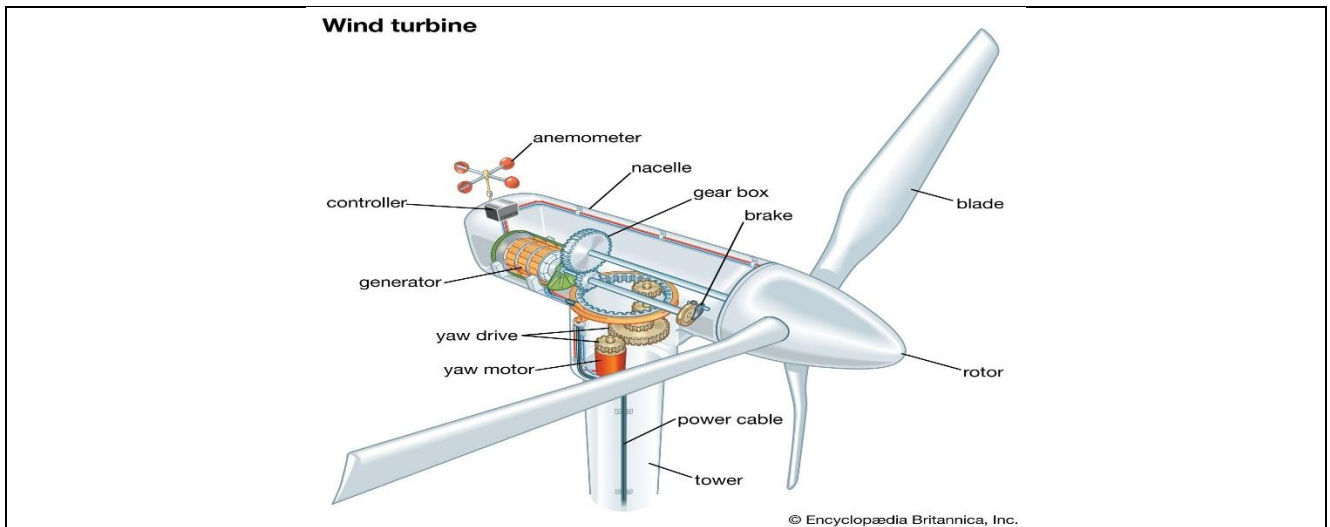


Figure 29. The internal structure of a modern horizontal-axis wind turbine(https://dishcuss.com/post/C40E4D974269979E369C1264009DE70D9CD83850/A57D545CAC8F0246D32A46757AFC6B186AD45750?utm_medium=organic&utm_source=yandexsmartcamera)

Figure 29 illustrates the internal structure of a modern horizontal-axis wind turbine. Each labeled component plays a specific role in converting wind energy into electrical energy.

1. **Blade** – Captures kinetic energy from wind. Its airfoil shape creates lift, causing the rotor to spin. Usually made of fiberglass or carbon fiber.
2. **Rotor** – The rotating part connecting blades to the shaft. Converts wind kinetic energy into mechanical rotation.
3. **Nacelle** – The housing that contains key components (gearbox, generator, brake, controller). Protects them from weather.
4. **Gear Box** – Increases rotation speed from 10–60 rpm (rotor) to about 1000–1800 rpm (generator). Some turbines use direct-drive systems instead.
5. **Brake** – Stops the rotor in emergencies or during maintenance. Can be hydraulic, mechanical, or aerodynamic.
6. **Generator** – Converts mechanical rotation into electrical energy through electromagnetic induction.
7. **Controller** – Starts and stops the turbine automatically, manages pitch angle, and prevents overload at high wind speeds.
8. **Anemometer** – Measures wind speed and sends data to the controller to decide when to start or stop.
9. **Yaw Drive and Yaw Motor** – Rotates the nacelle to face the wind direction,

maximizing efficiency.

10. **Tower** – Supports the turbine at height (60–150 m). Made of steel or concrete to resist wind loads.

11. **Power Cable** – Carries produced electricity down the tower to a transformer and power grid.

12. **Yaw Drive Mechanism** – Connects yaw motor to nacelle base for smooth orientation adjustment.

Physics of Wind Turbine Operation

Wind turbines convert wind's kinetic energy into mechanical and then electrical energy. The process follows this chain:

Wind → Rotor → Shaft → Generator → Electricity

The efficiency depends on aerodynamic, mechanical, and electrical factors. Faraday's Law states that an electromotive force (EMF) is induced when a conductor moves through a magnetic field.

Basic Principles of Wind Power Conversion

Wind energy is the kinetic energy of moving air:

$$E_k = \frac{1}{2}mv^2 \quad (1)$$

Power available in the wind:

$$P_{wind} = \frac{1}{2}\rho Av^3 \quad (2)$$

where ρ = air density ($\approx 1.225 \text{ kg/m}^3$), A = swept area of rotor (πr^2), and v = wind velocity (m/s). E = efficiency of the turbine. Power increases with the cube of wind speed. Greater power extraction:

- a) Increase in rotor radius (rr) results in larger swept area ($\rho\rho$);
- b) Increase in turbine height allows access to lower density air (ρ) and higher wind speeds (v)

Betz Limit

The maximum theoretical efficiency of energy extraction from wind is 59.3%, known as the Betz limit. In practice, modern turbines achieve 40–50% efficiency.

Aerodynamic Forces

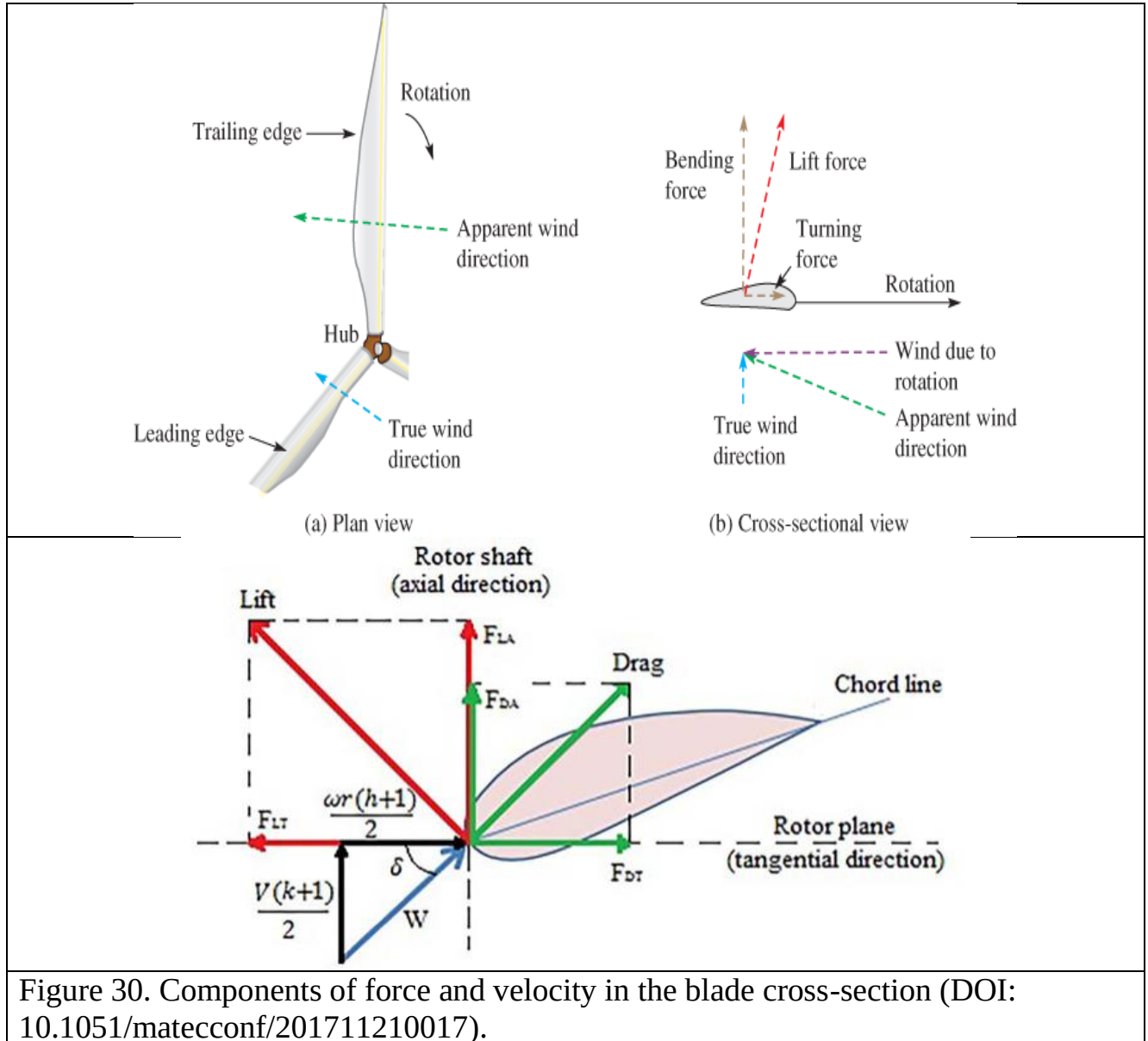
Lift force on a blade section(Figure 26):

$$L = \frac{1}{2} C_L \rho A v^2 \quad (3)$$

Drag Force on a blade section(Figure 26):

$$D = \frac{1}{2} C_D \rho A v^2 \quad (4)$$

Blades are designed to maximize lift while minimizing drag. The lift-to-drag ratio determines aerodynamic efficiency.

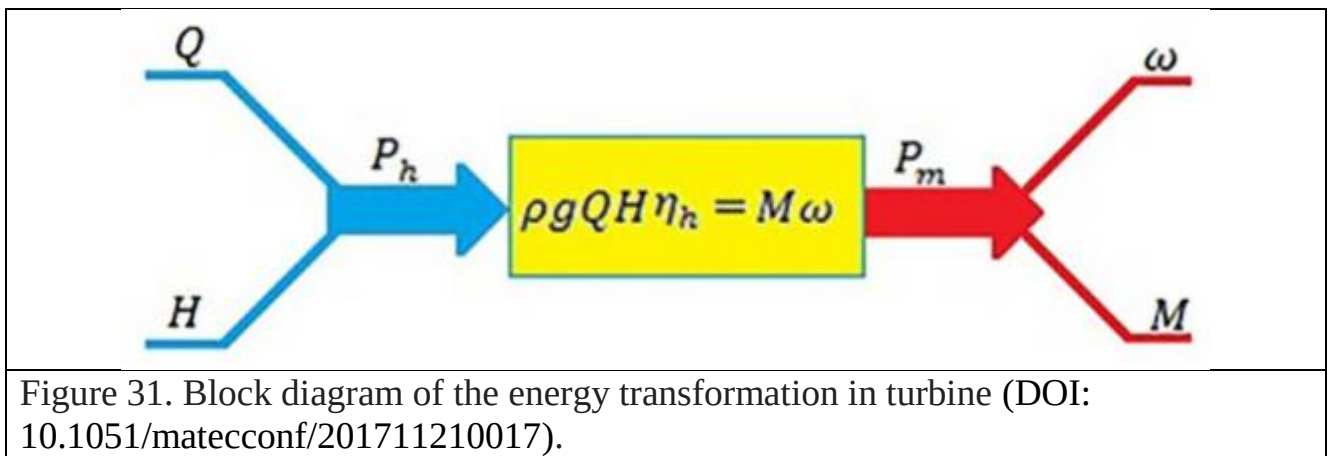


Aerodynamic performance is fundamental for efficient rotor design. Aerodynamic lift is the force responsible for the power yield generated by the turbine

and it is therefore essential to maximise this force using appropriate design. A resistant drag force which opposes the motion of the blade is also generated by friction which must be minimised.

The methodology used for aerodynamic calculations is the Blade Element Momentum Method. The fundamental components of the rotor are the blades [11, 12, 13]. They are the devices that convert the force of the wind into the torque needed to generate useful power.

A turbine is a hydraulic machine that transform hydraulic energy of a fluid into mechanical energy. The block diagram which shows the transformation of hydraulic energy (load H and flow Q) into mechanical energy (torque M and angular velocity ω) is shown in Figure 31.



Kinematic chain for wind turbines

The energy conversion chain is organised into four subsystems (as can see in Figure 32): aerodynamic subsystem, consisting mainly of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades; drive train, generally composed of: low-speed shaft – coupled with the turbine hub, speed multiplier and high-speed shaft – driving the electrical generator.

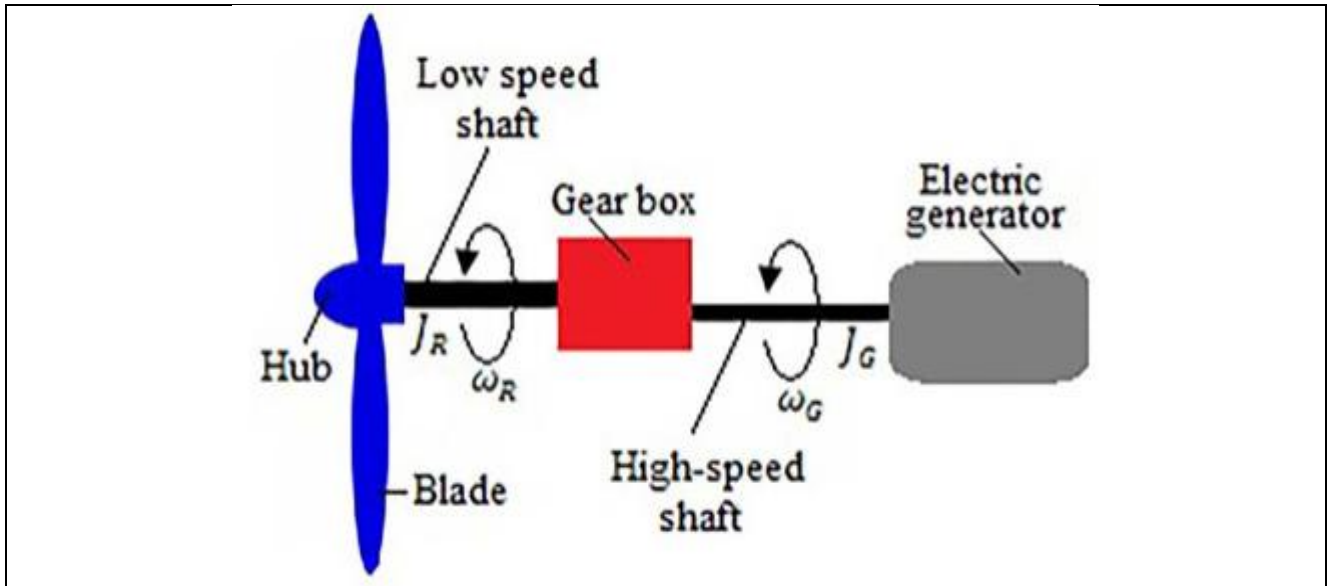


Fig. 32. The diagram of the drive train. (DOI: 10.1051/mateconf/201711210017)

After the analysis of the diagram presented in Figure 32, we can write the equations of equilibrium:

$$M_R - M_{GBi} = J_R \frac{d\omega_R}{dt} + B_R \cdot \omega_R \quad (5)$$

$$M_{GBe} - M_G = J_G \frac{d\omega_R}{dt} + B_G \cdot \omega_G \quad (6)$$

Where:

- B_R and B_G are the constant friction in the rotor and generator system
- M_R is the rotor torque;
- M_{GBi} is the gear box torque to the start;
- M_{GBe} is the gear box torque to the end
- M_G is the generator torque to the end;
- J_R is the moment of inertia of the rotor;
- J_G is the moment of inertia of the generator;
- ω_R is the rotational speed of the main shaft;
- ω_G is the rotational speed to the start of generator.

From (5) result:

$$\frac{d\omega_R}{dt} = \frac{M_R - M_{GBi} - B_R \cdot \omega_R}{J_R} \quad (7)$$

The moment of inertia of the rotor for a wind turbine with n blades [15] is given by:

$$J_R = n \cdot m \cdot r_i^2 \quad (8)$$

Where, n is the number of blades, m is the mass of one blade, and r is the radius of weight centre of blades. After analysis of relations (7) and (8) one can draw the following conclusion : importance of decreasing moment of inertia of rotor hence its inertial mass, will lead directly to increase rotational speed of main shaft so will enable faster start at low speed wind of power plant.

One of possible way to reduce the moment of inertia is given by reducing weight of blades. Wind turbine blades have been made from a variety of materials that range from wood to metals to composites. The key structural design requirements for the turbine's blades are: must be strong to resist the extreme loads, must be stiff to prevent collision with the tower, must be as light as possible to minimize the cost and the starting, and should be stiff and light to avoid resonance.

Table 1. Mass of the blade for the three materials.

Material	Steel	Aluminum	Epoxy carbon
Mass of blade (Kg)	685.37	241.85	139.69

7. Electricity Generation and Grid Connection

The generator produces AC electricity, which may vary in frequency. Power electronics such as converters and inverters stabilize the output for grid connection or battery storage.

8. Efficiency and Power Regulation

Power Coefficient (C_p):

$$C_p = \frac{P_{turbine}}{P_{wind}}$$

Modern turbines achieve C_p between 0.4 and 0.5.

Turbine Power Curves

Each turbine has a power curve showing **cut-in speed** ($\approx 3\text{--}4$ m/s), **rated speed**, and **cut-out speed** (≈ 25 m/s)(Figure 33).

Cut-In Speed: Speed below which power is not generated

Rated Wind Speed: Speed at which power is 100% of rated power

Cut-Out Speed: Speed at which turbine shuts down to protect rotor and drive train from damage.

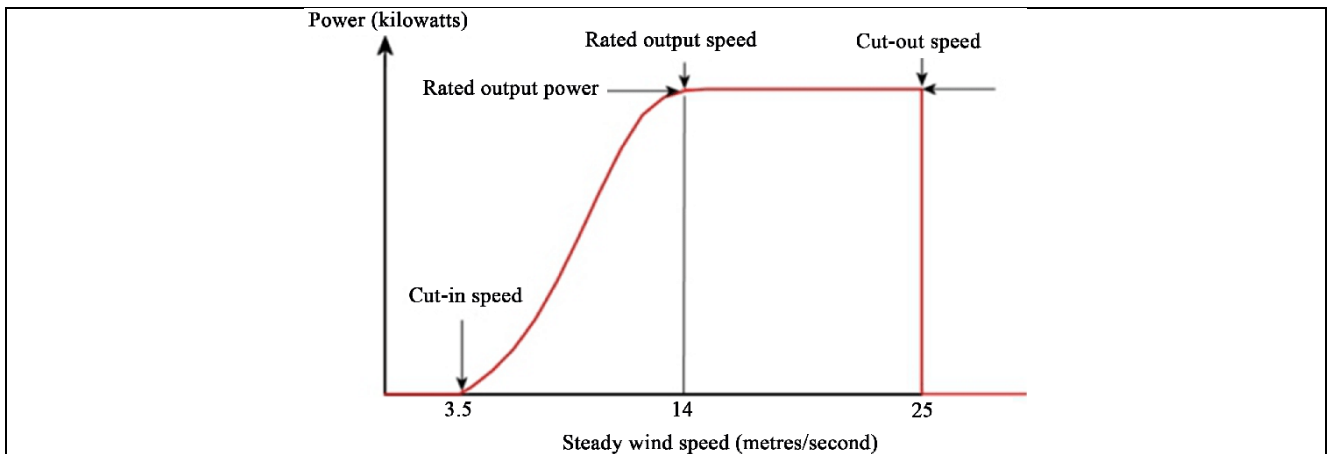


Figure 33. Power curve for a wind turbine (Source: Monnerie et al. (2015))

