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Unique Solar Energy: Emerging Technologies and a Comparative Yield Analysis

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ABSTRACT—

Solar energy is the fastest-growing source of renewable electricity, yet conventional ground-mounted silicon photovoltaic (PV) plants are constrained by land availability, the efficiency ceiling of single-junction cells and temperature-related losses. This paper reviews six unique solar energy technologies that address these constraints: perovskite and tandem cells, bifacial modules with single-axis tracking, floating PV, agrivoltaics, building-integrated PV (BIPV) and the solar updraft tower. A transparent analytical yield model, built on plane-of-array irradiation, a cell-temperature loss model and gain factors taken from the literature, is then used to compare five 1 MWp plant configurations for a semi-arid Indian site. For an assumed irradiation of 5.7 kWh/m²/day, the baseline fixed-tilt plant yields about 1,680 kWh/kWp per year, whereas a bifacial plant with single-axis tracking yields about 2,177 kWh/kWp, a gain of 29.6%. Floating PV gives a modest 3.2% gain through lower cell temperature, and an elevated agrivoltaic layout trades about 3% of energy for dual land use. The results indicate that technology selection should be driven by site constraints and economics as much as by headline efficiency. Challenges and future scope are also discussed.

***Index Terms*—agrivoltaics, bifacial modules, building-integrated photovoltaics, floating solar, perovskite solar cells, renewable energy.**

I. Introduction

The global shift away from fossil fuels has made solar energy one of the central pillars of sustainable power generation. India receives roughly 4–7 kWh/m² of solar radiation per day over most of its land area and has set a target of 500 GW of non-fossil electric capacity by 2030, with solar photovoltaic (PV) expected to form the largest share of this capacity [1]. Falling module prices, supportive policy and abundant sunshine have made large-scale solar plants economically attractive across the country.

However, the conventional approach of mounting monofacial silicon modules on fixed steel structures on open land has clear limits. First, a single-junction solar cell cannot convert more than about one-third of incident sunlight into electricity, as shown by Shockley and Queisser [2]. Second, module output drops as cell temperature rises, a serious concern in hot Indian summers. Third, utility-scale plants need large, flat and preferably non-agricultural land, which is increasingly scarce and expensive. These limits have encouraged the development of a group of less conventional, or "unique", solar technologies that raise efficiency, increase the yield per kilowatt of installed capacity, or open up new surfaces for solar generation.

The objectives of this paper are: (i) to review six unique solar technologies and explain their working principles, advantages and limitations; (ii) to present a simple analytical model for estimating the annual energy yield of a PV plant; (iii) to use the model to compare five plant configurations for Indian conditions; and (iv) to identify challenges and future scope. Section II gives the technical background, Section III reviews the technologies, Section IV describes the methodology, Section V presents and discusses the results, Section VI covers challenges and future scope, and Section VII concludes the paper.

II. Technical Background

A. Photovoltaic Conversion and Energy Yield

A PV cell converts photons having energy greater than the band gap of the semiconductor into electron–hole pairs, which are separated by the built-in electric field of the p–n junction and delivered to an external circuit as direct current. For a module of area A and efficiency η under irradiance G, the electrical power output is

$$P = \eta\, A\, G \qquad (1)$$

Module efficiency falls as the cells become hot. The cell temperature can be estimated from the nominal operating cell temperature (NOCT) [3] as

$$T_c = T_a + [(\mathrm{NOCT} - 20)/800]\, G \qquad (2)$$

and the temperature-corrected efficiency is

$$\eta = \eta_{STC}\,[1 + \gamma\,(T_c - 25)] \qquad (3)$$

where T_a is the ambient temperature (°C), G is in W/m², and γ is the power temperature coefficient, which is typically between −0.30 and −0.40 %/°C for crystalline silicon. The annual energy output of a plant of rated capacity P_{STC} (kWp) is

