Cost Competitiveness of Perovskite–Silicon Tandem PV in India by 2030

Introduction

India's solar energy landscape is poised for major growth and technological shifts by 2030. The country has set ambitious targets (on the order of 280–300 GW of solar by 2030) and solar PV is expected to become a cornerstone of the power mix . To meet these goals, emerging high-efficiency technologies like perovskite–silicon tandem cells are being explored alongside improvements in conventional silicon PV. Perovskite–silicon tandem photovoltaic (PV) modules stack a perovskite solar cell atop a silicon cell, capturing a broader spectrum of sunlight and potentially exceeding the efficiency limits of single-junction silicon. Laboratory tandem cells have already surpassed 29–31% efficiency in recent years, compared to ~22% for typical silicon modules . The key question is whether these tandem PV systems can deliver electricity at a **competitive cost** in India's context by 2030. This report examines the cost competitiveness of perovskite–silicon tandem PV for both utility-scale and rooftop applications, including critical metrics (LCOE, CAPEX, cost per watt, ROI), comparisons with mainstream silicon and other emerging technologies (thin-film CdTe, HJT, etc.), and the policy/incentive landscape that could influence deployment. All cost projections are given in the context of India's high solar resource and market conditions, with data-driven modeling assumptions and sensitivity analyses to capture best- and worst-case scenarios.

Utility-Scale PV: Tandem vs. Silicon Cost Metrics by 2030

Utility-scale solar farms in India have seen **steep declines in cost** over the past decade, making solar the cheapest new power source. By late 2023, the average capital cost for large-scale PV projects had fallen to a record low of around ₹3.3 crore/MW (approximately \$0.40/W) . This trend is driven by plummeting module prices – Indian mono-Si PERC module prices dropped ~30–37% in 2023 alone – and economies of scale in installation. According to the International Energy Agency, *new* solar in India is already cheaper than new coal power, and by 2030 current trajectories indicate solar PV will even undercut the operating cost of most **existing** coal plants . In other words, by 2030 utility solar LCOEs in India are expected to reach around ₹1.5–2.5 per kWh (≈2–3 ¢/kWh) in high-resource regions, assuming continued technology and financing gains.

Perovskite–silicon tandem PV aims to push these costs even lower by raising efficiency. Higher module efficiency increases the energy output per unit area, which can yield a lower levelized cost of electricity (LCOE) if the cost premium for the technology is not prohibitive. *NREL* analysts note that a tandem module needs at least **25% efficiency** to be **cost-competitive** with other solar technologies . Fortunately, tandem prototypes have already met this threshold; for instance, Oxford PV (a leader in commercializing tandem cells) announced a 27% efficient product in 2023 , and efficiencies >30% are expected by 2030 as the technology matures. The value of this efficiency is significant – a study showed that a **2.5% absolute efficiency gain** in a PV module can reduce cost per watt as much as doubling the manufacturing scale of a factory . In practice, higher efficiency means fewer modules, racks, and land area for the same power, trimming balance-of-system costs. An industry consortium in Europe (IPVF) projects that its tandem technology can **cut the cost of energy by ~15%** versus today's silicon PV . Similarly, BloombergNEF forecasts that by 2030 tandem modules could capture ~20% of the solar market in **premium use cases**, where their higher performance justifies a slight price premium .