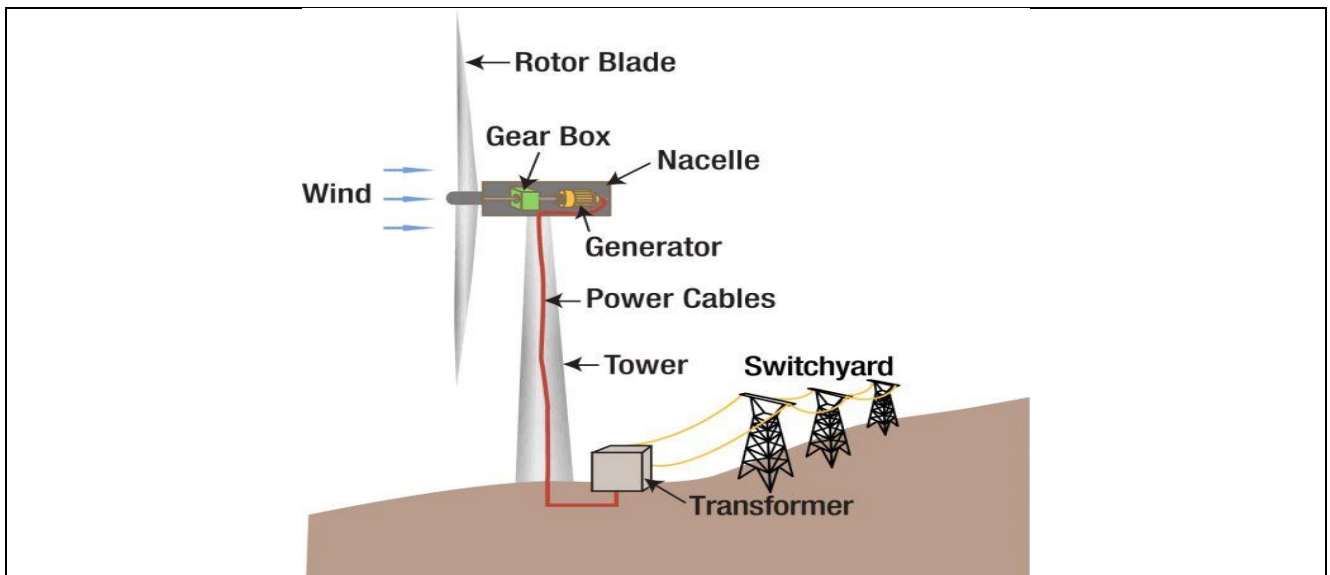
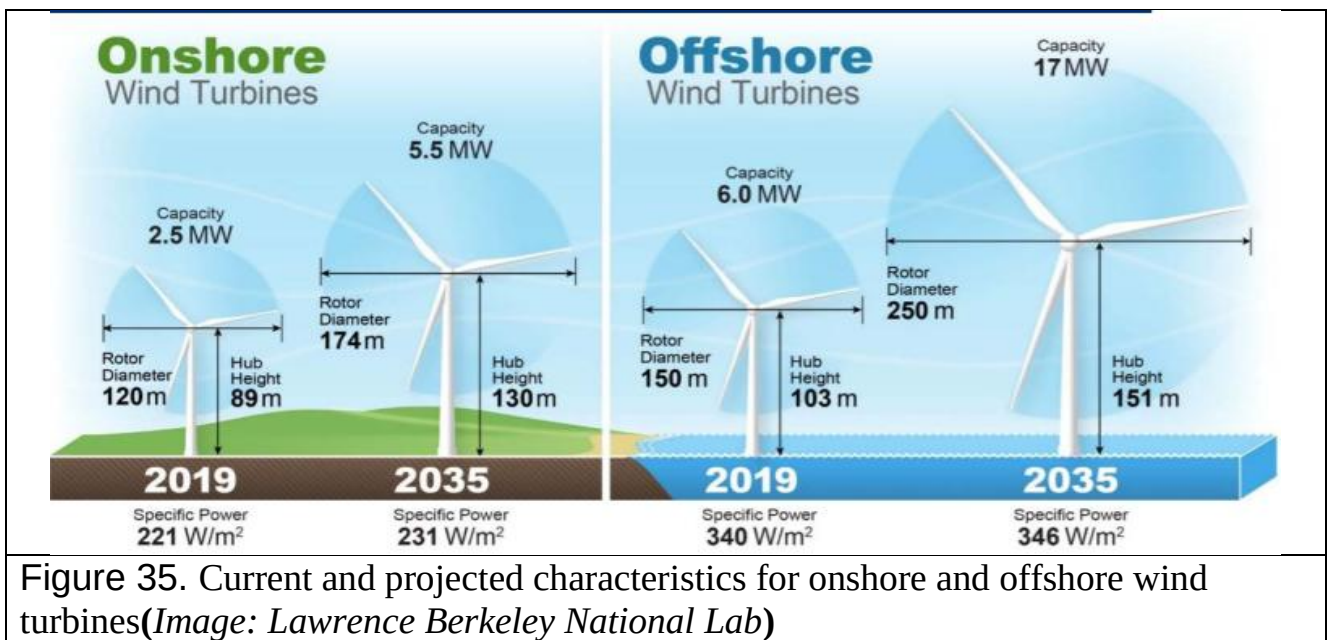


Figure 34. Process of Wind turbine

This schematic clearly demonstrates(Figure 34) the energy conversion process from natural wind flow to usable electricity, highlighting the interaction between **aerodynamic, mechanical, and electrical** systems within a wind turbine installation.

Onshore vs Offshore

Wind farms can be on **land (onshore)** or at **sea (offshore)**(Figure 35). Onshore turbines are typically smaller (1–5 MW) and cheaper per kW, but contend with land-use constraints, turbulence, and lower average wind speeds. Offshore turbines (see figure) are usually very large (8–15+ MW) and mounted on sturdy foundations or floating platforms.



Offshore wind benefits from stronger, steadier winds (higher capacity factors). For example, new offshore projects may exceed 60% capacity factor by 2050[3]. Offshore projects avoid land conflicts and often have higher yields, but they face higher costs (foundation, maintenance, transmission) and harsh marine conditions. Key contrasts include: - **Onshore:** Lower construction cost, easier access. Average capacity factor ~30–40% (e.g. ~34% in US[10]). Rated sizes typically 2–5 MW[3]. - **Offshore:** Higher yields (CF ~40–50+%), but much greater capital cost. Foundations must resist waves/corrosion. Average turbine size is larger (commonly 8–15 MW today[3]). For example, the GE Haliade-X (12 MW, 220 m rotor) is an offshore model.

- **Floating vs fixed:** Most offshore (≤ 50 m depth) use fixed monopile or jacket foundations; deeper waters require floating turbines (an area of active development).

Fixed vs. Floating Offshore Wind

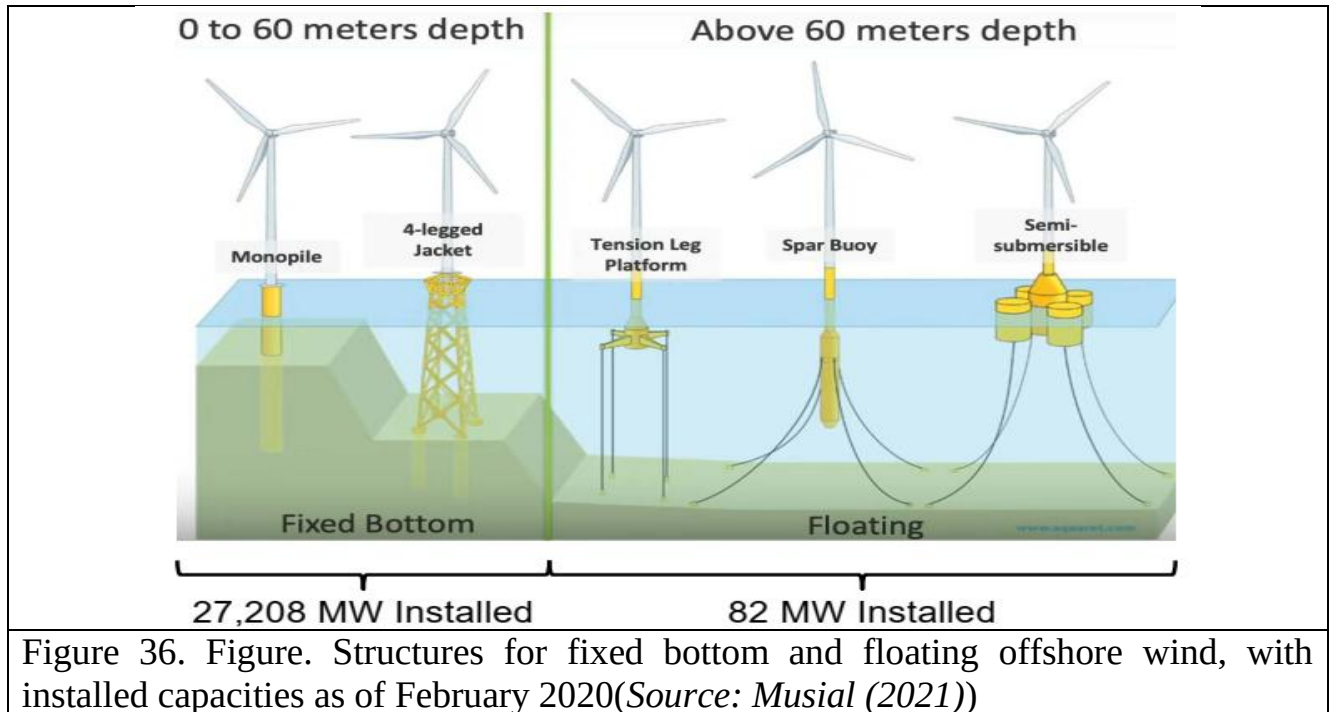


Figure 36. Figure. Structures for fixed bottom and floating offshore wind, with installed capacities as of February 2020(Source: Musial (2021))

In water depths greater than 60 m, floating structures may be more economical. “~80% of offshore wind resources are in waters greater than 60 m deep. Floating wind enables sites to be located further from shore, with better wind resources. Floating wind technology is expected to be widely deployed at utility scale starting in 2024.

Rotor Blades

Function: Capture wind energy and convert it into rotational motion.

Explanation: Blades act like airplane wings—creating lift due to air pressure difference between upper and lower surfaces.

Typical number: 2–3 blades (modern turbines usually 3 for balance and efficiency).

Materials: Fiberglass-reinforced polyester, carbon fiber composites.

Blade Design and Materials

Blades are critical for capturing wind energy. Modern blades are long, slender airfoils that twist from root to tip so that the angle of attack is optimal along the span. They incorporate aerofoil cross-sections (similar to aircraft wings) with **pitch control** (each blade can rotate slightly about its axis) to regulate rotor speed and power. Typical blades today range from ~20 m (small turbines) to 100+ m (largest offshore rotors). Longer blades sweep more area (power $\propto$ swept area), but must remain stiff and light.

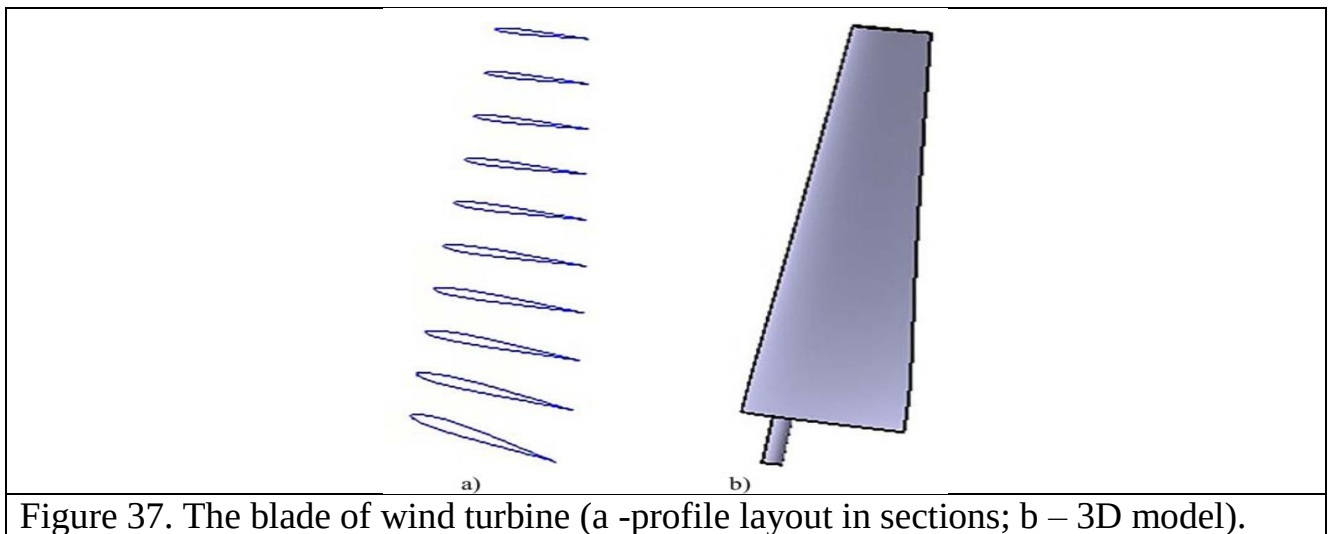


Figure 37. The blade of wind turbine (a -profile layout in sections; b – 3D model).

For a given situation, specifically for an average wind speed, $V = 7\text{m/s}$ and a rotordiameter $D = 5,8\text{ m}$, was made aerodynamic blade computing. In these conditions it wascalculated the blade in ten sections, as can be seen in Figure 37.a. 3D model of blade,presented in Figure 37.b, was obtained uniting the ten sections using Catia software. Othermethod to change dynamic and mechanical properties of wind turbine is modifying thematerial, which the blade is made of [13].

Figure 38 shows the geometry and aerodynamic design of a wind turbine blade. The blade is not flat—it has a twist angle distribution and chord distribution along its length to optimize aerodynamic performance.

Twist angle distribution: The blade is twisted so that each section meets the incoming wind at the correct angle of attack. The base has a larger twist angle, while the tip has a smaller one.

Chord distribution: The chord length (width of the blade) decreases from root to tip to balance lift and minimize drag.

Blade profile (airfoil): Each cross-section of the blade has an airfoil shape that generates lift, causing the rotor to spin.

Overall, this design ensures maximum energy extraction from the wind by maintaining optimal aerodynamic efficiency along the entire blade length.

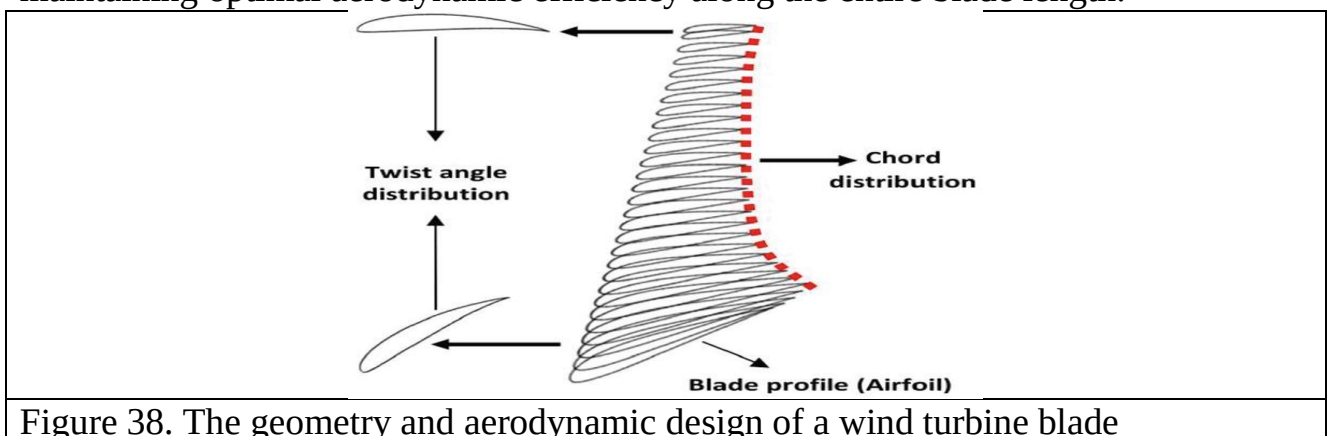


Figure 38. The geometry and aerodynamic design of a wind turbine blade

Materials for blades have evolved: early windmills used wood, early turbines tried steel (as in the 1941 Grandpa's Knob machine[1]), but failures led to fiberglass composites. Since the 1960s, blades have been made of **fiber-reinforced polymers** (usually glass fiber/epoxy)[1]. Modern large blades often include carbon-fiber reinforcements (in spar caps) to increase stiffness without adding weight[1]. Natural fibers (bamboo, flax) have been explored for cost or eco-benefits[1]. In summary: - **Airfoil shape:** Blades have aerodynamically optimized profiles, designed by computational tools. They are long and tapered, with twist to maintain optimal angle vs wind speed. - **Number of blades:** Most HAWTs use three blades. Two-blade designs exist (slightly cheaper but noisier), and one-blade designs are rare (balance issues). Three-blade sets offer smoother torque and lower vibration[5]. - **Composite construction:** Blades consist of layers of fiberglass (or carbon) fabric embedded in epoxy resin. The layup may include foam or balsa core sections for stiffness. The result is a strong, lightweight structure. - **Testing:** Blades undergo extensive static and fatigue testing to withstand years of cyclic wind loading.

Manufacturing Methods

Wind turbine components are built using specialized industrial processes:

- **Blade manufacturing:** Large blades are produced in two-shell molds. Dry fiber fabrics (glass or carbon) are laid into the mold, often in multiple layers with structural cores. Resin is then infused under vacuum (Vacuum-Assisted Resin Transfer Molding, VARTM)[1]. This vacuum infusion method yields high fiber content and low voids. Alternatively, prepreg (pre-impregnated) fibers are sometimes used for high performance (e.g. by Vestas)[1]. Older techniques (e.g. wet hand lay-up) have been largely replaced by automated infusion. After curing, the two halves are bonded together at the spar (root) and shell (leading/trailing edge) joints. Emerging technologies include automated fiber placement and segmented blade assembly (for easier transport)[1].
- **Tower construction:** Towers are usually cylindrical steel tubes (sometimes concrete or hybrid). Sections are formed by rolling and welding steel plates (spiral or longitudinal weld) on-site to avoid transport limits[2]. Recent innovation includes onsite spiral-welding techniques (e.g. Keystone Engineering) and even 3D-printing steel tower bases[24].
- **Nacelle/drivetrain:** The nacelle houses the gearbox (if present), generator, yaw drive, and electronics. Gearboxes (often helical spur) and generators (doubly-fed induction or synchronous) are assembled by specialized manufacturers. Direct-drive (gearless) turbines use large permanent-magnet generators to reduce maintenance.

- **Assembly:** Blades are attached to the hub (sometimes via bolted root connections). The rotor head, generator, and electronics are lifted by crane and mounted atop the tower. Onsite commissioning includes alignment and testing.

Manufacturing is now highly industrialized. Large factories (e.g. by Vestas, Siemens Gamesa, GE) can produce hundreds of blades and turbines per year. Continued R&D seeks lighter materials, better adhesive bonding, and recyclability (e.g. thermoplastic resins)[1].

Construction and Building of Wind Turbines(Figure 39)

1. Select a site with average wind speed > 5 m/s.
2. Construct reinforced concrete foundation.
3. Assemble and erect the tower.
4. Install nacelle and rotor assembly.
5. Connect electrical and control systems.
6. Test safety and grid connection systems.



Figure 39. Construction of Wind turbine

(https://www.dolcera.com/wiki/index.php?title=Different_Types_and_Parts_of_a_Horizontal_Axis_Wind_Turbines&mobileaction=toggle_view_desktop)

Performance and Efficiency

The **power** available in wind is given by $P_{wind} = \frac{1}{2} \rho A v^3$, where ρ is air density, A the rotor swept area, and v the wind speed. A turbine's actual power output P_{out} is P_{wind} times a power coefficient C_p . Betz's law sets the maximum theoretical C_p at 59.3%[6], but real machines fall below this. Modern large HAWTs can achieve $C_p \approx 0.40$ – 0.50 at optimal tip-speed ratios[3], meaning they extract roughly half of the

wind's kinetic energy. In practice, C_p depends on blade design and wind speed; drag-based Savonius rotors reach only $\sim 0.15\text{--}0.20$ [7], while lift-based designs (HAWT, Darrieus) can approach 0.45 at peak[3].

Thus, **efficiency** is calculated as

$$\eta = \frac{P_{\text{out}}}{P_{\text{wind}}} = C_p \times \eta_{\text{generator}},$$

where $\eta_{\text{generator}}$ ($\sim 90\text{--}95\%$) accounts for electrical losses in the drivetrain and generator. For example, a turbine in 12 m/s wind with 100 m² rotor ($A \approx 7850 \text{ m}^2$) has $P_{\text{wind}} \approx 7.0 \text{ MW}$. With $C_p=0.45$ and 90% generator efficiency, $P_{\text{out}} \approx 2.8 \text{ MW}$. Manufacturers quote such values as the “rated power” at a certain wind speed (e.g. 12–15 m/s).

Wind turbines are often characterized by a **power curve** (output vs. wind speed). Key points include **cut-in** (the low speed to start generating, $\sim 3\text{--}4 \text{ m/s}$), **rated** (peak output speed), and **cut-out** (high-speed shutdown, $\sim 25 \text{ m/s}$). Between cut-in and rated, P rises roughly with v^3 . Over the full year, the average output (capacity factor) depends on local wind distribution; typical onshore CF is 25–40%, offshore $\sim 40\text{--}50\%$ [3][10]. (For context, solar PV capacity factors are much lower— $\sim 17\%$ in 2024[10]—since sun availability is more variable and day-only.)

Characteristic efficiencies and values by type: - Savonius VAWT: $C_p \approx 0.15\text{--}0.20$ [7]. Self-starting; used for small power (e.g. meters, buoys) where cost and reliability matter more than efficiency[5]. - Darrieus VAWT: $C_p \approx 0.35\text{--}0.40$ (near-lift limit) at $\text{TSR} \approx 4$ [8]. Not self-starting; mostly experimental or niche uses. - 3-blade HAWT: $C_p \approx 0.40\text{--}0.50$ (peak)[3], typical modern utility machines. - 2-blade HAWT: slightly lower C_p ($\sim 0.35\text{--}0.45$) and more noise/imbalance, but lower cost. - Offshore HAWT: similar C_p but higher CF ($\sim 50\%$) due to steady winds[10].

Voltage–Current Characteristics: Unlike solar panels, wind turbines generate AC electricity via synchronous or induction generators. The turbine's electrical output is controlled by power electronics, not a fixed I–V curve. Instead, one uses the *power curve* or wind speed–power relationship (Figure 40). (If a small turbine drives a DC generator, an I–V curve could be drawn at fixed blade settings, but that is uncommon in utility systems.)