$$E = P_{STC} \times H_{POA} \times \mathrm{PR} \qquad (4)$$

where H_{POA} is the annual plane-of-array irradiation (kWh/m²) and PR is the performance ratio, which accounts for all system losses [3]. The capacity utilisation factor (CUF), widely used in the Indian solar industry, is

$$\mathrm{CUF} = E / (8760 \times P_{\mathrm{STC}}) \qquad (5)$$

B. Efficiency Limits and Loss Mechanisms

Shockley and Queisser showed that the maximum efficiency of a single-junction cell under unconcentrated sunlight is about 33.7%, reached at a band gap near 1.34 eV [2]. The limit arises mainly because photons with energy below the band gap are not absorbed, while photons with energy above the band gap lose the excess as heat (thermalisation). For silicon, with a band gap of 1.12 eV, the practical limit is nearer 29%, and commercial modules today operate at roughly 20–23% [4]. Further gains therefore require one of three strategies: using several junctions to match the solar spectrum better, collecting more light per installed watt (rear-side collection and sun tracking), or expanding the surfaces on which solar generation is possible (water bodies, farmland and building envelopes). The technologies reviewed in the next section fall into these categories.

III. Unique Solar Technologies

A. Perovskite and Tandem Solar Cells

Metal-halide perovskites, with the general formula ABX_3, were first used as light absorbers in solar cells by Kojima *et al.* in 2009, with an initial efficiency of about 3.8% [5]. Since then, laboratory efficiencies of single-junction perovskite cells have risen above 25% [4], one of the fastest improvements in the history of photovoltaics. Their band gap can be tuned between roughly 1.2 and 2.3 eV by changing the halide composition, and the films can be deposited from solution at low temperature, which promises low manufacturing cost.

The tunable band gap makes perovskites ideal top cells in tandem devices. In a perovskite/silicon tandem, a wide-gap perovskite layer (about 1.7 eV) absorbs high-energy photons and the silicon bottom cell absorbs the remainder, which has pushed laboratory efficiencies above 30% [4]. At the extreme, four-junction III–V concentrator cells have demonstrated efficiencies of about 46% [15]. Figure 1 compares approximate efficiencies of these technologies with the single-junction limit. The main barriers to commercialisation are the sensitivity of perovskites to moisture, heat and ultraviolet light, ion migration under bias, the use of lead, and the difficulty of coating large areas uniformly [6].

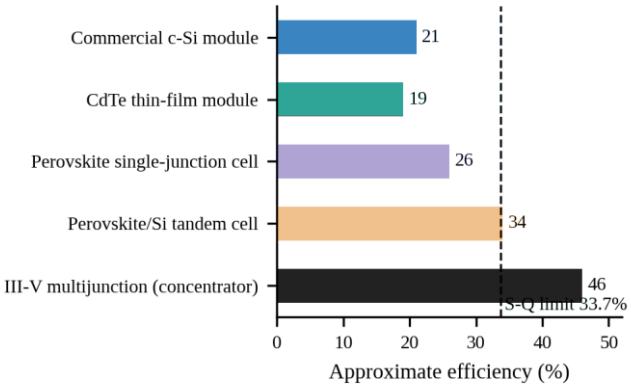


Fig. 1. Approximate efficiencies of conventional and advanced solar technologies compared with the Shockley–Queisser (S-Q) limit. Values are representative figures from [4] and [15].

B. Bifacial Modules and Single-Axis Tracking

Bifacial modules generate power from both faces: the front receives direct and diffuse light, while the rear collects light reflected from the ground. The rear-side gain depends on ground albedo, mounting height, tilt angle and row spacing, and is commonly reported in the range of 5–20% [7]. Light-coloured or sandy ground and elevated structures raise the gain, whereas dense shading and low mounting reduce it.

Sun-tracking systems increase the time during which the module faces the sun. A horizontal single-axis tracker rotates the modules about a north–south axis to follow the sun from east to west, and gains of 15–25% over fixed-tilt systems are widely reported for clear-sky regions [8]. Combining bifacial modules with trackers is now a common design in new utility-scale plants because the two gains multiply. The penalties are higher capital cost, moving parts that need maintenance, wind-stow requirements, and a lower tracking benefit under hazy or monsoon skies, when diffuse radiation dominates.