Projected CAPEX and LCOE: By 2030, a utility-scale perovskite–silicon tandem PV plant in India is expected to have a total installed CAPEX on the order of ₹35–45 million per MW (₹35–45/W, or roughly $0.42–0.55/W). This is somewhat higher on a per-MW basis than contemporary mono-Si projects, reflecting an initial premium for tandem modules. However, because each tandem module generates more power, the **effective cost per watt** of capacity can approach parity. For example, if mainstream single-junction silicon modules (~23–25% efficient in 2030) cost ~$0.20/W, a tandem module of ~30% efficiency might cost ~$0.25–0.30/W. Analysis by an IPVF research team found that a 30%-efficient tandem could tolerate an extra **$0.05–0.10/W cost** yet still deliver the same LCOE as conventional silicon . In concrete terms, a recent techno-economic study for India estimated future perovskite/silicon modules could have manufacturing costs around **$0.15–0.21/W** . At that module cost, a utility-scale system (including inverters, structures, etc.) might reach ~₹40/W. With India's high solar irradiance (≥1,800 kWh/kW/year in many regions), the **LCOE** for tandem PV could drop into the range of **₹1.5–2.0/kWh** (~1.8–2.4 ¢/kWh) assuming standard 25-year project life. Indeed, one **Indian case study** found that if perovskite modules achieve a **25-year lifetime**, their LCOE can be as low as **₹1.2–1.4/kWh** (~1.5–1.7 ¢/kWh) – extraordinarily low by today's standards, and **on par or lower** than projected silicon-only PV. Even with a shorter 20-year lifetime (accounting for potential durability limits of new technology), tandem systems are projected to produce power at ~₹2/kWh (≈2.5 ¢) , competitive with the best solar tariffs seen in India to date. These estimates assume that efficiency gains and moderate scaling offset the added costs of tandem manufacturing. Crucially, they also assume continued declines in balance-of-system costs (land, mounting, etc.) due to the smaller area needed per MW – factors that favor tandem especially in land-constrained or high land-cost scenarios.

Sensitivity considerations: The competitiveness of tandem PV at utility scale will depend on key parameters: **module lifetime and reliability** (degradation), efficiency, and financing costs. If tandem modules do not achieve long lifetimes, the LCOE advantage could evaporate. Durability is widely seen as the *largest technological risk* for perovskite-based PV – to approach a ~₹1.6/kWh (2 ¢) LCOE by 2030, perovskite layers must be engineered to last **20+ years** in harsh field conditions . A U.S. DOE report noted that without ~20-year longevity, perovskites will struggle against ever-cheaper silicon and CdTe modules . Conversely, if tandem modules show low degradation (e.g. <0.5%/year) and reach 30-year warranties (some silicon manufacturers are targeting ~30-year warranties by 2030), the effective energy yield over system life rises significantly, further **driving down LCOE**. Financing cost is another factor – early deployments of tandem tech may face higher interest rates or equity return demands (risk premiums) until banks gain confidence in their performance . This could initially raise project LCOE. However, strong policy support or insurance mechanisms could mitigate this, as discussed later. In summary, for utility-scale projects by 2030, perovskite–silicon tandems are **likely to be cost-competitive** with the most advanced silicon-only plants if technical milestones (high efficiency ~30% and sufficient durability) are met. In best-case scenarios, tandem PV could offer **slightly lower LCOE** than single-junction silicon, thanks to higher energy yield per rupee of investment . Even in a conservative case (moderate efficiency gain, minor cost premium), tandem PV should at least reach parity with mainstream solar on LCOE by 2030 .

Table 1 contrasts key 2030 projections for utility-scale systems using different PV technologies in India:

Technology (Utility-Scale, 2030)	Module Eff.	Installed CAPEX	LCOE (₹/kWh)	Notes
Mono-Si PERC/PERT (baseline)	23–25%	₹35–38/W (₹3.5–3.8 Cr/MW)	~2.0–2.5	Most widespread; continued cost declines expected.
Mono-Si TOPCon/HJT (advanced Si)	25–27%	₹37–40/W	~1.8–2.3	Higher efficiency silicon (n-type); marginally higher cost but lower LCOE due to efficiency.
Perovskite–Si Tandem (2T or 4T)	28–30%	₹40–45/W	~1.5–2.2	Efficiency ~30% can offset a ~\$0.05–0.1/W premium . Requires 20–25 yr lifetime for low LCOE .
Thin-Film CdTe (utility module)	~22–24%	₹35–38/W	~2.0–2.5	Continued improvements by 2030; competitive in high-temperature climates.
CIGS / Other Emerging	18–20%	₹40+/W	>2.5	Niche by 2030; lower efficiency limits competitiveness in India.

Notes: CAPEX in ₹/W includes all plant costs (modules, inverters, BOS) and is an indicative range for 2030. 1 Cr (crore) = 10 million rupees. LCOE ranges assume ~8–9% cost of capital, 25-year project, and high solar irradiation (~1,800 kWh/kW/year). Tandem data assumes stable performance over 20+ years; if lifespan were only ~10 years, tandem LCOE would rise to ~3–3.4 ¢/kWh (₹2.5+) , above the expected silicon baseline.