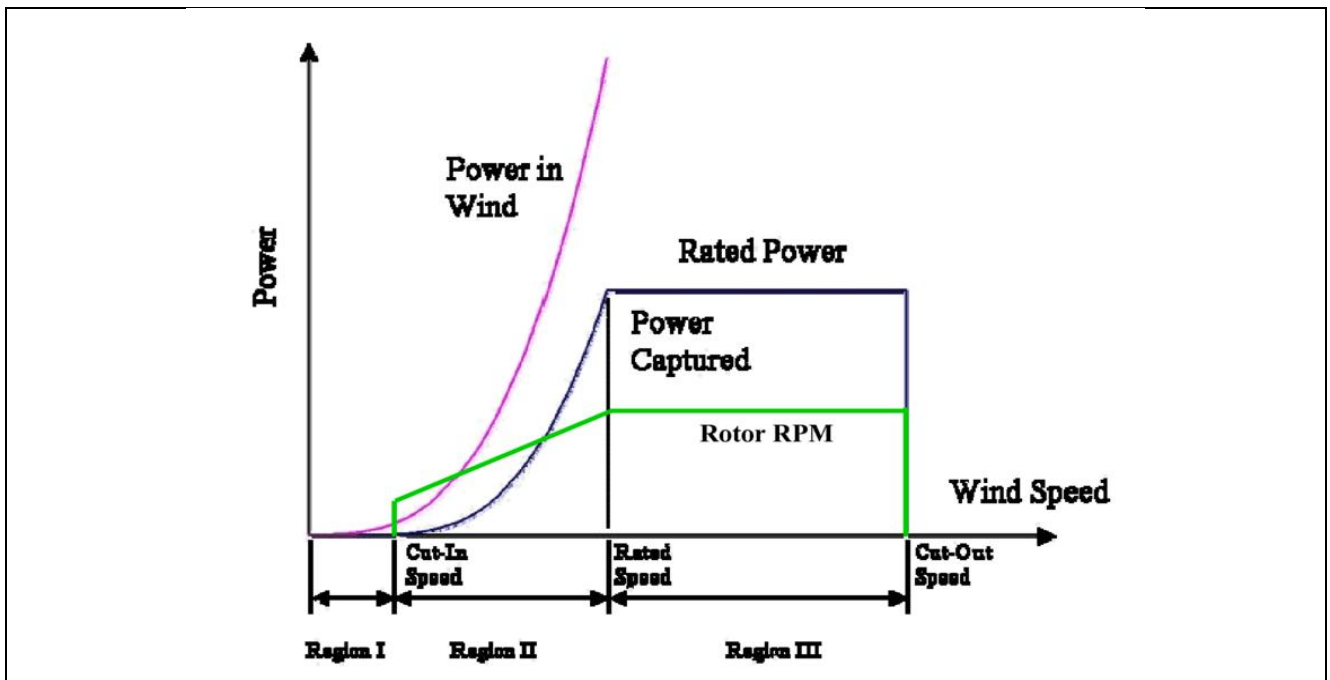


Figure 40. A typical power output versus wind speed curve.

Turbine Examples and Comparisons

Representative examples (Table) illustrate the range of wind turbine technology. For example, onshore utility turbines today often have 2–4 MW ratings with ~100 m rotors, whereas offshore machines exceed 10 MW with ~200+ m rotors [2][3]. The **DOE reports** that the average new U.S. turbine in 2023 was 3.4 MW with a 133.8 m rotor diameter [2] – about 4.4 times the rotor area of a 20-year-old machine. Larger rotors capture dramatically more wind (power $\propto$ area), which has driven growth: in 2023, 98% of U.S. new turbines had rotors ≥ 115 m across [2].

Table-2. The range of wind turbine technology

Type	Rated Power	Rotor Diameter	Typical Power Coefficient (C_p)	Notes
Onshore HAWT (3-blade)	~2,000 kW (2 MW)	~100 m	~0.45	Standard modern design. Example machine: 3-blade horizontal axis wind turbine. Capacity factor (CF) ~30-35%.
Small HAWT	~10-20 kW	~5-10 m	~0.35	Used on rural or agricultural sites. Lower tip-speed ratio leads to lower aerodynamic efficiency (~0.3-0.4).
Offshore	~12,000 kW	~220 m	~0.50	Large offshore machines, very

Type	Rated Power	Rotor Diameter	Typical Power Coefficient (C_p)	Notes
HAWT	kW (12 MW)			high yields. Capacity factor in favourable sites ~45-60%.
VAWT (Savonius)	~1-10 kW	~2 m	~0.15-0.20	Vertical-axis Savonius type. Simple and cheap, but low aerodynamic efficiency.
VAWT (Darrieus)	~50-500 kW	~20 m	~0.40	Vertical-axis Darrieus type in niche applications. Higher efficiency than Savonius but less common at large scale.

Rated Power: This is the turbine's nominal output under its design wind or operating conditions.

Rotor Diameter: The diameter of the swept area of the blades (for HAWT) or equivalent swept path (for VAWT). Larger diameter generally means more wind area and potentially more power.

Typical C_p : The power coefficient, defined as the fraction of the available wind power that the turbine rotor extracts. The theoretical maximum (the Albert Betz/Betz limit) is about 0.593. In real machines, typical values are lower due to aerodynamic, mechanical and control losses.

Notes: Provides context: whether the type is common, what wind-site conditions apply, and any typical capacity factor or special considerations.

These examples show that larger turbines (offshore) have higher capacity and often higher C_p due to more optimized blades. In all cases, real-world power output is slightly less due to losses in the gearbox/generator (~5–10%) and electrical systems.

Wind vs. Solar: Efficiency and Cost

Wind and solar compete and complement each other in renewable energy systems. In terms of **energy capture**, wind turbines (onshore) convert ~50% of wind power into electricity[8], whereas **solar PV panels** convert ~15–22% of sunlight (for commercial crystalline silicon panels). However, these percentages are not directly comparable because of different resource availability. A more relevant metric is **capacity factor**: wind turbines typically have higher capacity factors than solar PV in many regions. For example, global weighted capacity factor was ~34% for onshore wind vs ~17% for utility solar PV in 2024[10], reflecting the fact that wind often blows day and night, whereas solar only produces in daylight.

In terms of **cost and performance**, onshore wind is generally one of the cheapest sources of new electricity. The International Renewable Energy Agency reports (2024

data) that global average levelized cost of electricity (LCOE) was about **\$0.034/kWh** for onshore wind and **\$0.043/kWh** for utility solar PV[10]. Offshore wind is more expensive (~\$0.079/kWh) but improving. Thus, wind and solar are now often cheaper than fossil fuel generation in many markets.

Comparing key factors:

- **Energy yield:** Wind turbines (especially offshore) can deliver large amounts of energy continuously when windy; solar produces only in daylight. Their generation profiles often complement each other.
- **Land use:** Both require area; wind farms need spacing (turbines ~5–10 rotor diameters apart), but land can often be used for agriculture. Solar farms require continuous space or rooftops.
- **Environmental impact:** Both have low emissions; wind turbines are silent (noise ~35–45 dB at 350 m[3]) and pose some bird/bat collision risks. End-of-life recycling (especially blades) is an ongoing challenge for both wind and solar.

Finally, note advanced solar technologies: heterojunction (HJT) silicon cells are a leading PV innovation, achieving record efficiencies (~26–27%) in the lab. While HJT is a solar topic, it illustrates how solar cell *conversion efficiency* has been pushed upward, somewhat narrowing the fundamental efficiency gap with wind's power capture. In practice, choice between wind and solar depends on site resource (windy vs sunny), grid needs, and economics.

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Chapter X

10. SOLAR PANEL MAINTENANCE AND MONITORING IN PV SYSTEMS

10.1. Cleaning of Solar Panels

Cleaning of solar panels is an essential maintenance activity to mitigate soiling losses. *Soiling* refers to the accumulation of dust, dirt, bird droppings, and other debris on the surface of photovoltaic (PV) modules, which blocks or scatters incoming sunlight and thus reduces the light available for conversion to electricity[1]. Even small amounts of dust can have measurable effects, similar to a dirty car windshield that reduces visibility[1]. The impact of soiling on solar panel efficiency can range widely depending on environmental conditions: typical annual energy losses of around 5% are assumed in many performance estimates, but losses can span from 2% in rainy climates to as high as 20–25% or more in arid, dusty regions[1]. In extreme cases (e.g. desert environments with frequent dust storms), soiling can **drastically** cut output – studies have documented 20–50% energy yield reductions in desert regions, and even up to ~80% efficiency drop during severe events. Clearly, without intervention, panel soiling can severely undermine a PV system's performance over time.

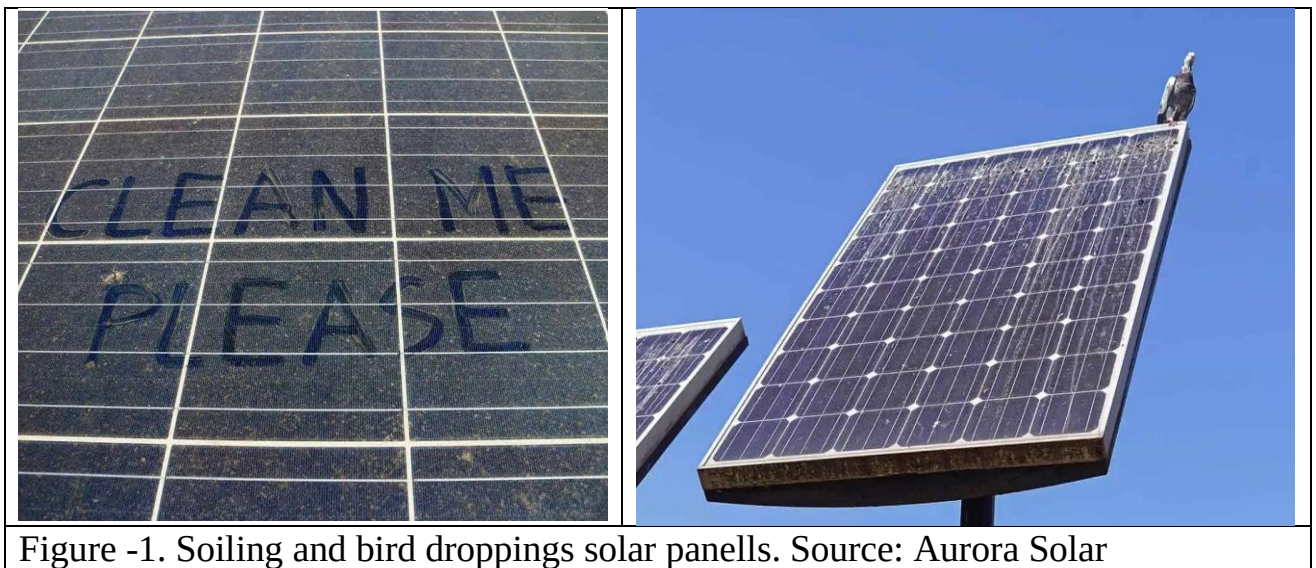


Figure -1. Soiling and bird droppings solar panells. Source: Aurora Solar

Theoretical Background: Soiling and Efficiency Loss

When sunlight hits a solar cell, any opaque material on the panel's glass will attenuate the light. In optical terms, dust and grime create a filtering layer that reduces the solar irradiance reaching the photovoltaic cells[1]. The effect is roughly proportional to the fraction of the glass covered or the light blocked, though it can be nonlinear if the

soiling is non-uniform. For example, a completely uniform thin film of dust might reduce light by a certain percentage across the whole panel, directly cutting output by a similar percentage. On the other hand, a localized opaque spot (like bird droppings) can disproportionately affect output by blocking current in one cell and potentially activating bypass diodes, which can reduce the contribution of an entire substring of cells[1]. Either way, soiling translates to lost energy.

Soiling Factor $S(t)$ in Photovoltaic Systems

Dust and dirt on a solar panel's surface block incoming sunlight. The *soiling factor* $S(t)$ is defined as the **fraction of light reaching the photovoltaic cells** at time t . In other words, $S = 1$ when the panel is completely clean (no loss of light), and $0 < S < 1$ when some sunlight is obstructed by soiling (dust, pollen, etc.). For example, if a heavy dust layer blocks 10% of the light, then $S \approx 0.90$. In PV performance models, $S(t)$ is used by simply scaling the incident irradiance or cell current by $S(t)$. Thus the effective irradiance on the cells is $S(t) \cdot I_{\text{incident}}$, and the panel's power output is roughly $S(t)$ times what it would be if clean.

Time Variation of $S(t)$

The soiling factor $S(t)$ **declines over time** as dust accumulates. Typically $S(t)$ starts at 1 (or near 1) right after cleaning or rain, and then gradually falls during dry, dusty periods. This creates a characteristic *sawtooth* profile: during dry spells soiling builds up and $S(t)$ drops (often approximately linearly with time), and then a rain or cleaning event “resets” $S(t)$ close to 1[33]. In practice many models assume a constant soiling rate between cleanings (e.g. $S(t) = 1 - \alpha t$ for some rate α), though some use exponential decay (e.g. $S(t) = e^{-kt}$) [33]. The key point is that $S(t)$ typically **decreases stepwise** (smoothly between cleanings, then jumping up when cleaned).

Impact on Panel Output

Because a PV panel's current (and thus power) is roughly proportional to the light hitting its cells, a lower $S(t)$ directly means lower power. In fact the *soiling ratio* is often defined as

$$SR(t) = \frac{E_{\text{soiled}}}{E_{\text{clean}}} = S(t),$$

where E is the energy or irradiance. Thus if $SR = 0.90$, the panel produces 90% of the energy of a perfectly clean panel (a 10% loss). Equivalently, the **soiling loss** is $1 - S(t)$. For example, a soiling factor of 0.95 corresponds to a 5% loss of available light (soiling loss), and one often simply multiplies all performance calculations by $S(t)$ to account for this. In commercial models like PVWatts or Sandia's PV array

model, one multiplies the plane-of-array irradiance by the soiling factor (SF) so that the output scales directly with $S(t)$. As a rule of thumb, even a few percent drop in S can noticeably cut annual energy yield. For instance, NREL data show many sites with an **insolation-weighted soiling ratio** around 0.95–0.98, implying roughly 2–5% average annual energy loss to soiling[36]. In short, any fraction of blocked light immediately translates to the same fraction of output loss.

Modeling Equations

Analysts sometimes write simple equations for $S(t)$. A basic model might assume a constant deposition rate α of dust, giving $S(t) = 1 - \alpha t$ (linear decrease) between cleans, or $S(t) = e^{-kt}$ (exponential). More sophisticated physics-based models relate S to the accumulated dust mass ω on the panel. For example, the HSU (Humboldt State) soiling model uses an empirical formula:

$$S = 1 - 0.3437\text{erf}(0.17\omega^{0.8473})$$

where ω is the dust mass per area and erf - error function[35]. In this formulation, S drops smoothly as ω grows, and when ω is reset to zero by cleaning, S returns to 1. Regardless of the exact formula, the **role** of $S(t)$ in any PV model is the same: it multiplies the incident light term (or module current) to account for the fraction of light lost to soiling.

Immediately after cleaning, $S(t) = 1$ (100% light transmission); as dust accumulates, $S(t)$ declines. Empirical studies have measured soiling accumulation rates on the order of 0.01% per day in very clean environments up to 0.5% per day in extremely dusty conditions[1]. This means that each day without cleaning, a panel might lose a tiny fraction of a percent of its output – but over weeks and months, these losses compound. If we assume a roughly linear accumulation, a simplified model could be $S(t) = 1 - \alpha t$ (for t in days and small α), though in reality deposition can be nonlinear and weather-dependent. In any case, **degradation rates** due to soiling are site-specific. For instance, one dataset found soiling rates around 0.03–0.15% per day in various U.S. locations, but about 0.5% per day in a Middle Eastern desert[1].

The relationship between soiling and power output is also influenced by weather events. Rainfall can act as a natural cleaning mechanism. A brief heavy rain may wash off a substantial portion of loose dust, partially restoring $S(t)$. Regions with regular rain (e.g. tropical or temperate climates) often exhibit lower average soiling losses (perhaps ~2% annually) because nature provides periodic cleaning[1]. Conversely, regions with long dry seasons and high dust (e.g. parts of the Middle East, North Africa, etc.) can see continuous accumulation and high losses if panels are left uncleaned for months[1]. Rain variability causes seasonal patterns: for example, Southern California PV systems have shown high soiling losses in the dry summer, dropping off after winter rains[1]. In summary, the theoretical impact of soiling is the

reduction of transmittance of the PV module's cover glass, thereby lowering the irradiance on cells and the resulting current. It creates a *parasitic absorption and reflection* layer. Removing that layer via cleaning restores the panels closer to their optimal light input.

Cleaning Frequency, Conditions, and Performance Degradation

Because soiling accumulates gradually, **cleaning frequency** is a key consideration in maintenance planning. The goal is to maximize energy yield (and revenue) by cleaning often enough to avoid large losses, but not so often that maintenance costs outweigh the gains. If we denote by ΔE the energy lost due to soiling between cleanings, and C the cost (or effort) of a cleaning event, an optimized schedule balances these factors. Theoretical models for optimal cleaning interval often treat soiling accumulation as roughly linear over time and then a reset upon cleaning. One simple model described by the National Renewable Energy Laboratory (NREL) assumes a steady soiling increase and found, for example, that a system accumulating an annual loss of 1.9% (if never cleaned) could limit the loss to $\sim 1.5\%$ with one cleaning per year, $\sim 1.3\%$ with two cleanings per year, and $\sim 1.2\%$ with three cleanings per year[1]. Diminishing returns are evident – beyond a certain point, additional cleanings yield only marginal improvement in average soiling levels.

Empirically, optimal cleaning frequency depends on local conditions like dustiness and rainfall. In some environments, *monthly* cleaning might be optimal, whereas in others *quarterly* or even just *biannual* cleaning suffices. A study in Palestine's climate concluded different optimal cleaning periods by season – e.g. during the dry summer months, monthly cleaning was warranted, whereas in wetter months a bi-monthly schedule sufficed[1]. Generally, more frequent cleaning is needed in the dry season and in desert or agricultural areas with high dust, whereas in rainy or cleaner environments panels can go longer. Many PV operators schedule at least an **annual** cleaning (often after pollen season or dusty summer, or before a high-insolation season) as a baseline. High-value or utility-scale installations in dusty locales may clean as often as monthly or even weekly if economics allow.

Optimal conditions for performing the cleaning are also important. It is widely recommended to clean panels during the early morning, late afternoon, or on overcast days – basically when the sun is low or absent[1]. There are a few reasons: (1) panels are cooler at those times, so thermal shock from cool water is minimized; (2) intense midday sun could quickly evaporate water and leave deposits or streaks; and (3) worker safety and comfort are better when it's not extremely hot. Cleaning when panels are cool helps avoid cracking the glass due to sudden temperature change (pouring water on a hot panel can cause rapid contraction of the glass surface). Additionally, panels should ideally be de-energized (system turned off) during cleaning for electrical safety[1].

Without cleaning, the **degradation of performance** continues until an equilibrium is reached (for instance, heavy dust might eventually saturate such that wind blows some off as fast as it accumulates). But in practice, performance will decline significantly over long periods. Real-world data from neglect cases show dramatic drops: one source noted efficiency losses reaching ~6.5% after two months without cleaning, and over 20% loss in heavily polluted/dusty environments if left for many months[4]. Thus, cleaning is not just a cosmetic task but critical to *recover* lost efficiency. Immediately after a cleaning, panels often show a jump in power output corresponding to the removal of the soiling loss percentage.

Figure 2 shows the main cleaning methods used for PV panels, while robotic cleaning could be considered an automated method or an independent major method



Rain as a cleaning substitute: Natural rainfall can partially clean panels. Light rain may only redistribute dirt (or worse, create mud streaks), but a strong rain can wash off most loose particles. Studies indicate annual rainfall can mitigate a portion of soiling losses – e.g. one European analysis found yearly gains of 2–10% in energy production attributable to rain cleaning panels periodically[1]. However, relying solely on rain is risky in regions with infrequent rain. In summary, site operators must evaluate how fast their panels get dirty and schedule cleaning accordingly. Some utilize sensors or data trends – for example, comparing a soiled reference cell to a clean one – to decide when cleaning is economically justified.

Manual Cleaning Methods

Manual cleaning is the most straightforward method: human workers physically clean the panel surfaces, typically using simple tools. For small installations

(residential rooftops, small commercial arrays), manual cleaning is common and cost-effective[1]. A basic manual cleaning procedure involves *soft* materials and gentle techniques: for instance, using a soft cloth, sponge, or brush with water to wipe the glass. It is critical that abrasive tools (metal scrapers, steel wool, abrasive scrub pads) are **avoided**, as they can scratch the tempered glass or its anti-reflective coating. Scratches not only reduce transparency but can also create stress concentrators on the glass. Manufacturers and installers often recommend using only non-abrasive implements – e.g. microfiber cloths, soft-bristle brushes or squeegees – and *mild* cleaning solutions[1].