C. Floating Photovoltaic Systems

In a floating PV (FPV) plant, modules are mounted on buoyant pontoons anchored on reservoirs, canals, lakes or irrigation tanks [9]. The concept offers several advantages: no land acquisition is required, the water surface cools the modules and so reduces temperature losses, shading by surroundings is minimal, and the cover reduces evaporation, which is valuable in water-stressed regions. FPV can also be combined with existing hydropower reservoirs, sharing the transmission infrastructure and allowing complementary operation. Large floating projects are now being developed on Indian reservoirs such as Omkareshwar in Madhya Pradesh. Design issues include mooring in the presence of water-level variation, corrosion and biofouling, higher balance-of-system cost, safe electrical installation over water, and the ecological impact on aquatic life, which still requires long-term study.

D. Agrivoltaics

Agrivoltaics (or agrophotovoltaics) places solar modules above or between crops so that the same land produces both food and electricity [10]. Because many crops saturate at light levels below full sunlight, partial shading costs little yield, and in hot semi-arid climates the shade may reduce crop water demand and heat stress. Dupraz *et al.* modelled land equivalent ratios exceeding 1.3, meaning that a combined system can need about 30% less land than separate crop and PV plots [10]. Reviews also show that outcomes depend strongly on the crop, panel density and local climate [11]. Practical challenges include higher support structures, clearance for farm machinery, a suitable choice of shade-tolerant crops, and a legal framework that treats the land as both agricultural and energy infrastructure. For rural India, where agriculture and solar pumping are closely linked, the concept is especially relevant.

E. Building-Integrated Photovoltaics

BIPV replaces conventional building materials, such as roof tiles, facade cladding, skylights and windows, with PV elements that also generate

electricity [12]. Because the PV element serves as part of the building envelope, it offsets material cost, generates power at the point of use and avoids transmission losses. Semi-transparent and coloured modules allow architects to maintain aesthetics and daylighting. The drawbacks are lower efficiency than optimally tilted modules because of non-ideal orientation and poor ventilation behind the module, higher cost per watt, more complex electrical and fire-safety requirements, and difficulty in replacing modules during the life of the building.

F. Solar Updraft Tower

The solar updraft tower (SUT) is a solar thermal technology that suits mechanical engineers well. A large transparent collector, similar to a greenhouse, heats the air beneath it; the hot air rises through a tall central chimney and drives turbines at the base [13]. The only prototype of significant size, built at Manzanares in Spain, had a 194.6 m chimney, a collector of about 244 m diameter and a peak output of 50 kW, and operated from 1982 to 1989 [13]. Its advantages are the use of simple materials, very low water consumption and the ability to generate after sunset because the ground stores heat. Its main drawback is low overall efficiency of the order of 1–2%, so commercial-scale plants of 100 MW or more would need very tall chimneys and very large collector areas [13]. Solar thermal systems more broadly are surveyed in [14].

TABLE I

Summary of Unique Solar Technologies

Technology	Key feature	Main limitation
Perovskite / tandem	Tunable band gap; efficiency beyond single-junction limit	Stability, lead content, large-area coating
Bifacial + tracker	Rear-side gain and longer sun exposure	Higher cost; tracker maintenance
Floating PV	No land needed; cooler modules; less evaporation	Mooring, corrosion, ecological impact
Agrivoltaics	Dual use of land for crops and power	Crop-specific; structure height and cost
BIPV	Replaces building material; on-site power	Non-ideal orientation; cost per watt
Solar updraft tower	Simple, low water use, night operation	Very low efficiency; huge structure

IV. Methodology

A. Site and Input Data

To compare the technologies on an equal basis, an analytical energy-yield model was built from (1)–(5). A representative semi-arid site on the Deccan plateau of India (latitude about 18°N) is assumed, with an annual plane-of-array irradiation of 5.7 kWh/m²/day for a fixed tilt equal to the latitude, which corresponds to 2,080 kWh/m² per year. During operating hours the average ambient temperature is taken as 33 °C and the average irradiance as 800 W/m². The input parameters, which are typical values drawn from the literature and industry practice [3], [7], [8], [10], [17], are listed in Table II. They are assumptions for an indicative comparison, not measured site data.