Rooftop PV and Distributed Applications

In the rooftop and distributed solar segment, perovskite–silicon tandem technology could be especially valuable by 2030. Rooftop installations in India often face space constraints – the total available roof area limits the system size. A higher-efficiency module allows more kW to be installed in a given area, or alternatively, the same kW in a smaller area. This is attractive for commercial/industrial (C&I) and residential users aiming to maximize generation from limited roof space or to meet a larger share of their energy demand on-site. By 2030, mainstream silicon rooftop modules may reach 22–23% efficiency (with premium monofacial or bifacial panels in the 400–450 W range for a standard size). Tandem modules, at ~28–30% efficiency, could offer 20–30% more power output in the same form factor – e.g. a tandem panel could be ~600 W in the size of today's 450 W panel. This higher wattage can **improve project economics** despite a higher unit cost, because many fixed costs (mounting structures, wiring, labor) scale with panel count or area rather than capacity.

Cost per Watt: Rooftop solar generally has a higher installed cost than utility-scale due to smaller project sizes and additional costs (mounting on existing structures, safety, etc.). In 2025, Indian rooftop PV costs are roughly ₹50–60/W ($0.60–0.72/W) for commercial systems and higher for residential . By 2030, continued price declines and standardized designs could bring typical rooftop CAPEX down to perhaps ₹35–45/W ($0.42–0.55/W), similar to utility-scale in 2023. The module itself makes up a significant portion of this (~40–50%). If tandem modules command a premium (say ₹5–10/W higher than silicon modules), the total rooftop system cost might be ~10–15% higher than using conventional panels. However, the energy yield would also be higher – potentially ~15–20% more kWh/year for the same kW rating (due to better low-light performance and spectrum utilization of tandem, aside from just nameplate efficiency). For a consumer or business, the **return on investment (ROI)** for rooftop solar often hinges on the **payback period** through electricity bill savings. In India, commercial consumers pay ₹6–10/kWh tariffs, so solar that can produce at ₹2–4/kWh LCOE yields substantial savings. Even today, typical rooftop PV payback periods are about *3–5 years* for commercial users – an exceptionally attractive ROI – thanks to net metering/behind-the-meter savings. By 2030, if tariffs rise and PV costs fall further, paybacks could remain in that range or better.

For tandem PV on rooftops, the ROI calculus will include the value of extra energy. If a tandem system costs ~15% more but generates ~15–20% more energy (especially during peak sun when output is inverter-limited for standard systems), the net effect could be a similar or even shorter payback compared to a silicon system. **Table 2** provides an illustrative comparison of a conventional vs tandem rooftop 10 kW system in 2030:

Metric (10 kW Rooftop System)	Silicon PV (2030)	Tandem PV (2030)
Module efficiency	~22%	~28%
Number of 500 W modules (for ~10 kW)	20 modules	*~16 modules* (600 W each)
Total installed cost (₹)	₹4,00,000 (@ ₹40/W)	*₹4,60,000* (@ ₹46/W)
Annual energy yield (Delhi example)	~15,000 kWh	*~18,000 kWh* (≈20% higher)
First-year bill savings (@ ₹8/kWh)	~₹1,20,000	*~₹1,44,000*
Simple payback period	~3.3 years	*~3.2 years*

Assumptions: This example assumes a commercial/industrial rooftop in a high solar region (Delhi, ~1500 kWh/kW/yr yield). Both systems 10 kW_dc. Tandem has higher output due to efficiency and slightly better thermal/low-light performance. Costs are notional for 2030 (no subsidies). As shown, the tandem system's higher upfront cost is offset by greater energy savings, yielding a comparable payback (~3 years). For space-constrained customers who cannot simply install more silicon panels (e.g. a factory with limited roof area), the tandem option allows higher annual savings (₹24k more here) from the same roof, potentially justifying the investment. Moreover, some consumers may be willing to pay a premium for **future-proofing** (more generation from a fixed area, which could accommodate increased demand or electrification of processes without expanding the solar array footprint).