A typical cleaning solution for manual cleaning is either just clean water or water with a mild detergent. Even household glass cleaners can be used if they do not contain harsh chemicals. An example recipe is a mixture of mild soap and vinegar in water[1], which helps dissolve grime but is gentle on coatings. The **water quality** is an important consideration: *deionized* or distilled water is preferred, because hard water (rich in minerals) can leave behind mineral deposits (water spots or scale) when it dries[1]. These residues can themselves reduce transmissivity or even chemically attack coatings over time. If tap water is used, often it's best to squeegee-dry the panels to remove any residue.

When cleaning manually, workers typically first *rinse* or wipe off loose dust (sometimes using a dry wipe or blower) so that rubbing does not grind dust particles against the glass. Stubborn dirt (like bird droppings or sap) might be softened with water and then gently scraped with a plastic blade or cloth. Pressurized water can be used but with caution – high-pressure power washers are generally **not** recommended, as they can force water into panel seals or cause micro-cracks; if used, pressure should be limited (e.g. one manufacturer suggests < 70–100 PSI)[1]. After cleaning, any soapy residue should be thoroughly rinsed off, since dried soap streaks can reduce performance.

One risk of manual cleaning is potential damage from untrained personnel. Walking on panels (for roof arrays) is dangerous and can crack cells; using ladders or reaching over arrays carries safety risks. Additionally, improper technique (e.g. cleaning a hot panel with cold water) can damage the module. Thus, while manual cleaning is **simple and requires low investment**, it must be done carefully. Solar farms often train their maintenance crews or hire professional cleaning services. For home systems, owners might clean panels themselves a couple of times a year with a garden hose and soft brush from the ground (if accessible), or hire professionals if the roof access is difficult. **Frequency** for manual cleaning in residential use is often once or twice a year in dry climates, as noted by module manufacturers[1].

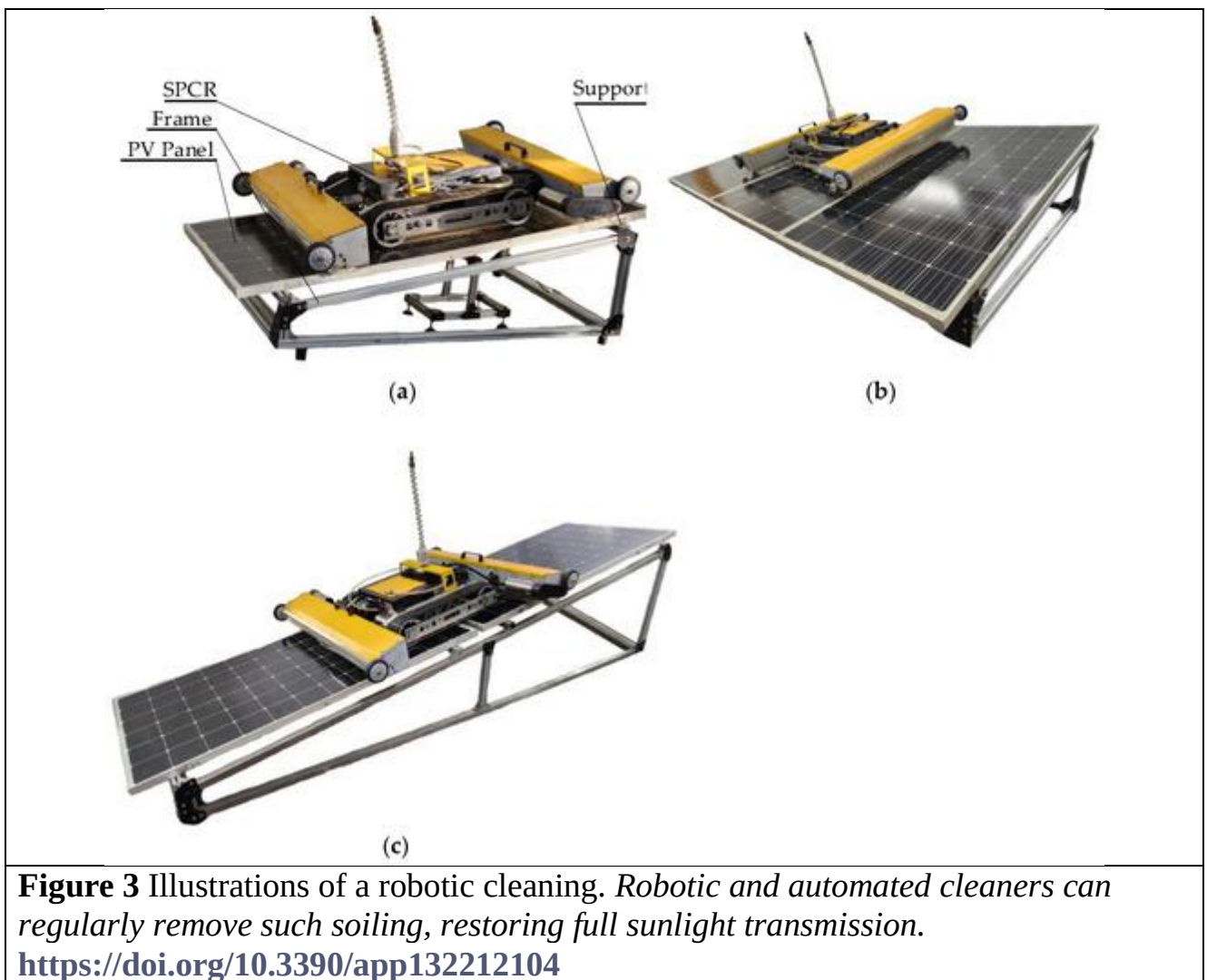
In summary, manual cleaning remains a viable method especially for smaller-scale PV systems. It offers flexibility (clean only when needed) and requires minimal equipment. However, for large utility-scale solar farms with thousands of panels, manually washing each panel with a hose and brush becomes labor-intensive and costly. This is where automated methods become attractive.

1.4 Automated and Advanced Cleaning Methods

For large PV installations, **automated cleaning methods** have been developed to efficiently clean vast numbers of modules with less human labor. These include robotic cleaners, fixed sprinkler systems, and even *self-cleaning* surface technologies. Each method has theoretical advantages and practical considerations:

- **Robotic Cleaning Systems:** These are autonomous or semi-autonomous robots that travel over solar panels to clean their surface. Robotic cleaners can be *water-based* (spraying water and brushing) or *waterless* (dry brushing or using microfiber rollers). Waterless robotic cleaning is especially valued in arid regions where water is scarce; it relies on gentle brushes or air blowers to remove dust[1]. Robots can be designed to traverse along panel rows (sometimes rail-mounted, or using the panel frames to cling and move). They usually operate at night or early morning to avoid interrupting production and to work when panels are cool. A major advantage is scalability: a set of robots can regularly clean a whole solar farm of tens of thousands of panels with minimal human intervention. Studies note that robotic cleaning is currently one of the most in-demand technologies for large-scale solar O&M[1]. Water-based robots provide thorough cleaning (needed for caked dirt or bird droppings) but consume water; waterless robots save water and have lower operational cost[2]. In practice, companies have reported significant water savings (on the order of 75% less water) by using robotic cleaners instead of manual washing[1].

Robotic systems typically navigate along each row of panels, using rotating brushes or wipers. Some are powered by batteries (recharged via a docking station, possibly solar-powered itself) and guided by rails or machine vision. The *theoretical optimization* is that robots can clean more frequently (even daily) to maintain very high performance with minimal incremental cost after installation. However, one must consider the capital cost of the robots and their maintenance (motors, brushes replacement, etc.), as well as ensuring they do not scratch the panels. Most use soft bristles, but over time even fine brushing could gradually abrade coatings – hence manufacturers of robots test and design bristles that minimize hardness relative to glass. **Figure 3** illustrates an example of a robotic cleaning unit in operation, gently brushing dust off PV modules.



Robotic and automated cleaners can regularly remove such soiling, restoring full sunlight transmission.[1]

- Automated Water Sprinklers:** This approach treats a solar array like a large car windshield that can be washed by a sprinkler system. Water spray nozzles are installed along the array (often at the top of each panel or row). On a programmed schedule (or triggered by sensors detecting dirt), the system pumps water to spray over the panels, effectively creating an “artificial rain” to wash off debris[2]. Sprinkler cleaning can be scheduled during night or early morning hours. The advantage is simplicity and uniform coverage: every panel gets water without manual labor. These systems can be built into the array from the outset. However, water quality is a concern – if not using demineralized water, sprinklers could leave hard water stains. Also, water use can be significant; in desert solar farms, using precious water resources is a cost and environmental consideration. Some advanced setups recycle water or use captured rainwater for this purpose. Sprinklers also do not

physically scrub the panel, so very stuck-on dirt might not be fully removed by water alone (some systems add a mild detergent to the water). Maintenance of the sprinkler plumbing (avoiding clogged nozzles, leaks) must be managed. Nonetheless, for small to medium installations (say a 100 kW rooftop), an automated sprinkler that rinses panels after particularly dusty days or on a weekly basis can be quite effective[2].

- **Self-Cleaning Coatings:** These are *technological modifications to the panel surface* to make it resistant to soiling. For example, hydrophobic (water-repellent) or hydrophilic (water-attracting) nanocoatings can be applied to glass so that dust either doesn't adhere strongly or is easily washed off by rain (in hydrophobic case, water forms droplets that roll and carry away dirt; in hydrophilic, water forms a sheet that wets and undercuts dirt)[2]. Other approaches involve electrostatic or piezoelectric mechanisms that can shake or electrically repel dust. In theory, if panels could be truly self-cleaning, it would eliminate manual effort. However, in practice these solutions have **limitations**: coatings can degrade under UV and weather, needing reapplication; they might only reduce, not eliminate, dust accumulation. Also, a coating that is too hydrophobic might actually suffer from dry dust accumulation until rain comes. Some commercial panels advertise "self-cleaning glass" which is essentially an anti-soiling coating, but field results vary. The MDPI study noted that such coatings (Nanofilm, etc.) can reduce the need for cleaning but may have low reliability or longevity[2]. Still, research continues in this area, and such coatings could be a supplementary strategy in conjunction with periodic cleaning.

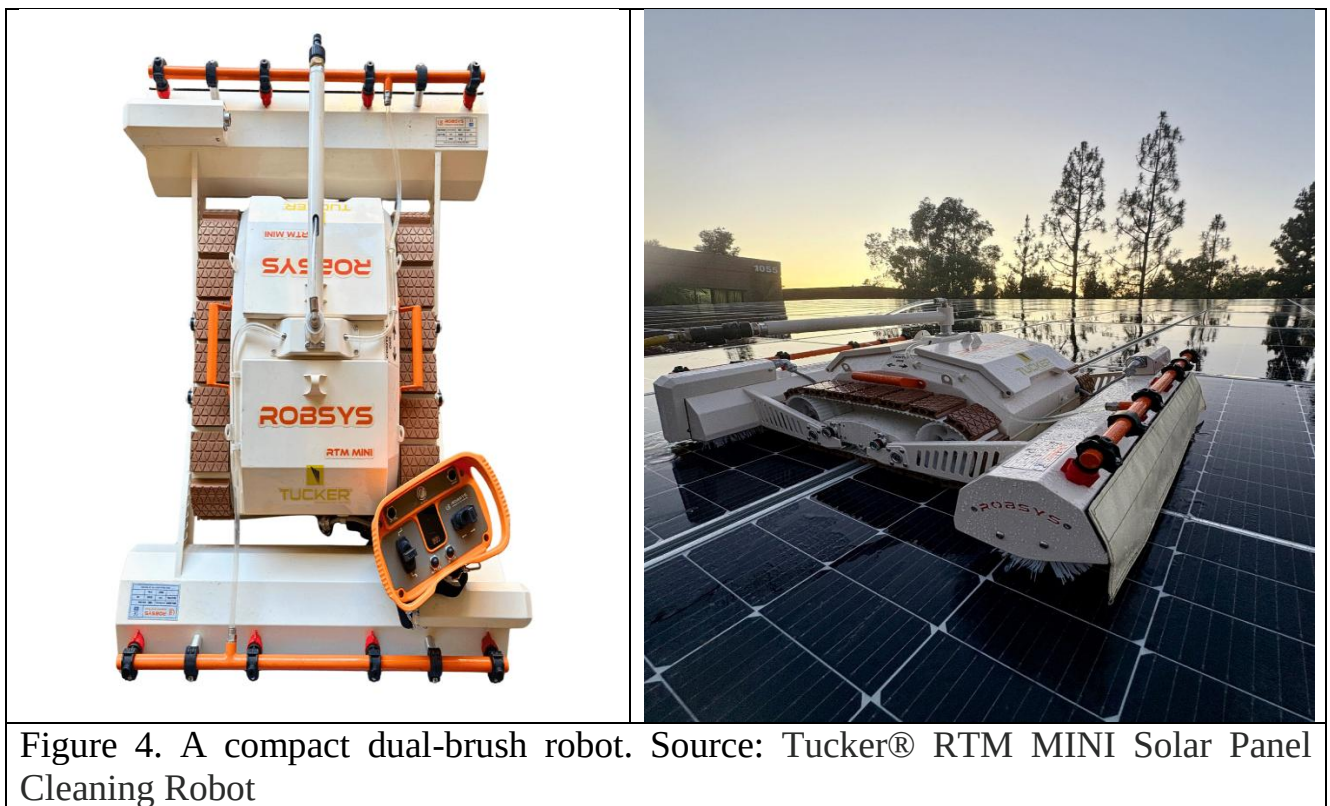
It's worth noting that one common natural *self-cleaning* aid is **tilt angle**. Panels mounted at steeper angles (e.g. 30–40° tilt) tend to accumulate less uniform dust than flat panels, and gravity helps some dirt slide off. Rain is also more effective at cleaning tilted panels. Flat or low-tilt panels (common in large flat-roof or tracker systems) accumulate more soiling and typically need more frequent cleaning or good self-cleaning coatings.

Cleaning Technologies and Tools

To implement the above methods, various **cleaning technologies** are utilized:

- **Brushes and Washers:** Traditional truck-mounted or handheld brushes are used in many solar farms. For instance, tractor-like vehicles with extendable rotating brush arms can drive along solar panel rows, brushing and washing panels much like a street sweeper or car wash brush. These can cover large ground-mounted arrays relatively quickly with a crew of operators. The brushes are usually made of soft nylon or a similar material to prevent scratching. Water or a cleaning solution is sprayed ahead of the brushes for lubrication and dirt removal. The risk of abrasion is controlled by soft bristles and constant water flow to carry particles away. Such systems might clean several MW of panels in a day. They require flat access between rows and careful operation to avoid misaligning or damaging panels.

- **Robotic Cleaners:** As mentioned, specialized robots exist. For example, some robots sit on the top edge of a row and have spinning microfiber rollers that traverse down the panel, cleaning as they go, then they move to the next row. Other designs include rail-guided robots or even drone-like crawlers. **A noteworthy example** is the water-free robotic cleaners used at some large solar parks, which sweep dust off nightly and have been cited to reduce cleaning water consumption drastically[5]. These robots often operate in groups, managed by a central control system, and can clean an entire solar field by moving from row to row. Some are even solar-powered themselves, recharging during the day. Figure 4 shows a photograph of a compact dual-brush robot designed to clean PV panels; such robots can cover significant panel area per day (one product claims up to 1 MW of panels cleaned daily by a single unit)[6].



- **Water Jets and Sprinklers:** Fixed spray systems include not only overhead sprinklers but also *under-panel* spray bars that wash the underside of inclined panels (not typically needed for performance, but in bifacial panels both sides matter). High-pressure nozzles can be installed to periodically blast dirt off, though careful design is needed to ensure even coverage. Some systems use robotic arms that move a high-pressure sprayer across the array.

- **Drones:** An emerging concept is the use of drone aircraft equipped with spray nozzles or brushes to clean panels from above. Drones could potentially access hard-to-reach installations (like tall rooftop arrays or solar panels on awnings). However, payload (water tank) limitations and stability make this challenging at scale, and this is not yet widespread.

Whatever the technology, **water quality control** is essential if water is used. Many large plants deploy water treatment (reverse osmosis or deionization units) to supply their cleaning systems. This prevents the issue of *mineral spotting*, which, if severe, can be as bad as dust in blocking sunlight. Additionally, any cleaning agents used should be verified not to damage the panel. Harsh chemicals (strong alkalis or acids) can etch glass or corrode frames and seals, and abrasive cleaners can remove the anti-reflective coating. Thus, manufacturers often specify acceptable cleaning fluids (usually just water and perhaps isopropyl alcohol for stubborn spots)[3].

Cleaning robots and devices must be designed to avoid damaging panels. For example, a robot that is too heavy could stress the glass or the mounting. Most robots spread their weight and are relatively light (some use suction or magnetic coupling to stay attached). There are also **safety interlocks** – e.g. disabling tracking movement when robots are on panels, to avoid a tracker moving while a robot is cleaning (if using on trackers).

In terms of *automation*, integrating cleaning with the plant's operation schedule is key. Many automated systems run at night to avoid any electrical hazard and to not interfere with production. Also, night cleaning means the panels are cooler and often dew has softened the dirt (making it easier to clean).

Risks of Cleaning: Abrasion, Water, and Damage

While cleaning is necessary, it also introduces potential **risks** to the solar modules if not done correctly:

- **Abrasion and Scratching:** Continuous cleaning, especially with improper tools, can gradually wear down the glass surface. Modern solar panels often have an anti-reflective (AR) coating on the glass to improve light transmission. This coating is relatively thin and can be scratched or eroded by rough contact. Using abrasive brushes or scouring pads can create microscratches that accumulate and lead to hazing of the glass over years. Even dust itself can be abrasive (think of fine sand particles) – rubbing a dusty panel *dry* is like sanding the glass. That's why it's recommended to first rinse off loose dirt and use plenty of water as a lubricant during cleaning. Non-abrasive cleaning implements and gentle pressure are the rule[3]. As a guideline, **do not** use metallic objects or abrasive powders on panels. If automated brushes are used daily, their bristles must be soft enough to avoid scratching even after hundreds of cycles.

- **Water-Related Issues:** Using water introduces concerns of mineral deposits (as discussed, use purified water ideally) and potential water ingress. Solar panels are designed to be weatherproof, but high-pressure water jets could force water into microgaps in seals or cable glands. Over time this might lead to **moisture ingress**, risking corrosion or electrical leakage. Hence, pressure washing should be gentle. Also, water left standing on panels (puddles) could attract dirt or cause localized cooling which might induce thermal stress in cells (though this is a minor concern). After cleaning, it is best if panels dry relatively quickly without residue. **Water temperature** is a concern too: pouring very cold water on a hot panel can rapidly cool the glass while the cells remain hot, potentially cracking the glass (thermal shock). Thus, either use ambient-temperature water or choose a cool time of day for cleaning[12].
- **Chemical Damage:** If inappropriate cleaning solutions are used (for example, ammonia-based glass cleaners in high concentration, or solvents), they could react with the panel's materials. Ammonia can sometimes damage anti-reflective coatings or backsheet materials. Similarly, strong alkali can etch glass. It's generally recommended to stick to mild soap solutions or manufacturer-approved cleaners[3]. Even seemingly harmless substances like vinegar (weak acetic acid) are used only in highly diluted form to avoid any long-term effect.
- **Structural and Electrical Damage:** Physical pressure on panels is dangerous. Leaning or stepping on a panel can cause microcracks in cells that permanently reduce performance. Therefore, cleaners should not put weight on the panels. Tools like long extension poles allow cleaning from the ground or walkway without climbing on modules[3]. Additionally, there is electrical risk – although panels are generally safe to touch on the glass, a cracked panel or exposed wire could present a shock hazard if water is applied. It is a best practice to *shut down* the PV system (or at least isolate the section being cleaned) to eliminate any voltage during washing[3]. For rooftop systems, this means turning off the inverter and possibly using the DC disconnect so that the panels aren't driving current. Workers typically wear insulated gloves and use insulated tools if cleaning large strings, just as a precaution.
- **Impact on Warranty:** Many solar panel warranties stipulate conditions for cleaning. For instance, using a pressure washer or abrasive cleaner might void the warranty if it damages the panel. Some warranties explicitly say to avoid metal tools and harsh chemicals[7]. Thus, abiding by recommended cleaning methods is not only good for the panels but also necessary to maintain manufacturer coverage. Frequent cleaning beyond what's recommended is usually fine if done gently, but if one were to, say, polish the panels daily with an abrasive compound, that would certainly reduce their lifespan.
- **Robotic Cleaner Risks:** While robots reduce human error, they carry their own risks. A malfunctioning robot could get stuck or scratch panels if a brush motor fails. There have been instances of robots sliding off and causing damage. Therefore, such

systems have safety features like edge detection to avoid falling off the array, and soft bumpers to prevent chipping panel edges. Regular maintenance of the robots is needed to ensure their brushes stay clean (an oily or dirty brush could smear panels or cause hotspots by leaving residues).

To mitigate risks, many operators adopt **best practices** such as: test cleaning a small section first, use recommended cleaning kits (some module manufacturers provide or endorse cleaning kits with proper detergent and brush), train personnel in gentle techniques, and schedule cleaning judiciously. When done correctly, cleaning can recover essentially all soiling losses without harming the panels. The efficiency gains – up to tens of percent in output for very dirty panels – make it a highly worthwhile part of solar PV maintenance[\[1\]](#). As an example of cleaning benefit, NREL reported that going from one annual cleaning to three annual cleanings could reduce the average soiling loss from ~1.9% to ~1.2% per year – a significant improvement in yield that can translate to thousands of dollars saved for a large plant.