TABLE II

Model Input Parameters

Parameter	Value
Plant capacity	1 MWp
Annual POA irradiation (H_{POA})	2,080 kWh/m²
Ambient temperature, T_a	33 °C
Operating irradiance, G	800 W/m²
NOCT	45 °C
Temperature coefficient, γ	−0.35 %/°C
Soiling / mismatch & wiring losses	3 % / 2 %
Inverter / availability & degradation losses	2.5 % / 1.5 %
Bifacial rear gain (albedo ≈ 0.25)	8 %
Single-axis tracker gain	20 %
Floating PV cell-temperature reduction	8 °C
Agrivoltaic layout factor	0.97
Grid emission factor [16]	0.7 tCO_2/MWh

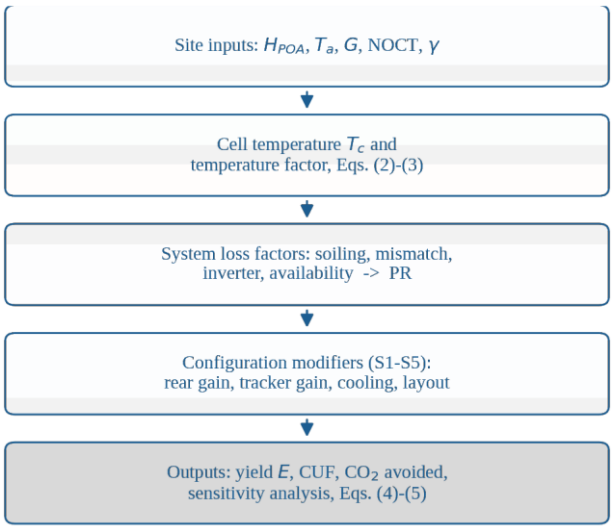


Fig. 4. Flow chart of the analytical yield model used to compare the plant configurations.

B. Plant Configurations

Five configurations of 1 MWp are compared. **S1** is the baseline: fixed-tilt monofacial modules. **S2** uses fixed-tilt bifacial modules with the rear gain in Table II. **S3** combines bifacial modules with a horizontal single-axis tracker, so the two gains are multiplied. **S4** is a floating plant, for which the cell temperature in (2) is reduced by 8 °C owing to water cooling and the yield is recalculated through (3). **S5** is an elevated agrivoltaic plant, in which wider row spacing and a modified tilt for crop light are represented by a layout factor of 0.97 on energy per kWp. Perovskite tandems, BIPV and the updraft tower are excluded from the numerical comparison because reliable large-scale performance data are not yet available or because they are not directly comparable on a per-kWp basis.

For the baseline, (2) gives a cell temperature of 58 °C and (3) gives a temperature factor of 0.8845. The product of the other loss factors is 0.913, so PR = 0.807, which lies within the 0.75–0.82 range usually reported for well-maintained plants in India. Substituting in (4) gives 1,680 kWh/kWp per year. Avoided emissions are computed as annual energy multiplied by the grid emission factor.

C. Economic Indicator for Extension of the Model

The present study is energy-based, but the same framework can be extended to economics. If C is the installed cost of the plant, C_{om} the annual operation and maintenance cost, i the discount rate and n the plant life in years, the levelised cost of electricity can be written as

$$\mathrm{LCOE} = (C \times \mathrm{CRF} + C_{om}) / E \qquad (6)$$

where the capital recovery factor is

$$\mathrm{CRF} = i\,(1+i)^n / [(1+i)^n - 1] \qquad (7)$$

The yields in Table III can be inserted directly in (6) once local prices are known, so that the extra energy of each configuration can be weighed against its extra cost. This step is left for future work because capital costs vary strongly with year, scale and supplier.