Beyond payback, one can consider the **internal rate of return (IRR)**: many commercial rooftop projects in India target IRRs around 12–18%. Both systems in the above example would easily clear that, with IRRs on the order of 25–30% thanks to the short paybacks. Thus, from an investor's perspective, tandem PV could provide equal or higher ROI by maximizing the energy yield per rupee spent – especially if any incentives for high-efficiency modules are introduced.

It's worth noting that by 2030, India's **residential** rooftop segment may also embrace high-efficiency modules. Although residential systems are smaller (and have higher per-Watt install costs, often ₹60–70/W), the appeal of maximum output in limited space (e.g. for urban homeowners) and premium aesthetics (tandem cells can potentially be made in bifacial/semitransparent styles for building-integrated PV) could create a niche market. However, the mass adoption in residential may depend on cost dropping to very near parity with standard panels, since upfront cost sensitivity is high in that segment.

Comparison with Mainstream and Emerging PV Technologies

By 2030, conventional silicon PV technology will itself have advanced significantly. The dominant single-junction silicon tech in 2025 – PERC (Passivated Emitter Rear Cell) – is gradually being superseded by next-generation designs like **TOPCon** (tunnel oxide passivated contact) and **HJT** (heterojunction) cells, which offer higher efficiencies around 25–26% in mass production. These improvements will narrow the efficiency gap between tandems and single-junction silicon. For instance, a bifacial HJT module with 25% front efficiency and bifacial gain might effectively achieve ~27% in certain conditions, partially eroding tandem's advantage. Additionally, **thin-film** technologies like cadmium telluride (CdTe) have made strides – First Solar reported CdTe lab cells at 24%+ efficiency and is targeting ~26% by late 2020s. Thin-film modules often have better temperature performance, which is beneficial in India's hot climate, and they avoid silicon supply constraints.

How tandem stacks up: Perovskite–silicon tandems have a theoretical efficiency ceiling above 40% (with optimized bandgaps), far higher than the ~29% Shockley–Queisser limit of single-junction silicon . Practically, if tandems reach ~30% by 2030, they will still hold a few percentage points advantage over the best silicon-only or CdTe modules (which might be ~25–27%). Those extra points of efficiency directly translate to a lower LCOE if costs are in a similar ballpark. **Multiple analyses converge on the finding that increasing efficiency is one of the most powerful levers to reduce LCOE** – it allows either more energy from the same investment or the same energy from less hardware. As one study put it, the "value of efficiency" can be quantified as the allowable cost premium for a higher-efficiency innovation without raising LCOE . For tandems, this value is substantial: a *Progress in Photovoltaics* analysis determined that a 25% efficient tandem cell must cost no more than a standard silicon cell to be competitive, but at 30% efficiency it could cost somewhat more and still win on LCOE . We saw earlier that ~5–10 ¢/W extra module cost is tolerable at 30% eff – a cushion that could accommodate the added manufacturing steps for perovskites. In contrast, HJT or TOPCon cells only marginally boost efficiency over PERC, so they have little room for extra cost; manufacturers have had to drive down those costs (e.g. by replacing expensive silver with copper) to gain market share. By 2030, it is expected that **HJT and TOPCon modules will be nearly as cheap as PERC**, thanks to scale and innovation, so they will present a moving target for tandems to beat.

Module and System Cost: Conventional silicon modules are projected to cost ~$0.18/W or less by 2030 (for standard ~25% efficient products) . Tandem modules, as discussed, might be in the ~$0.20–0.25/W range once in volume production . Thin-film CdTe could also be ~$0.18–0.22/W (First Solar's manufacturing roadmap suggests continued cost per watt reductions). BOS costs (inverters, mounting, etc.) are largely similar regardless of module type, but slightly fewer modules (due to higher eff) means slightly lower BOS cost for tandem – a modest savings conventional tech can't replicate unless they also boost efficiency. Therefore, at the **system level**, a tandem plant could cost only ~5% more upfront than a silicon plant of the same capacity, while producing ~10–15% more energy yearly. This essentially evens out the economics. Other emerging concepts like **all-perovskite multi-junctions** (tandems or triple-junction using two perovskite cells of different bandgaps) might achieve comparable efficiencies (>30%) without the silicon wafer, potentially lowering manufacturing costs further – however, those are unlikely to be mass-commercial by 2030 due to stability challenges. Thus, the main competitors for tandem PV in 2030 are improved silicon and thin-film technologies, both of which are also improving in cost and performance.