In closing of this section, it's clear that **clean solar panels = higher efficiency**. Plant operators must weigh the cost of cleaning (labor, water, equipment) against the energy regained. In many cases, a routine cleaning schedule plus occasional additional cleaning after extraordinary events (e.g. a dust storm or wildfire ash fall) is optimal. With technological advances like robotic cleaners and anti-soiling coatings, the industry is moving towards ensuring panels stay as clean as possible to harvest every ray of sunlight.

10.2. SCADA AND IT SERVICES FOR SOLAR PANELS

Modern PV installations are equipped with **monitoring and control systems** that leverage IT and SCADA technology to ensure optimal performance and rapid response to issues. **SCADA (Supervisory Control and Data Acquisition)** systems in the solar context refer to the hardware and software infrastructure that allows operators to *remotely monitor* the solar plant's operation, collect and log performance data, and even control equipment (inverters, trackers, circuit breakers, etc.) from a central interface[33]. In essence, SCADA provides the “eyes and hands” of an operator at a PV site without needing to be physically present. This section covers the SCADA architecture, the IT components and platforms used for PV monitoring (including examples like Sunny Portal, Solar-Log, PVsyst, SMA, SolisCloud), and considerations like cybersecurity and data integrity in these systems.

Overview of SCADA for PV Monitoring

A SCADA system for a solar PV plant integrates numerous sensors and devices spread across the site and funnels their data to a central system where it can be visualized and acted upon. At its core, SCADA comprises: (1) **data acquisition** from field devices, (2) communication of that data to a central station, and (3) a human-machine interface (HMI) or software platform for human operators to review status and send commands[8]. In a solar plant, relevant field devices include the solar inverters (which convert DC from panels to AC and often have built-in sensors for voltage, current, etc.), weather stations (measuring irradiance, temperature, wind speed), combiner box monitors, tracker controllers (if it's a plant with solar trackers), meters (measuring output to the grid), and protection devices (relays, switchgear). Each of these devices produces data – for example, an inverter might report its AC power output, DC voltage, internal temperature, etc., every few seconds.

The **purpose** of PV SCADA is multifold[8]:

- **Performance Monitoring:** Track how much energy the plant is producing in real time and cumulatively, and compare it against expected values. This helps ensure the system is running optimally. If production drops unexpectedly (e.g. due to a string outage or heavy cloud cover), the system flags it.
- **Fault Detection:** Immediately alert operators if any equipment is malfunctioning or offline[8]. For example, if one inverter trips or a tracker gets stuck, the SCADA can raise an alarm. Without SCADA, a fault could go unnoticed for days, causing energy loss. With SCADA, technicians are notified right away.
- **Remote Control:** SCADA allows remote operations such as resetting a tripped inverter, adjusting setpoints, or even curtailing output if instructed by the grid operator. “Supervisory control” means an operator can send commands from

the SCADA HMI to field devices (within the limits of what those devices permit). This avoids site visits for simple actions.

- **Data Logging and Analysis:** SCADA continuously logs data points (often at intervals like 5-min or 15-min for performance metrics, and even sub-second for certain protection events). This historical data can be analyzed to detect trends (like gradual performance degradation, or recurring fault patterns)[8]. Analysis might reveal, for instance, that every day around noon an inverter overheats and derates power – prompting a fix to the cooling system.
- **Automation and Optimization:** In some cases, SCADA can be programmed to automatically respond to conditions. For example, if a combiner detects current imbalance (maybe a string is out), the system could automatically flag it for maintenance. In more advanced setups, SCADA might integrate with control algorithms to optimize power flow – e.g. controlling battery storage or reactive power from inverters based on conditions.
- **Multi-site Management:** A utility or O&M company with multiple solar plants can tie all their site SCADA systems into a centralized platform, allowing a single dashboard to oversee an entire fleet of PV installations.

For small systems (residential or small commercial), the “SCADA” is often just a cloud-based monitoring portal provided by the inverter manufacturer – not a full industrial SCADA, but it serves a similar monitoring role. For large utility-scale solar farms, more elaborate SCADA setups are implemented, often similar to those in conventional power plants, with high reliability, real-time control, and integration with grid control centers.

In summary, SCADA in solar ensures the plant’s **visibility** and **controllability**. By having continuous eyes on all components, operators can ensure everything is “running as expected”[8] and dispatch repair crews only when necessary (saving time and money by avoiding unnecessary site visits)[8]. It transforms a solar farm from a passive set of panels into a smart, interactive system.

SCADA Architecture and IT Components

A typical **SCADA architecture** for a solar plant includes the following key components[8]:

- **Field Sensors and Devices:** These generate raw data. In a PV plant, primary data sources are the inverters (which measure DC input, AC output, etc.), string monitoring units (measuring current in each string of panels), weather sensors (irradiance sensor like a pyranometer, module temperature sensors, ambient thermometer, anemometer for wind). Each sensor/device often has its own embedded processor and communicates data digitally.

- **Remote Terminal Units (RTUs) or Data Loggers:** These are distributed units that collect data from the field devices and act as intermediaries[8]. An RTU in a solar plant could be, for example, a small industrial computer installed in an inverter control cabinet or central switchgear house. It polls the inverters and other sensors via communication protocols (like Modbus, CAN bus, or proprietary links) and aggregates that information. In many modern PV plants, the inverter itself can serve as a sort of RTU, sending data to the central system. But in larger plants, separate RTUs or a *SCADA gateway* is used to consolidate all device data. The RTU can also execute control commands: for instance, if the SCADA center sends a command to disconnect a breaker, the RTU at the site will receive that and actuate a relay.
- **Communication Network:** This connects the field to the central *Master Station*. Communication can be wired (Ethernet, fiber optics) or wireless (radio, cellular). Many utility PV plants use fiber optic networks or ethernet cabling to connect inverters and sensors back to the control room. Smaller systems often use the internet – for instance, a residential PV monitoring device might send data via Wi-Fi or cellular modem to a cloud server. Common protocols at this level include **Modbus** (a widely used protocol in solar for inverter communication), DNP3, or IEC 61850 for more advanced grid-tied communications. The network needs to be reliable and sometimes nearly real-time. Ethernet-based LANs are common within the plant[8], and then possibly a VPN or other secure link to remote monitoring centers. The communication network is part of IT, and ensuring minimal data loss and low latency is important especially if remote control commands are issued.
- **Master Station / SCADA Server(figure 5):** This is the central computer (or redundant computers) that run the SCADA software, database, and interface. The master station receives data from RTUs, time-stamps and logs it, and presents it on the HMI (Human Machine Interface). It also runs any automation scripts and alarm handling. In a local plant SCADA, the master might be a PC in the site control room. In a cloud-based monitoring scenario, the “master” is essentially a cloud server that the site devices report to. The **HMI** is the user interface – historically, a dedicated software application with graphical display of the plant (one-line diagrams, charts, etc.)[8]. Today, many systems have web-based HMIs or portals accessible from anywhere.
- **Databases and Data Historian:** Because PV plants generate a lot of data (each inverter may report dozens of parameters every few seconds), the SCADA system includes a database or *historian* to store time-series data efficiently. This allows trend analysis – e.g., plotting the power output of each inverter over the last month to spot any underperforming units.
- **Alarm System:** The SCADA software typically includes an alarm management component. When a parameter goes out of normal range or a device reports a

fault, an alarm is generated and logged. It can trigger notifications: screen pop-ups, emails, SMS to technicians, etc. For example, if inverter #3 stops producing power at noon, the SCADA will flag that and possibly send an email/SMS to the O&M team so they can investigate immediately. Alarm thresholds can be set (like if performance ratio drops below 0.8 for 1 hour, raise an alert about possible soiling or shading).

A simplified architecture diagram might show solar panels feeding inverters, inverters and sensors connected (via serial/Ethernet) to an on-site SCADA panel (data logger), which then sends data over the internet to a cloud SCADA platform, accessible by operators on a web dashboard. **Figure 5** depicts an example SCADA communication setup for a renewable energy plant, where remote units at each site feed data to a central HMI/master station.

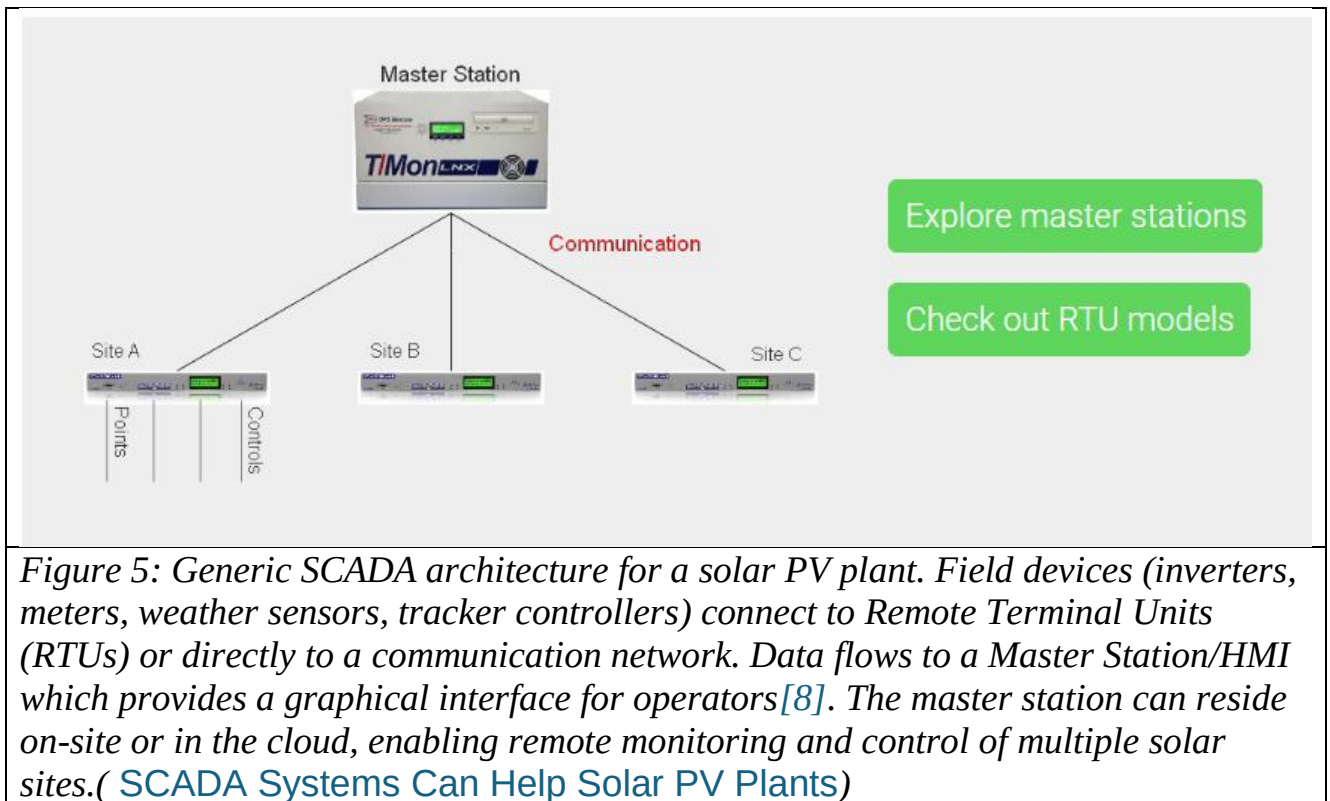


Figure 5: Generic SCADA architecture for a solar PV plant. Field devices (inverters, meters, weather sensors, tracker controllers) connect to Remote Terminal Units (RTUs) or directly to a communication network. Data flows to a Master Station/HMI which provides a graphical interface for operators[8]. The master station can reside on-site or in the cloud, enabling remote monitoring and control of multiple solar sites.([SCADA Systems Can Help Solar PV Plants](#))

In real implementations, many inverter manufacturers provide their own gateway devices that serve as the RTU. For example, SMA (a major inverter maker) offers the **Data Manager** or older *Cluster Controller* which aggregates all SMA inverter data and pushes it to the Sunny Portal (SMA's monitoring platform)[9][10]. Others simply embed an Ethernet port in each inverter and have them all report to a local SCADA PC(Figure 6).

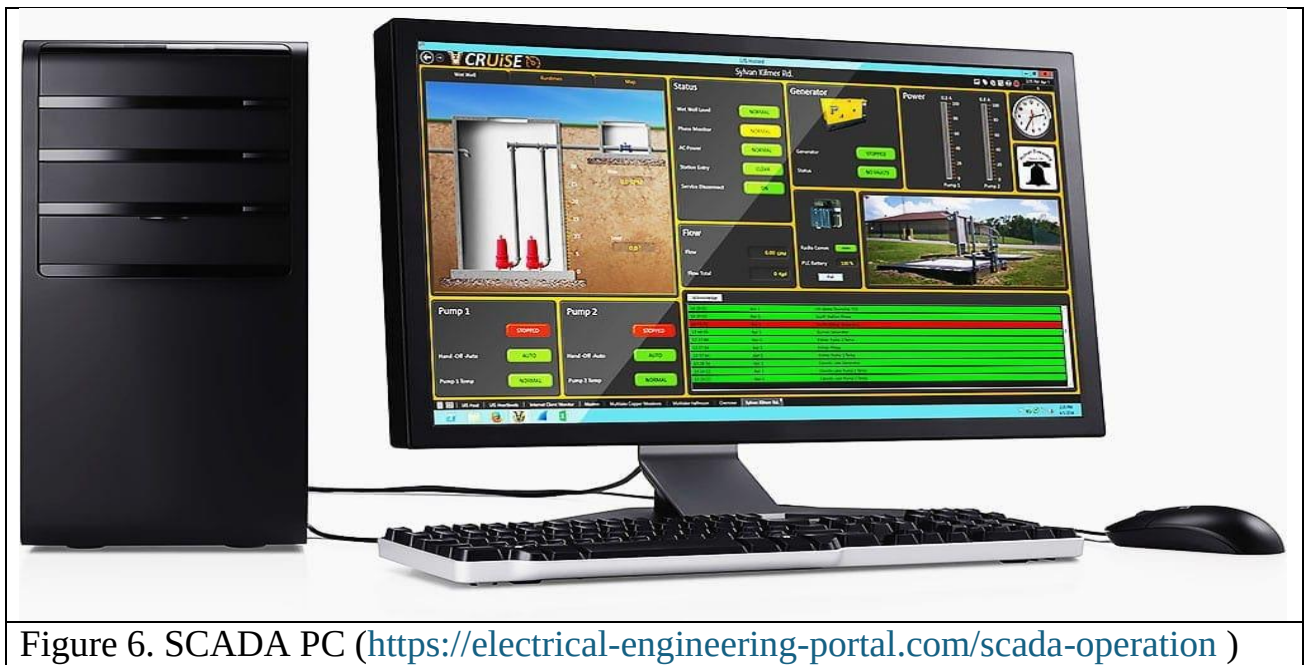


Figure 6. SCADA PC (<https://electrical-engineering-portal.com/scada-operation>)

IT services in solar monitoring also involve software that transforms raw data into useful information. This includes analytics software that can calculate KPIs (Key Performance Indicators) like performance ratio, capacity factor, or compare actual vs expected generation (perhaps using a model or simulation in the loop). Moreover, many SCADA systems allow integration with maintenance management – for instance, generating a work order in a maintenance ticket system when a failure occurs.

A robust SCADA design also entails **redundancy and reliability** for utility-scale projects. Often, critical SCADA links are redundant (two communication paths, backup power supplies for SCADA equipment, etc.) to ensure that the monitoring is always available. After all, if the SCADA goes down, the plant might still produce power but the operators would be “blind” to its status.

In smaller systems (residential/commercial), the architecture may be simpler: the inverter itself or a small logger collects data and directly sends it via the Internet to a vendor’s cloud service, where the user logs in via an app or website to see their system data. This is essentially a SCADA service, though it might not be labeled as such.

Remote Monitoring, Data Logging, and Alerts

Remote monitoring means that authorized users can access the PV system’s performance data from anywhere, not just on-site. This is usually achieved by connecting the SCADA or monitoring system to the internet. As mentioned, many inverter companies have cloud portals: the inverter pushes data to the cloud where it’s stored and displayed. For a more custom SCADA, operators might have a VPN into

the site network to view the SCADA screens remotely, or the site SCADA might publish data to a cloud database.

Data logging is inherent in SCADA – capturing data at regular intervals and saving it. Typical logging intervals for solar monitoring are 5 or 15 minutes for performance data (energy, power, irradiance) since that provides good resolution for analysis without too much data overload[10]. Faster logging (seconds or sub-second) might be used for electrical measurements when analyzing transients or detailed inverter behavior, but for general performance, 5-min averages are common. These logs allow calculation of daily output, and also allow one to go back in time to identify when a problem started. For instance, if one combiner has a blown fuse, its string current would drop to zero; by looking at historical string current data, one can pinpoint when that happened.

System alerts (alarms) are critical for O&M. The SCADA can be configured to issue alerts for events like: inverter fault or offline, communication failure (if an inverter stops reporting data, you get a comms alarm), low insulation resistance (ground fault warning), high temperature on a transformer, etc. Also, performance alarms like low power (if an inverter is producing significantly less than expected given the sunlight) can be set up. These alerts are presented on the HMI and also sent out via email/SMS to designated engineers. Many modern platforms also have mobile apps with push notifications. The idea is immediate awareness – as one SCADA vendor described, you want to *know* if anything is wrong so you can dispatch technicians promptly, saving time and revenue[8]. With remote monitoring, a single operator can keep an eye on multiple plants in real time, something that would be impossible with on-site meter reading only.

Trend analysis enabled by data logging helps in preventive maintenance. For example, trending the performance ratio (actual AC output vs expected based on irradiance) could show a gradual decline that might indicate soiling – prompting a cleaning schedule. Or a slowly rising inverter temperature over months might signal a clogged air filter that needs replacement. SCADA systems often include reporting tools to summarize data (daily reports, monthly energy, error logs) to support asset management. Technicians can use these logs to correlate events – e.g., see if faults occur at the same time as grid disturbances.

In many jurisdictions, especially for larger systems, data logs from SCADA are also used for **compliance and billing**. A utility-scale solar farm might need to report its generation to the grid operator; SCADA provides the authenticated meter readings for energy sold. It may also log availability (uptime) which is sometimes tied to power purchase agreements.

To illustrate, consider a large 50 MW solar farm: the SCADA will log every inverter's output every few minutes. If one inverter drops to 0, the system raises an alarm "Inverter 12 tripped at 14:05". The operator sees this on the dashboard, and also likely gets an email. They can remotely attempt a reset command via SCADA. If unsuccessful, they send a maintenance crew to check on-site. Meanwhile, the SCADA

logs allow them to see how long that inverter was down and estimate lost production. The logs might also show if other inverters had any anomalies around that time (was it an external cause like a grid voltage spike that tripped multiple units, or just a single inverter's internal fault?). This greatly enhances troubleshooting.

Another aspect of modern PV monitoring is **integration with asset management systems**: some SCADA or monitoring platforms allow you to track maintenance tickets, inventory of spare parts, etc., linking them to the alarms. This crosses into IT service management, ensuring that once an alert comes, it is documented and resolved.

Software Platforms and Tools for PV Monitoring

There are several software platforms and IT tools available – some are vendor-specific, others are third-party or generic – that serve the monitoring and analysis needs of PV systems. Below are a few notable examples, along with their key features:

- **Sunny Portal (by SMA Solar Technology):** Sunny Portal is one of the world's largest online PV monitoring platforms, tailored for systems using SMA inverters. It provides professional management, monitoring, and presentation of PV system data for both residential and commercial plants[11]. Users (plant owners or installers) can register their PV system on Sunny Portal and then access live and historical data from anywhere via the web. Key features of Sunny Portal include real-time status monitoring of all devices, visualization of power and energy yield (graphs of daily, monthly, yearly production), and alerts for system events. It also allows comparing actual yields with expected values to detect deviations quickly[10][11]. Sunny Portal (especially the newer Sunny Portal powered by *ennexOS*) supports high-resolution data (down to 5-minute intervals) and remote parameter configuration of SMA inverters[11]. For example, an installer can update inverter settings via the portal without visiting the site. Sunny Portal's scale is significant: as of recent figures, it had over 900,000 registered PV systems worldwide monitoring more than 40 GW of PV capacity – reflecting how widely used it is. It provides secure data access (SMA achieved ISO/IEC 27001 certification for the platform's data security) and features like user role management (owner vs guest view) and basic reporting/alarm functionality[11]. In summary, Sunny Portal is an **all-in-one cloud SCADA** for SMA-based systems: once the hardware (inverters, data managers) are set up and linked, the portal offers a dashboard to track performance, yields, and even energy flows in a home energy system. It is an example of a vendor-provided IT service that simplifies solar monitoring greatly.
- **Solar-Log (WEB Enerest) Monitoring:** Solar-Log is a third-party PV monitoring and energy management system that works with a wide range of

inverter brands. The Solar-Log system typically includes a hardware data logger installed on-site, which gathers data from inverters and meters, and a web platform (Solar-Log WEB Enerest) where the data is uploaded and displayed. A good monitoring app or platform, as Solar-Log emphasizes, should fulfill several points: (1) recording all relevant data (production, feed-in to grid, self-consumption, grid draw, etc.), (2) informing the operator immediately in case of irregularities or faults, (3) providing simple visualization of yields and system status, and (4) ensuring data security in the process[14]. Solar-Log's platform indeed offers these. It presents the energy balance of the PV system (quantities of energy produced, consumed, and fed to grid) in real-time and historically[14], often including nice graphics and even calculations of CO₂ savings. It sends out alerts if, for example, an inverter is not performing or if the system isn't meeting expected production. Solar-Log can also do some basic fault analysis – identifying which string or inverter is underperforming by comparing data. Another feature is *portfolio monitoring*: installers or O&M providers can monitor many sites from one interface by using Solar-Log's multi-plant capabilities. Data security is taken seriously, using encrypted data transfer and secure servers[14]. One can access Solar-Log via web or mobile app to check the status of their system on the go. Solar-Log also provides an interface for energy management – controlling loads or storage based on PV production. To illustrate, if a site has Solar-Log, the user might open the app and see that at the moment their PV system is producing X kW, out of which Y kW is feeding into appliances and Z kW to the grid; if an inverter fault occurs, a message would pop up immediately with likely cause, helping expedite the resolution[14]. Thus, Solar-Log serves as a robust monitoring **service** bridging the gap between various hardware brands and providing a unified IT platform for solar performance tracking.