V. Results and Discussion

A. Comparative Yield Results

The results are given in Table III and Fig. 2. The baseline plant (S1) produces 1,680 MWh per year from 1 MWp, equivalent to a CUF of 19.2%, which agrees with the 18–20% range typical of fixed-tilt plants in peninsular India. This agreement gives confidence that the model is realistic.

TABLE III

Estimated Annual Performance of 1 MWp Plant

Scenario	Yield (kWh/kWp)	CUF (%)	Change (%)	CO_2 avoided (t/yr)
S1 Fixed-tilt	1,680	19.2	0.0	1,176
S2 Bifacial	1,814	20.7	+8.0	1,270
S3 Bifacial + tracker	2,177	24.9	+29.6	1,524
S4 Floating PV	1,733	19.8	+3.2	1,213
S5 Agrivoltaic	1,630	18.6	−3.0	1,141

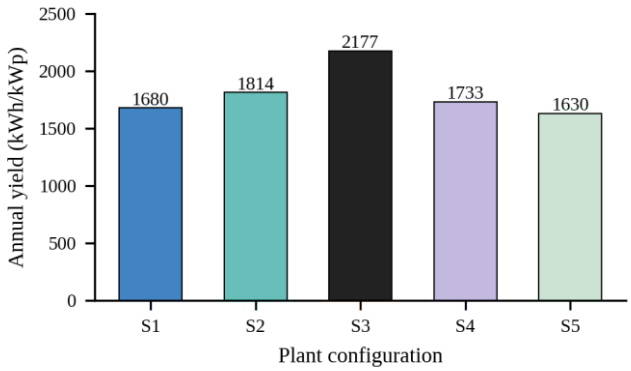


Fig. 2. Estimated annual energy yield per kWp for the five plant configurations S1–S5 (S1: fixed-tilt; S2: bifacial; S3: bifacial with tracker; S4: floating; S5: agrivoltaic).

The bifacial tracker plant (S3) gives the highest yield, 2,177 kWh/kWp, which is 29.6% above the baseline and raises the CUF to 24.9%. Bifacial modules alone (S2) give a 8% gain without any moving parts, which makes them a low-risk upgrade. The floating plant (S4) gains 3.2%: the 8 °C reduction in cell temperature lowers the thermal loss from 11.6% to 8.8%. This result is consistent with the idea that the principal benefit of floating PV is land saving, with cooling as a secondary benefit. The agrivoltaic plant (S5) produces 3% less energy per kWp than the baseline, but because the land continues to produce crops, its value must be judged on the combined output of food and electricity rather than on electricity alone [10].

In terms of emissions, each 1 MWp plant avoids between 1,141 and 1,524 tonnes of CO_2 per year at the assumed grid emission factor. Over a 25-year module life, the best-performing configuration avoids several thousand tonnes more than the baseline, which shows that even modest percentage gains are significant at scale. For land use, fixed-tilt plants are commonly said to need about 4–5 acres per MWp, trackers need somewhat more because of row spacing, and floating PV needs none, so land-constrained sites favour S4 and S5 while land-rich sites favour S3.

B. Sensitivity Analysis

Because the gain factors are uncertain, the model was re-run with each key input varied over a plausible range while the others were held at their base values. The results are summarised in Table IV. The rear gain of bifacial modules, varied from 5% to 15%, changes the S2 yield between 1,764 and 1,932 kWh/kWp. A tracker gain of 15–25% moves the S3 yield between 2,087 and 2,268 kWh/kWp, so even the low-end estimate remains clearly above the baseline. Floating PV is the least sensitive option: a cell-temperature reduction of 5–12 °C changes the yield by only 47 kWh/kWp. A 5 °C rise in ambient temperature reduces the baseline yield by about 33 kWh/kWp, which confirms the importance of cooling in hot climates.