A crucial differentiator might be **degradation and warranty**. Silicon and CdTe PV will have decades of field data and typically offer 25–30 year warranties by 2030 (with <0.5%/yr degradation). Tandems will need to demonstrate similar durability. If any hint of shorter lifespan or faster output decline emerges, financiers may prefer sticking with the proven tech even if tandems show slightly better initial LCOE under optimistic assumptions. On the flip side, if tandems are proven and perhaps offer unique advantages (lighter weight panels, flexible formats, semi-transparent modules for skylights etc.), they could command a premium market segment. BloombergNEF's projection of ~20% market share by 2030 likely assumes tandems initially serve **premium niches** (space-constrained commercial roofs, applications needing high performance) , while mainstream utility projects still largely use the cheapest available silicon modules unless tandems achieve outright cost parity.

In summary, **perovskite–silicon tandem PV is expected to be broadly competitive with – and in certain metrics superior to – mainstream PV technologies by 2030**. It can deliver **lower LCOE** than silicon PERC and even edge out advanced silicon or CdTe in high-irradiance, land-constrained scenarios, provided the technology matures as projected. Table 1 (in the previous section) encapsulated the comparison: tandem LCOE ~₹1.5–2.2/kWh vs. silicon ~₹1.8–2.5, thin-film ~₹2.0–2.5. The differences are not huge, meaning economics will vary case by case. Other emerging innovations (bifacial gains, trackers, storage hybridization) will also influence competitiveness but apply to all PV types. Notably, if tandem tech stumbles (e.g. fails to achieve long lifetimes), there are enough improvements in conventional PV that India's solar goals can still be met – but with tandem, the **solar revolution** could be accelerated with even cheaper and more abundant clean electricity.

Policy and Incentive Outlook for 2030

Public policy will play a significant role in determining the cost structure and adoption rate of tandem PV in India. The Government of India, through the Ministry of New and Renewable Energy (MNRE), has launched multiple schemes that will influence solar technology deployment:

- **Production-Linked Incentive (PLI) Scheme:** India's PLI for solar manufacturing (Tranche I in 2021 and Tranche II in 2022) encourages domestic production of high-efficiency PV modules. Manufacturers bidding for PLI incentives are scored partly on module efficiency – for example, bonuses for ≥21% efficient modules, etc. This has led many winning firms to plan **n-type silicon technologies (TOPCon, HJT)** for their new factories. While perovskite tandems were not ready for commercial lines at the time, the policy indicates a direction: efficiency and advanced tech are prioritized. If tandem PV reaches commercialization by late 2020s, future incentive programs could similarly favor it. India's industrial strategy could even earmark funds for **pilot tandem manufacturing lines**, seeing it as a leapfrog opportunity to lead in next-gen solar. In fact, MNRE has already started supporting R&D in this area – in Feb 2025, it awarded a **$10 million grant to an IIT Bombay-incubated start-up (ART-PV)** to establish a manufacturing line for high-efficiency tandem cells . That project achieved a 30% small-area 4T tandem cell and aims to scale it with industry partners . Such funding signals that by 2030, India hopes to have indigenous capability in tandem PV, potentially reducing costs via local production and economies of scale.
- **Import Duties and ALMM:** Since April 2022, India imposed a Basic Customs Duty (BCD) of 40% on imported modules and 25% on cells to encourage domestic manufacturing. Additionally, an Approved List of Models and Manufacturers (ALMM) policy requires government-supported projects to use approved domestic panels. These measures could affect tandem PV costs. In early years, if tandem panels are only made abroad (e.g. by European or Chinese firms) and not yet on ALMM, projects using them might face cost penalties (duty, or ineligibility for certain tenders). However, by 2030 if domestic manufacturers (possibly under PLI support) start making tandems, they would be protected from imports and enjoy the same 40% price buffer that current local modules do. Policymakers might even extend higher BCD on older tech to push adoption of superior tech once local supply exists. It's a delicate balance: protectionism raises short-term costs (India saw a module import surge in 2023 when ALMM was briefly suspended to reduce costs), but it can incubate a domestic industry that eventually lowers costs. For tandem PV, a likely scenario is small-scale imports for demo projects by ~2025–27, followed by domestic production by 2030 if the tech is proven, aided by these policy frameworks.
- **Subsidies and Tax Incentives:** Historically, India provided accelerated depreciation and capital subsidies for solar. By 2030, direct subsidies for utility-scale projects are expected to taper off as solar is already least-cost. However, **interest rate subsidies or blended finance** might be offered for novel tech projects (to counter the higher perceived risk). For example, a concessional green finance line could help a 100 MW tandem PV plant get built to showcase the technology's bankability. On the rooftop side, the government's rooftop solar program (such as the residential subsidy scheme and net metering regulations) will impact ROI. As of mid-2020s, residential systems get ~20–40% capital subsidy for certain sizes, and net metering up to 500 kW is allowed in many states. By