- **PVsyst:** Unlike the others mentioned, **PVsyst** is primarily a *design and simulation software* rather than a real-time monitoring tool. It is widely used in the solar engineering field for system design, energy yield estimation, and analysis. PVsyst allows users to model a PV system (components, location, weather data) and simulate its expected production. In the context of maintenance and monitoring, PVsyst can be used to analyze measured data as well – it has a **data analysis** tool where you can import measured performance data from a plant and compare it to the simulation to identify discrepancies. PVsyst is essentially an offline tool that provides theoretical benchmarks and detailed loss breakdowns. For example, after a year of operation, one might input the actual irradiation and production, and PVsyst can help back-calculate soiling losses or other inefficiencies by comparing to the clean simulation. A brief description from the official documentation: “*PVsyst is a PC software package for the study, sizing and data analysis of complete PV systems. It deals with grid-connected, stand-alone, pumping and DC-grid PV systems, and*

*includes extensive tools for solar energy and component data.”[15]. As an IT service in a broad sense, PVsyst supports monitoring by serving as a **reference model** – operators often use it to predict expected output (taking into account weather), and then monitoring systems report actual output. The comparison of actual vs. expected (from PVsyst) is a powerful way to detect underperformance. Additionally, PVsyst helps in planning maintenance: for instance, it can simulate the effect of cleaning or the effect of a tracker, etc., aiding decisions.*

- **SMA (other IT services):** SMA, aside from Sunny Portal, offers various components like **Sunny Home Manager** and **SMA Energy Meter** which together create an energy management system for home PV. The Sunny Home Manager monitors all energy flows in a home (PV generation, home consumption, grid import/export) and can even control smart appliances[16][12]. It ties into the monitoring by providing real-time energy flow diagrams and optimizing self-consumption. For larger plants, SMA’s older **Cluster Controller** (now largely superseded by Data Manager) was an on-site SCADA gateway that could integrate with utility SCADA via protocols like Modbus or *SunSpec*. SMA also provides a **Mobile App (SMA Energy App)** that connects to Sunny Portal for convenient monitoring on smartphones[12][11].
- **SolisCloud (by Ginlong Solis):** SolisCloud is a modern cloud-based monitoring and management platform for PV systems equipped with Solis inverters (a popular inverter brand). It is described as an intelligent PV monitoring and maintenance system that integrates real-time monitoring, precise data, and alarm notifications[17]. Through the SolisCloud web portal or mobile app, users can see detailed real-time data on their solar system’s performance: current power output, daily/monthly energy yield, as well as the status of any connected batteries or loads[18]. One feature of SolisCloud is a very user-friendly **energy flow diagram** that shows how power is moving between the PV panels, battery, home, and grid in real time (with color-coded arrows). This helps users immediately grasp their system status. The platform logs historical data and provides analytic tools to observe performance trends over time[18]. It also supports multi-site management for installers—meaning an installer can monitor all their customers’ Solis inverter systems in one dashboard. **Alerts and smart notifications** are a big focus: SolisCloud will generate alerts for any inverter faults or abnormal performance and can push these to the user’s phone or email so issues can be addressed swiftly[19]. For example, if an inverter unexpectedly goes offline, the app would send an alert. It also offers remote control capabilities like updating inverter firmware or changing settings remotely (with appropriate permissions). SolisCloud emphasizes a few key functions: real-time monitoring, smart fault detection & alerts, historical data & trend analytics, and an easy-to-use interface for both

end-users and professional installers. Essentially, it is a cloud SCADA dedicated to Solis systems. Given that it's "cloud-first," cybersecurity measures (encryption, secure logins) are in place to protect user data. SolisCloud's integration with third-party services is possible too (it offers an API for retrieving data, which can be used by energy management companies)[20]. In summary, SolisCloud serves as a one-stop IT platform for monitoring PV production, managing energy storage, and receiving O&M alerts, illustrating how inverter manufacturers are providing sophisticated software to complement their hardware.

- **Other Platforms:** There are many others in the market – e.g., **SolarEdge** has its own cloud monitoring (with module-level performance data because SolarEdge optimizers report each panel's output), **Enphase** has Enlighten for their microinverters, **Huawei** offers FusionSolar monitoring, etc. Additionally, independent platforms like **AlsoEnergy's PowerTrack**, **Locus Energy**, and **SkySpark** are used for large portfolios to aggregate data from various sites and run advanced analytics. These often provide executive dashboards, custom report generation, and even predictive maintenance analytics (using machine learning to predict failures). **Open-source or custom SCADA:** Some engineering teams set up SCADA using frameworks like Ignition by Inductive Automation (popular in industrial SCADA) to create custom dashboards and controls for their solar farms[21].

All these software tools aim to ensure the PV systems are performing as intended and to give stakeholders (from homeowners to utility operators) clear visibility and control. They are an integral part of PV asset management – without them, one would have to rely on manual readings or monthly utility bills to infer performance, which is not sufficient for modern requirements.

IT Architecture: Sensors, Communication, and Cloud Integration

To delve a bit more into the **IT architecture** underpinning these services: a solar monitoring system often involves distributed IoT (Internet of Things) devices. The sensors (like energy meters, temperature sensors) and inverters form the *Internet of Things* layer of the PV plant, each with some communication interface. The communication can be wired (e.g., RS485 serial lines daisy-chained between inverters and loggers, Ethernet cables, power line communication) or wireless (Wi-Fi modules in inverters, Zigbee, cellular).

Protocols like **Modbus TCP/IP** (over Ethernet) or Modbus RTU (over serial) are extremely common for inverter and meter data. Increasingly, **MQTT** (a lightweight IoT protocol) is being used by some devices to publish data to brokers (especially in newer residential IoT energy devices). The data then might go to a local gateway

which aggregates it and sends it to the cloud. In cloud-based systems, **REST APIs** or MQTT or even FTP can be used to transfer data to the server.

For example, consider a setup: Each inverter is connected via Ethernet to a router on site. That router provides internet (maybe via 4G cellular). The inverters push data to the cloud server (either by opening a connection and sending data periodically, or the cloud polls them). The cloud server authenticates the system and stores data in a database. The user logs in through a web interface to see the data. This is an **edge-to-cloud** architecture, with minimal on-site processing beyond data collection.

In more mission-critical scenarios (large plants), the architecture might be two-tier: local SCADA (for immediate control and fast response on-site) plus cloud replication (for remote monitoring and aggregation). The local SCADA ensures that even if internet is down, the plant is still monitored on-site and can respond to grid commands. The cloud then syncs when connection is up to update central records.

Cybersecurity and data integrity are crucial in such IT architectures, which leads into the next topic.

Cybersecurity and Data Integrity in Solar SCADA

As solar PV plants become more digitized and connected, they increasingly face the same cybersecurity challenges as other industrial control systems and power infrastructure. **Data integrity** means ensuring that the data reported by the monitoring system is accurate and not tampered with, and **cybersecurity** means protecting the system from malicious attacks that could disrupt operations or falsify data.

Historically, PV plants were relatively simple and often not networked – early solar installations might have had a standalone logger with no internet connectivity. The cybersecurity risk was minimal then. But now, with large solar farms providing essential power and with remote control possible, attackers might target them for various motives. In recent years, cybersecurity professionals have noted that renewable energy systems (including solar farms and battery storage) can be vulnerable entry points to the broader electric grid if not secured[\[22\]](#).

Threat vectors for PV SCADA include:

- **Inverter or Gateway Hacking:** Inverters run firmware and often have communication modules. If an inverter's software has a vulnerability (and many use Linux-based controllers), a hacker could exploit it if the inverter is accessible via the network[\[22\]](#). Once in, they might alter the inverter's settings, turn it off, or even induce unsafe operating conditions (e.g. override protections). There have been demonstrations of taking over smart inverters remotely.

- **SCADA Network Intrusion:** If the solar plant's SCADA network isn't isolated or properly firewalled, attackers could penetrate it (perhaps through the corporate network or via a maintenance laptop that got malware) and then send rogue commands. An infamous example in the power sector is the Ukraine grid cyberattack in 2015, where attackers took control of SCADA to open breakers and cause outages[22]. A solar farm could theoretically be forced to disconnect or stop producing.
- **Data Manipulation:** A subtler attack is altering the data reported (data integrity attack). For instance, malware could falsify the production data to mask a problem or to claim more energy than actually produced (though financial settlements typically rely on utility meters which are harder to hack). However, compromised data could lead operators to wrong conclusions or miss faults. Ensuring data integrity means using checksums, secure protocols, and access control to prevent unauthorized data changes.
- **Denial of Service (DoS):** Attackers might flood the SCADA network or overload the inverter communication, causing loss of monitoring and possibly forcing the plant into a safe default mode. Or ransomware could encrypt the SCADA servers, effectively "blinding" the operators until they restore systems from backups (much like what happened to Colonial Pipeline's IT network in 2021, which indirectly led to shutting the pipeline)[22].
- **Physical Access and Insider Threats:** Plugging in a simple USB with malware could infect a SCADA workstation (reminiscent of Stuxnet, which spread via USB to target nuclear centrifuges)[22]. In a solar site, an insider or a trespasser could theoretically plug into an ethernet port in an inverter or comm cabinet if not secured and inject malicious commands or viruses.

The consequences of cyberattacks on solar plants can range from loss of revenue (if generation is halted), equipment damage (in extreme cases, e.g. an attacker disabling protections could overheat inverters or cause battery malfunctions), or grid instability (imagine a coordinated attack turning off many large solar farms suddenly, causing a drop in generation on the grid). Therefore, cybersecurity is now a *primary concern* for solar asset owners[22], especially as the capacity of PV on the grid grows.

Measures to enhance cybersecurity and data integrity:

The approach is often framed as an *identify-protect-detect-respond-recover* cycle[22]:

- **Identify:** Audit the system to know all devices and potential vulnerabilities. This includes keeping an inventory of all network connections, open ports, services running on inverters/SCADA, etc., and assessing the risk of each[22]. For example, identify that the inverter's web interface uses a default password or that the data logger runs an outdated OS.

- **Protect:** Implement defenses. One basic step is to avoid default credentials – e.g. change all default inverter passwords, use strong unique passwords or keys[22]. Network segmentation is vital: one recommended method is to create separate networks for different devices so that, say, one compromised inverter cannot directly talk to another; all communication should go through the secure SCADA gateway which can filter and firewall traffic[22]. Use firewalls at the plant perimeter and even between subnetworks to only allow necessary traffic (for example, the inverters might only be allowed to communicate to the SCADA server’s IP and nothing else). Enable encryption where possible – many modern systems support HTTPS or VPN tunnels for data to the cloud; if not, using a site VPN can prevent interception. Physical security of network access (locking cabinets, using port security on switches) helps prevent unauthorized plug-ins. Also, ensure all software/firmware is up to date: manufacturers release patches for known vulnerabilities, and keeping firmware updated closes doors that hackers exploit[22].
- **Detect:** Use intrusion detection systems or at least monitor network for unusual behavior[22]. For instance, if an inverter starts sending data at odd times or an unknown device connects, detection systems can alert operators. Also, monitor the data itself for anomalies – a cyberattack might manifest as weird data (e.g., negative power output or impossible performance values). There are research efforts on using machine learning to detect data integrity attacks in solar farms by looking for data patterns that don’t match physical expectations[24]. Even simpler, SCADA alarms for “*inverter not responding*” could hint at a denial-of-service attack if multiple go down simultaneously.
- **Respond:** Have an incident response plan. If a breach is detected – say, an operator notices that a setting was changed without authorization or an inverter is behaving erratically due to suspected malware – there should be a procedure to isolate that device (disconnect it from network), safely fall back to manual control if needed (some plants can be operated locally), and involve cybersecurity experts[23]. Just as importantly, **Recovery** plans (backups of SCADA configurations, ability to do a full reinstall of system software, etc.) ensure minimal downtime[23]. For data integrity, maintaining redundant logs (e.g., data stored both on site and in cloud, or having a read-only data recorder) can help recover any data that was manipulated.

A concrete example of a protective measure is using a VPN for remote access: rather than leaving the plant SCADA open on the internet, an operator must VPN into a secure network to access it, greatly reducing exposure. Another example: some large PV sites implement **whitelisting** on inverter communications – i.e., the inverter will only accept commands from a particular IP or from the on-site controller, so an external packet would be ignored.

Grid operators and regulatory bodies are increasingly requiring cybersecurity standards for solar and wind plants, especially as they become a significant part of the power system. In the U.S., the NERC CIP standards (critical infrastructure protection) might apply to solar farms above certain sizes, requiring measures like background checks for personnel, logging all remote access, etc. In Europe, similar guidelines are emerging (often under more general ISO 27001 information security or the network and information systems (NIS) directive for energy).

Data integrity is also about ensuring the data is accurate and trustworthy. Besides cyberattacks, data can be corrupted by noise or errors. Thus, SCADA systems often implement error-checking (CRC checks on data packets, validation rules that flag implausible values). Additionally, time synchronization (using NTP or GPS clocks for all devices) ensures that data logs have correct timestamps – important when diagnosing events or correlating with other systems (like grid events).

From an academic viewpoint, one interesting scenario is *false data injection*: if hackers altered irradiance sensor readings to fool the system into thinking production is fine when it's not (covering up a sabotage where they actually disconnected some panels), the operators might not realize a problem. To mitigate that, cross-checks are used: e.g., comparing multiple irradiance sensors, or comparing neighboring plants' data to spot anomalies.

In conclusion, as PV plants become part of critical energy infrastructure, their SCADA and IT systems must be robust against cyber threats. The solar industry is adapting by hardening devices, employing secure communication protocols, and following best practices from the IT world (access control, encryption, regular audits). Plant operators, on their part, are training personnel on cybersecurity awareness (e.g., not plugging unknown USB drives, using secure passwords)[\[22\]](#). All these efforts aim to maintain the **integrity, availability, and confidentiality** of solar plant data and controls. Integrity so that the data reflects reality, availability so that the monitoring/control is always functional when needed, and confidentiality so that sensitive information (like plant performance or operational commands) isn't exposed to unauthorized parties. With these in place, solar SCADA systems can be trusted to operate safely in an increasingly connected world.

10.3.TWO-AXIS SOLAR TRACKERS (TILT AND AZIMUTH OPTIMIZATION)

To maximize energy capture from the sun, solar arrays can be mounted on **tracking systems** that follow the sun's path across the sky. A **two-axis tracker** (dual-axis tracker) is a mechanism that adjusts the orientation of solar panels in both the horizontal (azimuth) and vertical (tilt/elevation) axes, so that the panels remain as directly faced towards the sun as possible throughout the day and across seasons[25]. This section explores the theoretical background of solar irradiance and why tracking helps, the differences between fixed, single-axis, and dual-axis systems, the components and control algorithms of two-axis trackers, design considerations including performance gains, and real-world application and maintenance issues.

Solar Irradiance and the Need for Tracking

The power output of a solar panel is proportional to the intensity of sunlight hitting its surface and the cosine of the angle of incidence (the angle between the sun's rays and the panel's perpendicular). When sunlight strikes the panel head-on (perpendicular, or 0° incidence angle), the panel receives full intensity. If the sun's rays are at an angle, the effective area is reduced by a cosine factor (Lambert's cosine law). For example, if the sun is at a 60° incidence angle from the normal of the panel, the panel receives only 50% of the intensity ($\cos 60^\circ = 0.5$). Therefore, to **maximize irradiance capture**, a panel ideally should always face the sun directly (incidence angle 0) as the sun moves.

In a fixed-tilt system, the panels are set at a fixed tilt and orientation (e.g., facing true south in the northern hemisphere, at an angle equal to the latitude or optimized for yearly production). This fixed orientation is a compromise – it will be somewhat optimal at solar noon for a certain season, but during mornings, evenings, and other seasons the angle is far from ideal. *Single-axis* trackers improve this by moving either in one plane (usually tracking the sun's daily east-west motion). A typical single-axis tracker might have panels that rotate from east in the morning to west in the evening, following the sun's azimuth, while tilt is fixed at a certain angle. This ensures the sun's rays hit closer to perpendicular each day, though it cannot adjust for the seasonal height change of the sun. *Dual-axis* trackers go a step further by adjusting both azimuth (east-west rotation) and elevation (tilt up/down)[25], essentially keeping the panel's normal aligned with the sun's position (within mechanical limits). Thus, a dual-axis tracker can capture the maximum possible direct sunlight at all times of day, all year.

The theoretical benefit is an increase in the collected **direct beam irradiance**. Under clear skies, the sun's beam contributes the majority of energy. If a panel is normal to the sun, it captures 100% of that beam; if at a tilt, it captures less. By tracking, we eliminate most cosine losses. There's also diffuse irradiance (light

scattered from the sky). Diffuse light comes from all directions; a fixed panel will capture a certain amount of diffuse depending on its view of the sky dome, whereas a tracker might sometimes tilt away from some diffuse light (for example, in the morning a tracker faces east, it “sees” less of the west sky). However, the diffuse component is usually much smaller than the direct component on clear days, so trackers primarily boost the direct component capture. On very cloudy days, when light is mostly diffuse and isotropic, trackers provide little advantage since the sun’s position is irrelevant in diffuse conditions – in those times, even fixed panels receive similar diffuse irradiance as a tracker.

The **astronomical basis** for tracking is the sun’s trajectory: it rises in the east, sets in the west (azimuth changes $\sim 180^\circ$ through the day), and its altitude angle is low in early morning, highest at solar noon, then low at sunset. Seasonally, the sun’s maximum altitude at noon is higher in summer and lower in winter (by an amount equal to the tilt of Earth’s axis, i.e., $\pm 23.5^\circ$ relative to the equator sun angle). At high latitudes, seasonal variation is huge (sun very low in winter, very high in summer). A fixed tilt cannot be optimal for both winter and summer sun angles; a tracker can adjust accordingly.

In summary, tracking is needed to capture more of the available irradiance. The potential gain is highest in areas with a lot of direct sunlight and where the sun traverses a large portion of the sky. In a location with many cloudy days, the gain from tracking is lower. The benefit is also more pronounced at lower latitudes where the sun travels a more overhead path (there’s still significant direct irradiance in morning/evening that a tracker can capture). In very high latitudes, during summer the sun is up for long hours (trackers help follow it in a circle around the sky), but in winter the sun may barely rise – trackers can tilt vertical to catch that low sun (some designs even “table flip” to catch low-angle sun), but there’s limited energy anyway in deep winter.

Fixed vs Single-Axis vs Dual-Axis Systems

Fixed-Tilt Systems: These have panels mounted at a stationary angle and orientation. They are mechanically simple (no moving parts), which makes them low cost and low maintenance. The tilt is usually chosen to maximize annual energy (often roughly equal to latitude if unrestricted), or optimized for season if needed (e.g. steeper tilts in high latitudes to favor winter). Fixed systems capture less morning/evening sun because the panels aren’t facing the sun at those times, and less winter midday sun if tilt isn’t high enough. However, because you can pack fixed panels densely (they don’t move, so spacing is mainly to avoid shading at noon of winter), they can use land area efficiently. In terms of yield, fixed systems are the baseline at 100% for given capacity.

Single-Axis Trackers(Figure 7): These typically rotate around one axis. The common single-axis design is a horizontal axis aligned North-South, with the panels rotating in the East-West direction (tilting from east-facing to west-facing as the day

progresses). This is often called a *horizontal single-axis tracker (HSAT)* or “east-west tracker”. It handles daily motion but not seasonal (tilt relative to horizontal is fixed or limited). Another type is a vertical-axis tracker, which rotates like a turntable (pan) to follow the sun’s azimuth, but the panels themselves stay at a fixed tilt – this captures some daily motion but obviously can’t adjust elevation. The HSAT is more popular for large solar farms. It keeps panels roughly facing the sun all day, except there is some cosine loss because it can’t adjust the tilt for the sun’s height – at solar noon if the sun is high, the panel is already horizontal (flat) so it’s fine; in early morning, the sun is low on the horizon in the east – a horizontal axis tracker facing east will still be tilted horizontally, which isn’t directly facing a low sun (so early morning capture is limited by the fixed tilt angle of panels in the tracker structure). Some single-axis trackers are tilted (the axis is tilted from horizontal) – *tilted single-axis trackers* or TSAT – which is a compromise to capture more of high latitude sun.