2030, if these continue or expand, they will naturally improve ROI for any rooftop PV, including tandem. One could envision a future **incentive for high-efficiency systems** – e.g. an additional subsidy for systems using modules above a certain efficiency (to encourage modern tech), although no such scheme is confirmed yet.

- **Renewable Purchase Obligations (RPO) and Green Tariffs:** Strengthening RPOs (mandating utilities and large consumers to source a percentage of power from renewables) will increase demand for solar capacity. This high demand environment is generally favorable for all solar tech. If tandem PV can deliver energy at a slightly lower cost or with other benefits, it will find a market. Additionally, C&I consumers in India are increasingly adopting "green tariffs" or setting up captive solar/wind. By 2030, corporate sustainability goals might drive adoption of the most efficient panels (for maximizing output from their installations). There is also discussion of **carbon credit or premium for advanced tech** if it demonstrably uses fewer materials (perovskites use far less silicon, potentially a lower carbon footprint). While mainstream silicon is already quite low-carbon in operation, tandem's reduced material usage (the perovskite layer is microns thin and uses common elements) might become a selling point if carbon accounting of supply chains gains importance.
- **Grid Integration and Storage Policy:** As solar's share grows (18% of generation by 2030 per IEA), India is promoting energy storage (batteries) to smooth solar output . Tandem PV's impact here is indirect – by making solar cheaper or more space-efficient, it could accelerate deployment, necessitating storage sooner. But importantly, if tandem lowers LCOE further, it could offset some of the cost of adding batteries (keeping solar+battery combined costs low). Policy support for storage (such as a battery tender or subsidy) could thus amplify the deployment of whichever PV tech is most cost-effective by 2030 – tandem included.

In essence, India's policy landscape by 2030 is geared toward massive solar deployment and self-reliant manufacturing. This favors any technology that can be produced domestically and deployed at scale cheaply. Perovskite–silicon tandems have a path to fit this narrative, especially if pilot programs show success in the late 2020s. Government backing in the form of R&D grants (as already seen) and manufacturing incentives could bring down the learning curve costs. Meanwhile, the large-scale rollout will depend on market forces shaped by RPO targets, auction designs, and the comparison with ever-cheaper conventional PV. We might see initial tandem PV projects under schemes like **"lighthouse" solar parks** or as part of flagship installations (for example, a smart city project using high-efficiency panels on limited land). If these demonstrate even marginal cost or performance benefits, policymakers could officially recognize tandems in standards and tenders.

National-Level Projections and Sensitivity Analysis

To synthesize the analysis, we consider a **national-level scenario** for 2030: Suppose India reaches ~300 GW of solar PV. Even if only a small fraction (say 5–10%) of new installations around 2030 use perovskite–silicon tandem modules, that would mean several tens of GW of tandem PV deployed. The cost competitiveness will determine whether tandem captures that share. Based on the data compiled:

- **Baseline expectation:** Tandem PV LCOE ≈ ₹1.9/kWh (±0.3) versus silicon ≈ ₹2.1/kWh (±0.3) under typical conditions. In other words, a slight edge to tandem on energy cost, assuming ~30% efficiency tandem modules at ~$0.22/W and silicon ~25% at ~$0.18/W. CAPEX for a tandem project might be ~5–10% higher initially, but the boost in annual kWh yields equal or lower LCOE . In ROI terms, utility developers would see similar or better project IRRs with tandem if these assumptions hold, meaning there is an economic incentive (however small) to adopt tandem for new plants by 2030.
- **Optimistic scenario:** Tandem technology progresses faster – e.g. 33% efficient modules available, stable 25-year performance, and manufacturing scale achieved (perhaps via global production of >20 GW/year by 2030, bringing economies of scale). In this case, module costs might drop to ~$0.15–0.18/W (nearly on par with silicon), and tandem LCOE in India could approach ₹1.3–1.5/kWh (well under 2 ¢/kWh) . This would decisively beat even the cheapest coal power and potentially allow solar + storage to become the default new power source. Under such conditions, tandem PV could rapidly become the technology of choice for most new installations (assuming supply can meet demand), because it simply generates more energy for the same cost. Nationally, this would accelerate India's renewable energy targets and reduce the need for as much land per MW. Sensitivity analyses indicate that every 1% absolute increase in tandem efficiency (beyond 30%) yields roughly a 3–4% reduction in LCOE , and achieving a 30-year lifespan instead of 20 years can cut LCOE by ~20–25% . So pushing those parameters to the optimistic end drastically improves competitiveness.
- **Pessimistic scenario:** Technical hurdles persist – for instance, tandem modules only reach ~26–28% efficiency in mass production by 2030 and/or exhibit 5-10% degradation in the first few years (which some early perovskite experiments have shown). Additionally, manufacturing may be limited, keeping module prices high (>$0.30/W). In this scenario, tandem LCOE could end up higher than silicon, perhaps ₹2.5–3/kWh or more, once you factor in needing more frequent replacements or performance losses. Developers might then shy away from tandems except in special cases, and the technology would remain in pilot scale until further improvements. The sensitivity to **lifetime** is particularly high: as shown earlier, a tandem module with only a 10-year life yields an LCOE ~3.0–3.4 ¢/kWh (₹2.5–2.8) , which is above the projected ~2 ¢ for standard PV in 2030. Thus, if durability isn't solved, cost goals likely won't be met. Similarly, if the cost of capital for tandem projects is say 2–3 percentage points higher (due to risk perception), the LCOE could be ~10–15% higher than an equivalent silicon project under normal financing – potentially negating the efficiency benefit. Mitigating this will require either guarantees or a track record to bring financing terms in line with conventional projects.
- **Policy sensitivity:** If we layer on policy impacts, one can imagine a scenario where carbon pricing or other externality costs favor solar further. By 2030, if a modest carbon tax or cost is applied to fossil generation, even relatively expensive solar becomes

attractive, so tandem vs silicon competition is an internal solar sector matter rather than against fossil fuels. On the other hand, if supply chain issues (for example, critical materials in perovskites or glass or encapsulants) cause price volatility, policy might need to intervene. Currently, perovskite tandems fortunately do not rely on extremely scarce materials – the perovskite layer uses common metals like lead or tin (lead-based perovskites are prevalent, though environmental regulations might push lead replacement). Indium (used in transparent conductive oxide layers) could be a supply concern, but that's also used in other PV. So material costs are not expected to be a limiting factor; still, recycling and circular economy strategies (which NREL is researching) may be promoted to keep tandem PV sustainable and cost-effective long-term.

At a national level, the **deployment of tandem PV will likely start gradually** – perhaps a few pilot MW in the mid-2020s, scaling to hundreds of MW by late 2020s if initial projects go well. By 2030, one could see a handful of GW of tandem capacity, especially if the technology is included in government-backed projects. The **cost competitiveness threshold** is essentially that tandems must match or beat the **₹/kWh of silicon PV under real project conditions**. All evidence suggests this is achievable by 2030: *"Tandem modules must have an efficiency of at least 25% to be price competitive… The next steps for commercialization are to improve reliability and scale up production"* . Those steps are underway globally, with companies like Oxford PV, Microquanta, and academic labs hitting required efficiency marks and now focusing on scaling and stability. India's high solar irradiance actually makes it a friendlier market for a slightly less durable module (more sun means you recoup the investment faster), but to truly compete in **levelized terms**, a 20+ year life is needed . Given the concerted R&D efforts and rapid progress (perovskite PV efficiencies rose from ~3% to ~25% in a single decade), experts remain optimistic that by 2030 tandem PV will not only be a **technically viable** option in India but also an **economically attractive** one .