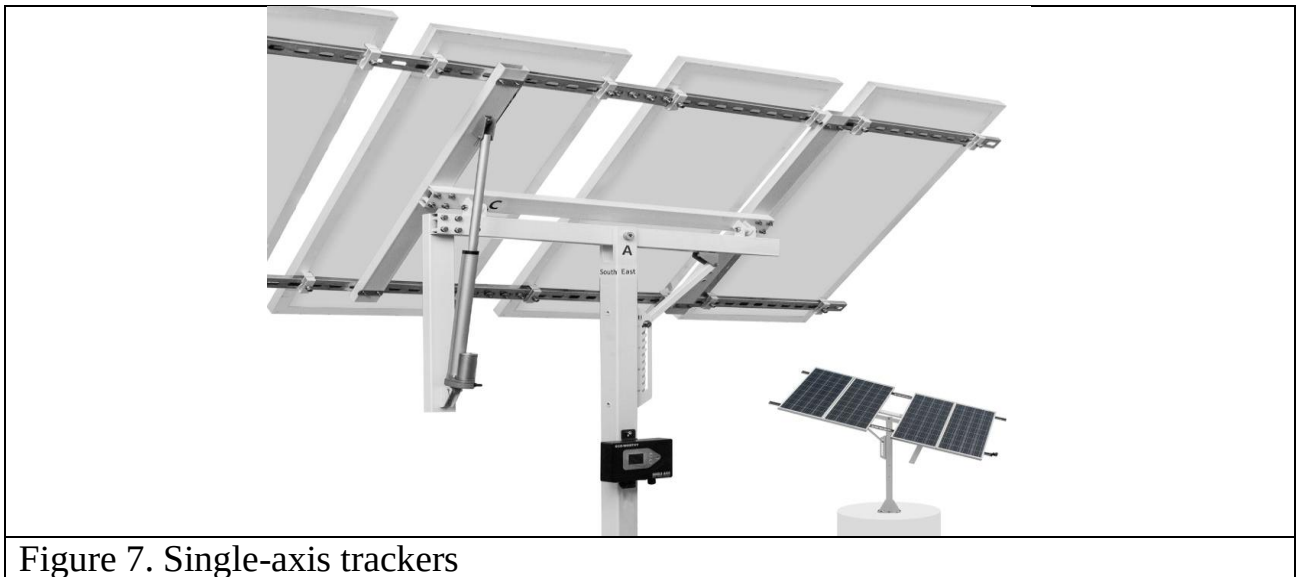


Figure 7. Single-axis trackers

Performance-wise, **single-axis trackers** can significantly boost energy yield: industry literature and field data show on the order of 10% to 25% increase in annual energy compared to fixed tilt[26]. The higher end of that range (20-25%) is seen in sunnier climates at lower latitudes, and the lower end (10-15%) might be in higher latitudes or cloudier regions[26]. For example, a study for mid-latitude sites found single-axis gave ~36% more annual output than optimally fixed panels in one case[27], though that seems a bit high and likely site-specific. A more typical figure is ~15-20%. In any case, the gain is substantial, which is why single-axis trackers have become common in utility-scale projects.

Dual-Axis Trackers(Figure 8,9): These can follow both daily and seasonal changes precisely. They have two degrees of freedom – often implemented as one axis (e.g., a vertical pole for azimuth rotation) and a second orthogonal axis (tilting

the panel up/down). Dual-axis systems can orient the panels *normal* to the sun at all times (if unconstrained). This maximizes the irradiance capture at every moment. The theoretical energy gain of dual-axis vs fixed depends on location, but often quoted gains are 30–40% more than fixed tilt annually[24][26], and about 5–15% more than single-axis (since single-axis already captures a lot)[27][28]. For instance, an industry source notes dual-axis tracking can increase yield >40% over fixed[24]. Another source suggests single-axis might give ~20% and dual-axis ~34% over fixed at certain sites[29]. Essentially, dual-axis recovers that last chunk of energy that single-axis misses (mostly in winter and very early/late in day when the sun is at low elevation).

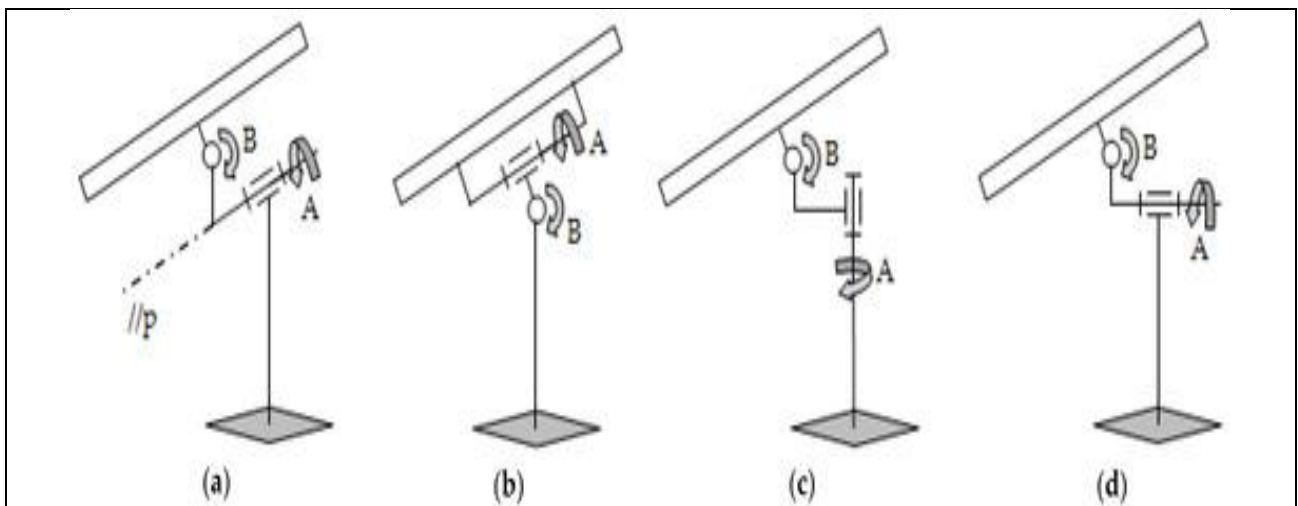


Figure 8. Basic types of dual-axis tracking mechanisms: (a) equatorial; (b) pseudo-equatorial; (c) azimuthal; (d) pseudo-azimuthal.

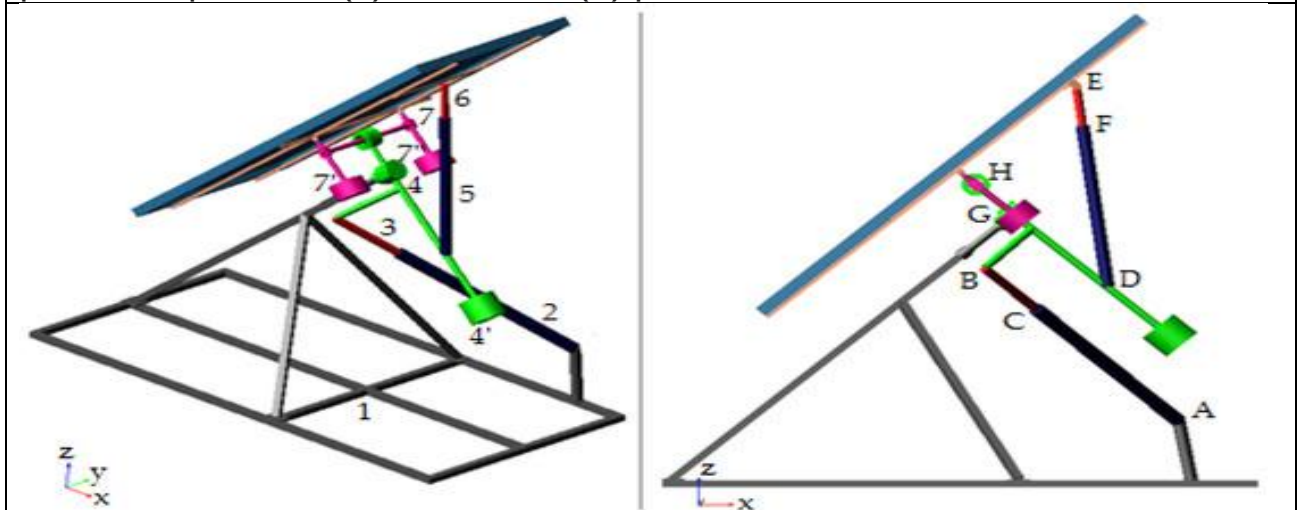


Figure 9. MBS model of the equatorial dual-axis tracking system.

Dual-axis trackers come in different designs: **Tip-Tilt** type (panel array can rotate about vertical and horizontal axes that intersect at the panel's center or so) or **Azimuth-Altitude** type (like a dish antenna mount). One common design is like a

large post (pole) that can spin (azimuth) and a tilting frame on top (elevation). This is often seen in smaller installations or concentrated photovoltaic (CPV) systems. There are also “two-axis” systems that are essentially a tightly coupled combination of single-axis trackers (like a pseudo-dual where one axis might adjust tilt seasonally a few times a year manually, and the other tracks daily). But here we focus on fully automated dual-axis.

Comparative Summary:

- *Cost and Complexity:* Fixed is simplest and cheapest (both in initial cost and O&M). Single-axis adds motors/actuators for one axis and a control system – higher cost and some maintenance (lubrication, motor replacement eventually). Dual-axis roughly doubles the number of actuators or at least adds complexity to control two axes, and often requires a sturdier support (since it must handle various panel orientations and more dynamic stresses). Dual-axis trackers are typically more expensive and have more things that can go wrong (thus historically less commonly deployed at large scale, unless the energy gain was absolutely needed, like in limited space or CPV systems).
- *Land use:* Trackers require spacing to avoid shading each other when panels tilt. Single-axis trackers typically are spaced a bit further apart than fixed (especially if they tilt a lot, you don’t want one row shading the next at low sun angles). Dual-axis trackers often need even more spacing, since they can orient in many angles including potentially casting longer shadows. A study by GSES showed an example where to produce ~3 GWh/year, a fixed system needed ~22,257 m², single-axis needed ~26,709 m², and dual-axis needed ~51,395 m² – dual-axis required more than double the land area of fixed for the same energy, due to spacing requirements[24]. This is a key consideration: if land is constrained, sometimes adding more fixed panels is better than spreading out dual-axis trackers. However, in that example, the dual-axis needed significantly fewer panels to achieve the energy target (5292 modules vs 6930 for fixed)[26], but each tracker needed a lot of space. So if land is very expensive, dual-axis might be disadvantageous; if modules are expensive but land is cheap, dual-axis could make sense by using fewer modules more efficiently.
- *Use Cases:* Fixed systems are standard for most small installations and many large ones where cost minimization is paramount. Single-axis is very popular in utility solar farms in sunny regions (e.g., much of the large solar in the U.S., India, Australia uses single-axis trackers to boost output during morning and late afternoon peaks, which also often aligns better with demand). Dual-axis trackers are used in some cases like high latitude sites trying to maximize winter production, or more commonly in *concentrated PV (CPV)* and solar thermal (concentrated solar power) because those absolutely require direct normal alignment (CPV modules use lenses/mirrors that need direct sunlight). The **SmartFlower** is a well-known dual-axis product for residential decorative

use – it unfolds like a flower and tracks the sun on two axes (aiming to produce more energy in a compact footprint). Another context is *agrivoltaics* where panels are dual-axis to sometimes move panels to avoid shading crops at certain times.

Mechanical and Control Components of Two-Axis Trackers

A two-axis tracker system involves several mechanical and control elements:

Mechanical Components:

- **Mounting Structure:** Typically a robust frame holding one or many solar panels. Dual-axis trackers can be designed to hold a single large panel (like a dish shape for CPV) or multiple panels on a frame (common in photovoltaic trackers, e.g., a frame of 10-20 panels on a pole). The structure must allow motion in two degrees: azimuth rotation (usually around a vertical axis) and tilt (around a horizontal axis). Some designs use a *gimbal-like* arrangement or a yaw-pitch arrangement (like how a telescope is mounted).
- **Actuators:** Motors or actuators drive the movement. Commonly, one axis (azimuth) might use a **slew drive** or gear motor at the base of the pole to rotate the entire top assembly. The other axis (tilt) often uses a **linear actuator** (electric piston) or a rotary actuator with a gearbox to tilt the panel frame up and down[98]. Actuators need to be strong enough to handle wind loads. They usually move slowly (over several hours to go through full range) so speed is not critical, but torque and holding strength are.
- **Bearings and Gears:** There are bearings that allow smooth rotation on each axis. Large slew bearings are used for azimuth in many systems. Gearboxes or screw drives translate motor motion to panel motion, often with high gear ratios to hold position without continuous power (so the wind doesn't back-drive the panels).
- **Support Pole or Foundation:** Dual-axis trackers often are on a single steel pole anchored in concrete (for pedestal type). This pole must bear not only the static weight but dynamic forces from wind when panels are at various angles. The foundation must resist tipping and twisting. Some designs use a truss or four-post support for larger frames.
- **Wind Protection Mechanisms:** High winds are the nemesis of trackers. Mechanically, systems often have a **stow position** (like horizontal or at a certain tilt that minimizes wind profile) to which they move when wind above a threshold is detected. The design may incorporate dampers or shock absorbers to prevent oscillations in wind. Additionally, anemometers (wind speed sensors) feed into the control system; if wind exceeds, say, 15 m/s, the controller might immediately move all trackers to stow (usually flat or edge-on to wind, depending on design) to reduce risk of damage. Mechanical **end stops**

or brakes may exist to prevent the tracker from going beyond safe angles or to lock it during extreme events.

- **Cabling and Joints:** Flexible cable carriers or rotary joints handle the electrical cables to the panels as the tracker moves, ensuring wires don't tangle or fatigue. These must be weatherproof.

Control Components:

- **Controller Unit:** Each tracker or each group of trackers has a controller – often a microcontroller or PLC (Programmable Logic Controller) – that decides the angles to move to and drives the motors accordingly[30]. In distributed designs, each tracker has its own small controller and maybe communicates with a central system for synchronization or monitoring. The controller stores or computes the sun's position and compares it to current angle (from sensors or encoders) to issue commands.
- **Sensors:** There are two main approaches to sensing for control: **open-loop (calculation-based)** and **closed-loop (sensor-based)**. In an open-loop system, the controller uses an algorithm (astronomical calculations) with the known time, date, and location (which might be hard-coded or obtained via GPS) to compute the desired azimuth and elevation angles[23]. It then moves the tracker to those angles using motor encoders or position feedback sensors to know when it reached the target. This doesn't require observing the sun directly; it trusts the calculation (which is usually very accurate to $<0.01^\circ$). In a closed-loop system, **light sensors** are used: often a set of photodiodes or photoresistors arranged in a quadrant configuration (north, south, east, west sensors) or as in one method a "radiometric cube" with sensors on its faces[31]. The tracker's controller then moves the panels until the light sensor outputs are balanced – meaning the sun is centered[23]. Each method has pros/cons as noted earlier. Some advanced trackers use a hybrid: they use astronomical positioning as a baseline and then fine-tune with sensor feedback to correct any misalignment or flexing.
- **Position Feedback:** Even if using pure astronomical control, it's important to have feedback on actual angle – this can be via encoders on the motors (rotary encoders giving angle) or potentiometers/tilt sensors giving the current tilt angle. Feedback allows the controller to adjust precisely and also to calibrate if any slip occurred.
- **Drive Control:** The controller usually includes motor drivers or relays to power the motors in either direction. Some trackers use DC motors, others AC or stepper motors. For fine control, stepper motors or servo motors are ideal (they can move a precise amount). Simpler systems might use DC motors that run until a limit switch or angle reached. Motor control must also consider

stalling (e.g., if a motor is trying to move but the tracker is blocked or in heavy wind, stall current can be high, so current limiting or cut-outs are needed).

- **Central Supervision:** In a solar farm with hundreds of trackers, a central supervisory system might coordinate them, mainly for stowing all in wind or for communication with SCADA. It might also implement backtracking (in single-axis, backtracking is a strategy to avoid inter-row shading by not fully tracking at low sun angles; for dual-axis, inter-row shading can also occur if not enough spacing, so a similar strategy could be used if needed). The central system can also gather performance data (e.g., if each tracker has an irradiance sensor, they can be used to measure actual sunlight and so on).

Control Algorithms: For dual-axis, the core algorithm is to compute solar angles. The **Solar Position Algorithm** (SPA) is a well-known precise algorithm that given latitude, longitude, date, time (and optionally atmospheric parameters) gives the sun's azimuth and elevation to high accuracy. Simpler formulae (based on spherical astronomy) can also be used for slightly less precision which is usually fine for tracker alignment. For example, one formula uses solar declination and hour angle to get elevation:

$$\sin\alpha = \sin\phi\sin\delta + \cos\phi\cos\delta\cos H,$$

where α is solar altitude, ϕ is latitude, δ is sun's declination, H is hour angle. And solar azimuth A can be found from:

$$\sin A = \frac{\cos\delta\sin H}{\cos\alpha}, \quad \cos A = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi},$$

with some sign adjustments depending on quadrant. These equations come from geometry of Earth-sun position. The tracker's controller essentially implements these or uses a library. Many controllers actually just have a pre-loaded ephemeris or iterative calculation each day.

The controller will then output an **angle command** for azimuth (like "rotate to 85° east of south") and for elevation ("tilt up to 45°"). It might update these commands every few minutes – trackers don't need continuous motion; typically moving in small increments every 1-5 minutes is enough to effectively follow the sun without noticeable energy loss, and this reduces wear. Some trackers even move in discrete steps a few times an hour.

Important in control: ensuring the tracker doesn't overshoot or oscillate. Some use PID control on the motor to smoothly approach the angle. Others simply have slow speed such that it's not an issue.

Backtracking (for multi-row installations): If dual-axis trackers are close together, one might shadow another when the sun is low. Backtracking algorithms intentionally misalign trackers slightly to reduce shade on neighbors. This is more common in

single-axis row setups. In dual-axis farms, they usually space far enough or arrange so shading is minimal. If needed, the control can incorporate neighbor awareness.

Safety controls: limit switches to prevent over-rotation (e.g., azimuth might be limited to say 270° range to avoid twisting cables too far, etc.), tilt limits (to not tilt beyond horizontal either way unless design allows). Also manual controls for maintenance – like a technician can put tracker in a certain position to service it (and lock it out from moving).

To illustrate a control sequence on a sunny day: At dawn, if using astronomical, the tracker knows the sun's azimuth even before it rises (below horizon). Often trackers “*sleep*” at night in a westward position or stow flat. Some are programmed to pre-position for sunrise (i.e. go to east horizon position just before dawn). Then as sun comes up, it starts tracking, moving in azimuth and tilt accordingly through the day. Around sunset, once sun is below horizon, some trackers might reset (go back to east ready for next morning, or go to a stow angle). Others might simply stay at last position and then reverse. Different strategies exist. If high wind hits midday, wind sensors trigger all controllers to go to stow angle (maybe flat horizontal to reduce tilt, or sometimes straight up vertical to let wind pass through – the optimal stow angle can differ by design). After wind subsides, they return to tracking.

Mechanically controlling two axes under wind loads means robust control is needed to avoid *galloping*. If a gust hits and the panel starts to oscillate, the control might have to damp that (some trackers have active damping using the motors, others rely purely on mechanical damping).

Maintenance aspects in controls: The electronics (controllers, sensors) must be weather-hardened (often IP65 enclosures, wide temperature tolerance). They usually are powered by the plant's own power (small AC or DC supply). Some standalone trackers have a small PV panel and battery just to power their motors and controllers, making each tracker independent of grid – useful for off-grid or simpler wiring.

Algorithms and Optimization for Sun Tracking

We've touched on algorithms in control; here we focus on the theoretical approaches to track the sun and optimize the angles:

Astronomical Algorithms: As noted, these rely on precise calculation of the sun's position based on time and location. The sun's position is given by two angles: solar altitude (or zenith which is 90° - altitude) and solar azimuth. A dual-axis tracker's aim is to minimize the angle between the panel normal and the sun's rays (i.e., keep that angle at 0). In other words, set panel's surface tilt = sun's altitude, and panel's compass direction = sun's azimuth (with some reference like panel azimuth 0 = due south in northern hemisphere). Most controllers use published algorithms such as NOAA's Solar Position Algorithm or even simpler solar geometry formulae which have an accuracy better than 0.01° – more than enough, since a small misalignment of say 1° results in $\cos 1^\circ \approx 0.9998$, negligible loss. These algorithms often require

converting the local time to true solar time (accounting for longitude and equation of time), calculating declination δ from day of year, hour angle H from time, etc.