Conclusion

By 2030, perovskite–silicon tandem photovoltaic systems are projected to be **cost-competitive in India** across both utility-scale and rooftop sectors. These tandem modules, offering efficiencies around 30%, can deliver more energy per installed watt, which translates to lower LCOE if manufactured at scale. Our analysis indicates tandem PV farms could achieve LCOEs on the order of ₹1.5–2.0 per kWh (≈2 ¢/kWh) in India's sunny climate, rivaling or undercutting the cost of energy from even the most advanced single-junction silicon or thin-film PV systems . For rooftop solar, tandems can maximize output from limited space and yield 3–5 year paybacks that are comparable to conventional panels , making them an attractive proposition for commercial and industrial users aiming to reduce electricity bills.

Compared to mainstream silicon PV (which itself will improve in efficiency and cost by 2030), tandems are poised to provide a slight economic edge – essentially **doing more with the same infrastructure**. Other emerging technologies like CdTe thin-film and silicon heterojunction will remain strong competitors, but tandems' higher efficiency gives them a cushion to absorb a small cost premium while still matching or beating the LCOE of those alternatives . The key uncertainties lie in long-term durability and scaling of manufacturing. Should current R&D efforts succeed in delivering 20- to 25-year lifetime tandem modules, the economic case in India becomes very robust . On the policy front, India's push for renewable energy and domestic manufacturing creates a favorable environment for tandem PV deployment. Initiatives such as PLI incentives, import duties favoring local production, and direct R&D funding (e.g. MNRE's support for tandem cell startups) will help drive down costs and build confidence in the technology . By 2030, one can expect to see the first few gigawatts of tandem PV in operation, with performance data proving out their value proposition.

In conclusion, perovskite–silicon tandem PV is on track to join the Indian solar market as a **cost-competitive solution** by 2030, complementing the existing silicon fleet. It offers the potential for even cheaper solar electricity (sub-₹2/kWh) and higher returns on solar investments, thereby supporting India's aggressive renewable energy goals and potentially accelerating the energy transition. While continued innovation is needed to fully realize these gains, the **outlook is optimistic**: with the right combination of technology maturation and supportive policy, tandem PV could herald a new era of ultra-low-cost solar power in India – delivering clean energy abundance with improved efficiencies and solid economics. The next few years (2025–2030) will be critical in scaling production and validating longevity, but if successful, perovskite–silicon tandems will indeed be a **competitive contender** among solar technologies fueling India's sustainable energy future.

Sources:

1. Moreno Castillo et al., *EUPVSEC 2021 – Cost Assessment of Future Tandem Perovskite-Silicon Modules and LCOE Comparison to Silicon Technologies* .
2. Bhupesh Verma et al., *Global Challenges* (Wiley) 2022 – *Costing Analysis of Scalable Carbon-Based Perovskite Modules Using Bottom-Up Technique* .
3. PV Magazine India (Apr 2025) – *Rooftop Solar to Reach 25–30 GW by FY27* .
4. PV Magazine Global (Nov 2020) – *Hidden costs for scaling perovskite cells* .
5. NREL Press Release (Jan 2025) – *Improving Tandem Efficiency Can Lower PV Cost per Watt* .
6. Reuters (Feb 2023) – *"Perovskite solar goes commercial as yield gains align with market forces"* .
7. IEA India Energy Outlook (2021) via CarbonBrief – *"India on cusp of a solar revolution"* .

8. Mercom India Research (Q4 2023) – *Large-Scale Solar Cost Trends* .
9. BloombergNEF (2024) – *Solar Technology Market Projections* .
10. MNRE/Perovskite-Info (Feb 2025) – *MNRE grants $10 M for tandem solar cell plant* .