For optimizing energy capture, one also considers constraints: if the sun is very close to horizon, sometimes trackers might not bother to chase it below a certain altitude due to shading from terrain or inefficiency (they might have a cutoff like don't track when sun $< 5^\circ$ elevation because output is anyway low and diffuse dominates). Also, some dual-axis trackers might have limited range (maybe they can't tilt beyond a certain point). The algorithm must handle those gracefully.

Sensor-Based Algorithms: If using light sensors, the algorithm is typically to drive motors until sensor balance is achieved. This can be implemented with a simple proportional control: e.g., if the east sensor sees more light than the west sensor, rotate east until they equalize[23]. Similarly for north vs south sensors for tilt. One challenge is when the sun is obscured (cloudy) – sensors might become noisy or equal but sun is not actually centered. That's why often a hybrid approach is used: revert to predicted position during cloudy periods or incorporate a threshold that if overall light is low, don't aggressively hunt. The **sunflower algorithm** essentially (like a sunflower turning to the brightest light) is intuitive and works well under direct sun conditions.

Hybrid and Advanced Strategies: Some research suggests combining both sensor and calculation to get benefits of each[32]. For instance, an active sensor might fine-tune after the astronomical has positioned within say 5° .

Precision vs Energy: It's worth noting that an error of a few degrees in pointing causes a very small energy loss (cosine of 3° is 0.9986). So controllers don't need to be extremely high precision at all times; being within $\sim 2\text{--}3^\circ$ of perfect alignment yields $>99\%$ of maximum irradiance. The bigger factor is to avoid gross misalignment (like tens of degrees).

Optimization Considerations: The algorithm may also consider **backtracking** (especially in single-axis). For dual-axis, if array spacing is limited, one could incorporate a strategy where in early morning/late evening, instead of fully facing the sun (which would make a low angle that casts a long shadow on the next row), the tracker might stay a bit more upright to reduce shadow length. This sacrifices some irradiation on the panel but maybe allows more energy on adjacent rows – a system-level optimization. On flat terrain with independent dual-axis and enough spacing, backtracking is usually not needed.

Energy Gain Estimates: On the optimization side, one calculates expected energy gain by integrating incident irradiance over a day/year for each type. Tools like PVsyst or NREL's SAM can simulate fixed vs tracking. As mentioned, typical performance gain numbers: single-axis $\sim +15\text{--}25\%$, dual-axis $\sim +30\text{--}40\%$ vs fixed[24]. One specific reference: dual-axis can yield $\sim 20\%$ more than single-axis, which already gave $\sim 20\%$ over fixed, so roughly 44% over fixed (not in all cases but a ballpark)[27]. This matches the 40-50% region for ideal scenarios.

Edge cases: At very high latitudes (like 65°N), in summer the sun might circle around the sky without setting – a dual-axis would continuously follow it (with potentially a “flip” at lower midnight sun altitudes to avoid going upside down). In winter, the sun is very low or not present. The gain there might be huge in summer (because fixed panels oriented south won’t catch northern-path sun well, but dual-axis can) – but this is a niche scenario.

Astronomical algorithm example: Controllers often use something like:

Given latitude ϕ , longitude L .

Compute current date/time -> Julian day or similar.

Compute solar declination δ and equation of time E .

Compute solar time = standard time + E correction + $4*(L - L_{\text{stdz}})$ (min).

Compute hour angle $H = 15^{\circ} * (\text{solar time} - 12\text{h})$.

Then:

elevation $\alpha = \arcsin(\sin\phi \sin\delta + \cos\phi \cos\delta \cos H)$

azimuth $A = \arctan2(\sin H, (\cos H * \sin\phi - \tan\delta * \cos\phi))$ (with appropriate quadrant adjustments, yielding an angle relative to south or north).

The controller might convert azimuth to the tracker’s reference (some trackers might define 0° azimuth as East, etc.). Then it moves motors accordingly. This is done maybe every minute.

Control System Design: The dual-axis tracker control is essentially a 2-input-2-output system (desired vs actual angles). Simple control suffices since it's slow-moving. Many just use bang-bang (move until sensor balanced or angle reached). Others use closed-loop with small error tolerance to stop. Given the low speeds, dynamic control issues like overshoot are minor.

Power Consumption of Tracking: The algorithms also might be designed to minimize unnecessary movement to save power. Trackers use a small amount of power (motors running intermittently). Typically, power usage of a tracker might be a few kWh per year per motor, which is very small compared to the thousands of kWh gained from the extra solar energy. For instance, a single-axis tracker might consume $<0.5\%$ of the extra energy it yields for motor power. Dual-axis have two motors, slightly more usage but still small. The control can implement deadbands (like if sun moves $<0.5^{\circ}$ since last move, don’t move yet) so that motors aren’t constantly nudging.

System Design Considerations and Performance Gains

The design of a dual-axis tracker system must account for structural, environmental, and economic factors:

- **Structural Design:** The tracker must withstand worst-case winds. At certain wind speeds (e.g., 100 km/h or more, depending on location codes) the

structure should survive even if control fails. This often means panels should be able to feather (go flat) or the structure is beefy enough to handle loads. Dual-axis trackers, with panels elevated, can act like big sails, thus require strong foundations and materials. Fatigue loading from daily motion and wind vibrations is considered – connections must be robust. Often steel or aluminum structures are galvanized or coated to prevent rust.

- **Array Layout:** As noted, spacing between trackers is a design variable. They should be spaced to avoid shading at least during critical times. Some layouts stagger trackers or elevate them higher to allow closer spacing (but tall poles cost more). The land terrain matters too: on a slope, trackers might shade ones downhill if not careful. Many designs assume a flat area and align trackers in a grid.
- **Energy Yield vs Land Use:** If land is not a limiting factor and one aims for maximum output per panel, dual-axis is ideal. If land is limited but panels are cheap, perhaps one could just add more panels fixed tilt to get the same energy as fewer panels on trackers. There is a trade-off: trackers yield more energy per installed watt (raising capacity factor), which can be beneficial where grid connection capacity is limited (you get more MWh per MWAC of interconnection). Some utility projects choose single-axis for that reason: they can maximize use of their inverter capacity in morning and evening too. For dual-axis, the economics have to justify the higher cost and maintenance.
- **Maintenance & Reliability:** More moving parts mean higher maintenance. There's potential downtime if a tracker fails (though if one tracker fails, it only affects the panels on it, not the whole system – local impact). O&M teams need to inspect trackers, tighten bolts, grease gears, check sensor calibration, etc. There's also the risk of **misalignment** over time – e.g., if an encoder drifts or a gearbox slips a tooth, a tracker might not point exactly where it thinks it is. Regular calibration or referencing might be needed. Some trackers occasionally do a **find home** routine: e.g., once a day or week, go to a known physical reference (like a limit switch) to recalibrate the position reading.
- **Performance Gains:** The theoretical gain of dual-axis tracking is capturing nearly the entire direct normal irradiance available. In numbers: If a fixed south-tilted panel at latitude tilt might get X kWh/year, a dual-axis could get X plus an extra 30-45%. For example, in a location with 5 kWh/m²/day average insolation on fixed tilt, dual-axis might get around 6.5-7 kWh/m²/day[26]. Real world, as cited, single-axis ~1.1 to 1.3 times energy of fixed, dual-axis ~1.3 to 1.4 times fixed (some references claim up to 1.5). The exact boost depends on diffuse fraction. In a high direct sun desert, the difference between fixed vs tracking is huge because so much direct can be gained. In a cloudy place, tracking yields little extra because direct component is small.

We can quantify: In an entirely clear sky scenario, a tracker will always get the direct normal irradiance (DNI) component fully. A fixed tilted panel gets at best something like the cosine of incidence integrated over day. If the sun moves $\pm 75^\circ$ in azimuth and $\pm 23^\circ$ in altitude seasonally, fixed loses those cosines. That is the 30-40%. In an entirely diffuse scenario, tracker and fixed both just get (diffuse on horizontal * panel tilt factor, etc.), difference maybe $\pm 5\%$ if any. So the actual gain = DNI fraction * (1/cosine losses). Many climates have DNI fraction maybe 60-80% of total.

- **System Integration:** If using trackers, each row or unit might have its own controls and power consumption – designers factor this in the electrical design, maybe providing an auxiliary power supply or using the plant's output via a step-down transformer to power them. Some trackers could also have backup power or manual stow in case of power failure (so you can still move them to safe position if grid is down but a storm comes).
- **Effects on Inverter Sizing:** Trackers produce a more peaked output over more hours. In the morning and late afternoon, more power than a fixed system would. This can affect inverter loading: often in single-axis systems, the DC/AC ratio (oversizing ratio) is made higher because the tracker broadens the production curve, allowing more DC to be installed per inverter without clipping. For dual-axis, you might similarly adjust DC/AC ratio. Performance gain means potentially a higher capacity factor – meaning a 1 MW tracker plant might produce as much energy as a ~ 1.3 MW fixed plant.
- **Real-World Applications:** There are large dual-axis tracker plants, though fewer than single-axis. Some notable uses include many off-grid or remote systems where maximizing output is key (e.g., powering telecommunication towers with minimal panels). Also, as mentioned, concentrated photovoltaic (CPV) systems *require* dual-axis trackers because CPV modules use lenses to focus sunlight into solar cells – they need to be within $\sim 0.5^\circ$ alignment of the sun or they lose focus. Companies like Amonix and others built CPV arrays on dual-axis trackers in high DNI regions.
- **Economics:** Historically, dual-axis trackers were considered not cost-effective for standard silicon PV, given how panel prices fell. It was often cheaper to add 30% more panels than to buy dual-axis trackers. However, if land or space is extremely constrained (like an urban environment or a solar tree concept), dual-axis could help extract maximum energy from limited area. There's also maintenance cost – one must account that over 20-25 years, motors and gears might need replacement, adding to O&M costs. Reliability improvements have been made; many trackers are designed with >10 -year life on actuators, but still.
- **Climate and Maintenance:** In snowy regions, trackers have an advantage that they can tilt vertically to dump snow off panels (whereas fixed panels might accumulate snow if not steep enough). So in winter, dual-axis trackers could

clear themselves by moving. They can also avoid snow buildup by not remaining flat during snowfall. In dusty areas, trackers do not help dust – in fact, flat positions might accumulate more dust, but they often stow vertically at night which can let dust slide. Also, being able to position vertically might help when rain comes, letting rain wash better.

- **Shadow and Diffuse considerations:** One slight disadvantage is that a horizontally oriented fixed array can catch some diffuse light from the whole sky dome; a two-axis tracker pointed at the sun sees less of the sky (just around sun) – however, this effect is minor because diffuse is usually much less than direct when sun is out, and when sun is not out (cloudy), trackers often default to horizontal or some optimum angle to catch diffuse (some algorithms optimize for diffuse if sun obscured). In fully overcast conditions, best orientation is actually horizontal (to see most sky); trackers could detect low direct light and just go flat to maximize diffuse collection.

Real-World Applications and Maintenance of Two-Axis Trackers

Applications: Dual-axis trackers are found in various scales:

- **Small-scale (Residential/Community):** Products like the SmartFlower (a sculptural 2-axis tracker) are aimed at homes or public installations wanting maximum visibility and output in a small footprint. Also, some homeowners or off-grid setups mount a few panels on a pole with dual-axis tracker to follow the sun and charge batteries more consistently through the day. These applications value the extended power availability (morning and evening) and sometimes the aesthetic or educational aspect (seeing solar panels move with the sun can be engaging).
- **Commercial/Industrial:** Some factories or commercial sites with limited roof space have installed dual-axis trackers on the ground or rooftop if structurally feasible. The higher energy yield can improve ROI if energy prices are high and space is limited.
- **Utility-Scale:** While most utility PV uses single-axis, there have been utility projects with dual-axis. They typically occur where land is plentiful enough and the latitude maybe medium to high, or where a technology like CPV is used. For instance, in Spain and Italy during the early 2010s, some PV plants used dual-axis trackers because feed-in tariffs rewarded maximum production and land was available. In India, a few plants tested dual-axis to squeeze more out of smaller plots.

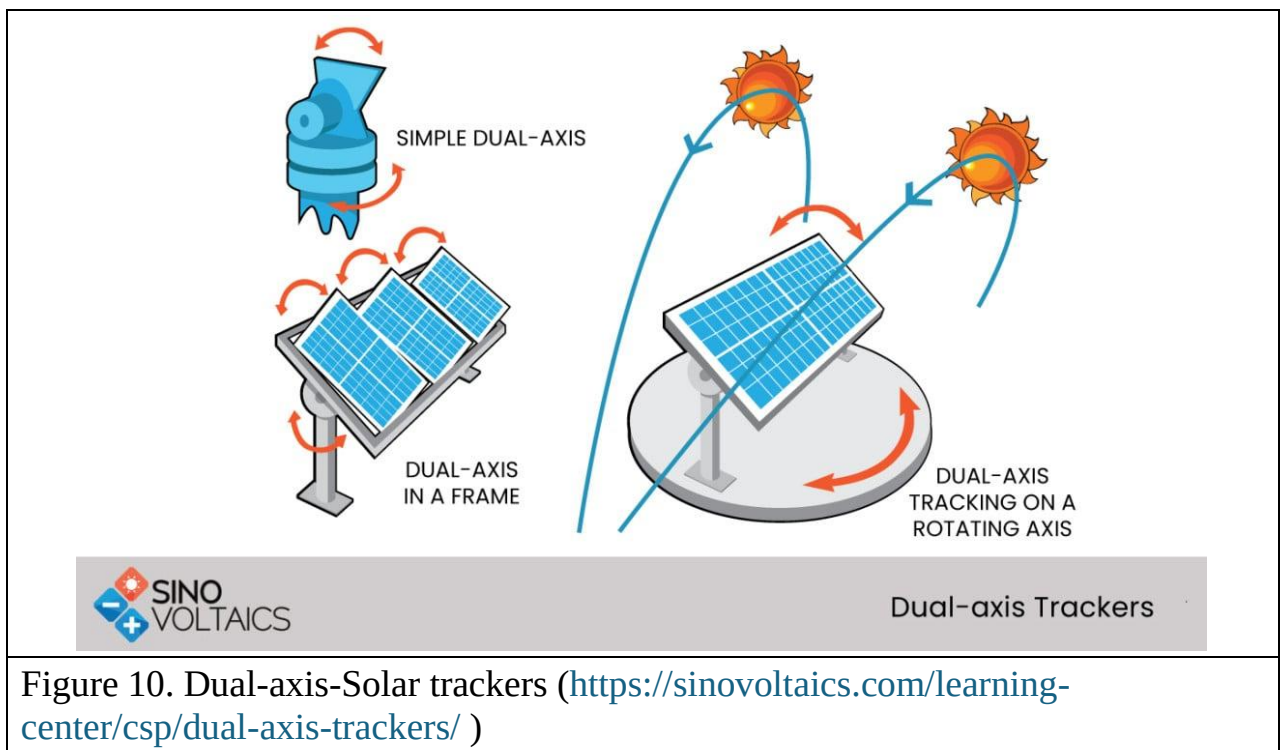


Figure 10. Dual-axis-Solar trackers (<https://sinovoltaics.com/learning-center/csp/dual-axis-trackers/>)

- **Concentrated Solar Power (CSP) & Heliostats:** In solar thermal power (like power towers or dish Stirling systems), dual-axis mirrors (heliostats or dishes) are essential. Those are a type of dual-axis tracker (tracking the sun to reflect onto a central receiver or concentrate on a receiver). Lessons from those fields also feed into PV trackers. However, CSP heliostats can be enormous and have their own control complexities (coordinating thousands of mirrors).
- **Agrivoltaics:** There is research into using dual-axis trackers in fields so that one can optimize both farming and energy (e.g., move panels to allow more light to crops at certain times). A dual-axis could even be programmed to sometimes orient vertically (to let full sun to crops) or to provide shade as needed. This dynamic control is promising in agrivoltaics.

Performance in Real World: Real data from a dual-axis tracker plant will show a more “rectangular” daily production curve – starting earlier, peaking around midday but not dropping as sharply as fixed after noon, and extending later in day. The energy yield per installed kW is higher. For example, if a fixed system yields 1500 kWh/kW/year, a dual-axis in same location might yield 2000+ kWh/kW/year. This improves the capacity factor of the plant (the ratio of actual energy to potential if running at full power continuously). Solar fixed might have 15-20% capacity factor; dual-axis might raise it to ~20-25% in a good sun region.

Maintenance Concerns:

Maintaining dual-axis trackers involves:

- **Mechanical Checks:** Bolts can loosen due to vibrations and movement – periodic torque checks on critical bolts (especially on the mounting of motors, gearboxes, the slew bearing bolts, etc.) are necessary. Lubrication of moving parts (gear teeth, actuator joints) as per manufacturer schedule (maybe annually or biennially).
- **Motor/Actuator Maintenance:** Actuators might need inspection and occasional replacement after a certain number of cycles. If electric motors have brushes (DC motors) those wear out. Many designs now use brushless motors or stepper motors for longevity.
- **Sensor Calibration:** If using sun sensors, they can get dirty or drift; they should be cleaned and checked. If using encoders, ensure the zero position calibration is still correct. Sometimes after a strong wind event, a tracker might slip a bit – the control system should detect if it's off (maybe by comparing expected vs actual sun sensor reading) and allow recalibration.
- **Electrical Maintenance:** The moving nature means cable flex – cables in drag chains should be of high flex rating, but still they might wear. Inspect cables for insulation wear or strain. Ensure that cable twist around the azimuth axis is managed (often by a slip ring or generous loop) – slip rings (if used to pass power through a rotating joint) need maintenance or replacement as they have contacts.
- **Cleaning and Soiling:** Trackers might accumulate less uniform soiling since they move. But maintenance might include cleaning panels which on a tracker can be tricky if at various angles – often one would command the tracker to a convenient angle (like horizontal or a comfortable tilt) for manual cleaning or robot cleaning. It's a nice aspect that you can adjust panel angle to help cleaning (e.g., tilt down to let rain flush off dirt thoroughly).
- **Monitoring Trackers:** SCADA systems often monitor tracker status. If a tracker is stuck or not moving (no current draw on motor when expected, or position feedback not changing), an alarm can be raised. O&M crew then knows maybe motor failed or something jammed. It is important to fix because a stuck tracker basically becomes a fixed panel at the wrong angle, potentially losing a lot of energy, and could also strain if others move differently (in some designs multiple trackers share a drive, but usually each is independent).
- **Reliability:** Over years, how do trackers hold up? Good designs have demonstrated high reliability, but environment plays a role. Sand storms can erode mechanical parts, so sealing is important. Cold climates require ensuring actuators don't freeze (some have heaters or use low-temperature grease).
- **Software:** The control software might need updates if issues are found. Possibly remote update is possible if networked. Ensuring cyber safety (as

mentioned in SCADA section, trackers too could be a point to secure, though usually they're on a dedicated network).

- **Failure Modes:** Common failure modes include: actuator failure (loss of motion on one or both axes, leaving panel stuck maybe at an odd angle – immediate loss of production and risk if wind comes from a bad angle); sensor failure (which might make it mis-track – but many will default to some safe mode if sensor invalid); communication failure (if one tracker's control loses comms with central, it might either continue on internal schedule or freeze – depending on design – needs checking); power failure (if grid down, some trackers might not move – ideally they have a battery backup or go to safe position on loss of power).
- **End of Life:** At end of project life (~25 years), trackers may need major refurbishment or removal. Panels might last 30+ years, but trackers may or may not. That adds complexity in decommissioning or repowering (replacing with new modules might require recalculating weight and wind).

Case Studies: An example real-world dual-axis installation is the *Les Mées* solar farm in France (some sections were dual-axis I believe), or various in Germany (where higher latitude made dual-axis attractive under feed-in tariffs). These showed good performance but also the higher O&M costs relative to fixed.

Many places have chosen single-axis as a sweet spot of gain vs complexity. Dual-axis tends to appear either in small niche or in special high DNI contexts (like CPV). However, the principles remain important academically, as sun-tracking is key to maximizing solar intercept, and with increasing value on time-of-use generation (e.g., generating later in day is more valuable in some markets), dual-axis could see interest if it can deliver more late afternoon energy than single-axis (which it can, by adjusting tilt to catch lower sun).

In sum, two-axis trackers embody a high-tech approach to solar harvesting: they add mechanical and control complexity to maximize the geometric coupling between panels and sunlight. They exemplify an interdisciplinary design challenge – combining mechanical engineering (structures and mechanisms), control systems (algorithms to follow the sun precisely), and economic optimization (cost vs gain). For a bachelor's level engineering student, understanding dual-axis trackers involves kinematics (two rotational degrees of freedom), dynamics (wind loads, inertia), control theory (sun tracking algorithms), and photovoltaic performance analysis (how much extra energy).

Despite more maintenance, the concept of dual-axis tracking remains attractive where maximizing energy per panel is crucial or for technologies that demand direct normal alignment. As technology advances, we may see more robust and cost-effective tracker designs, possibly making dual-axis more common if energy markets favor highest output.

In any case, tracking systems, whether single or dual, highlight how **mechanical innovation can boost the efficiency of solar energy systems** by simply improving how panels interface with the moving light source, the sun. The trade-off between moving parts and static simplicity continues to be a central engineering decision in solar farm design.

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