TABLE IV

Sensitivity of Annual Yield (kWh/kWp) to Key Inputs

Input varied (affected case)	Low	Base	High
Rear gain 5 / 8 / 15 % (S2)	1,764	1,814	1,932
Tracker gain 15 / 20 / 25 % (S3)	2,087	2,177	2,268
Cooling 5 / 8 / 12 °C (S4)	1,713	1,733	1,760
Irradiation 5.2 / 5.7 / 6.2 kWh/m²/day (S1)	1,533	1,680	1,827
Irradiation 5.2 / 5.7 / 6.2 kWh/m²/day (S3)	1,986	2,177	2,368
Ambient 38 / 33 / 28 °C (S1)	1,647	1,680	1,713

Irradiation is the dominant input. Figure 3 shows that the yield of every configuration rises almost linearly with irradiation, and that the absolute advantage of the bifacial tracker plant over the baseline widens as the site becomes sunnier, from about 453 kWh/kWp at 5.2 kWh/m²/day to about 541 kWh/kWp at 6.2 kWh/m²/day. Accurate site-specific irradiation data are therefore the first requirement in any real feasibility study.

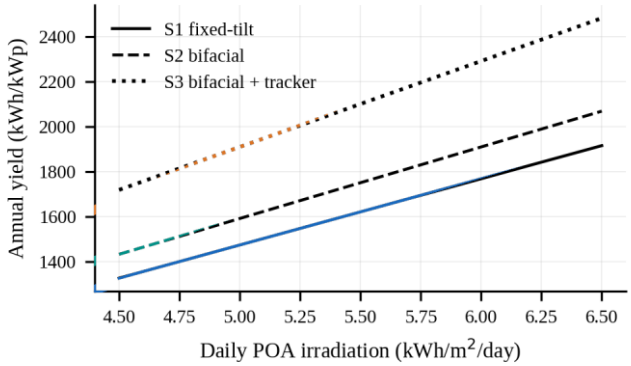


Fig. 3. Variation of annual yield with daily plane-of-array irradiation for configurations S1, S2 and S3, calculated with the model of Section IV.

C. Application Guidelines and Limitations

The review and the model together suggest practical guidelines. For land-rich, high-irradiation sites with mainly direct sunlight, bifacial modules on single-axis trackers (S3) give the best energy per rupee of land and grid connection. Where land is costly or contested but water bodies exist, floating PV (S4) converts unused surface into a power plant. In farming districts, agrivoltaics (S5) can give farmers a second income without taking land out of cultivation, and in dense urban areas BIPV is the only practical route to solar generation. Perovskite tandems are best treated as a technology to monitor

and pilot, not yet to deploy at scale.

TABLE V

Qualitative Suitability of Unique Solar Technologies

Technology	Maturity	Land need	Best-suited setting
Perovskite / tandem	R&D / pilot	As for PV	Any, once durability is proven
Bifacial + tracker	Commercial	High	Open, sunny, light-ground sites
Floating PV	Commercial, growing	None (water)	Reservoirs, canals, irrigation tanks
Agrivoltaics	Pilot / early commercial	Shared with crops	Farmland with shade-tolerant crops
BIPV	Commercial, niche	None (building)	Urban roofs and facades
Solar updraft tower	Prototype	Very high	Flat, arid, low-cost land

D. Comparison with Published Findings

The model outputs are consistent with trends reported in the literature. The 8% bifacial gain used here lies inside the 5–20% band reviewed in [7], and the 15–25% tracker gain agrees with the range summarised in [8]. For floating PV, reviews report that water cooling improves output modestly and that the greater benefit is the avoidance of land and the reduction of evaporation [9]; the 3% gain computed here is in line with that observation. For agrivoltaics, the small energy penalty and the large land-use benefit follow the pattern described in [10] and [11]. The baseline CUF of about 19% is also typical of operating fixed-tilt plants in peninsular India. Because the quantities in Table II are mid-range values, the comparison should be read as a ranking of options and a demonstration of method, not as a prediction for a specific site.

Three limitations of the analysis should be noted. First, the gain factors are mid-range literature values, and real gains vary with albedo, mounting height, diffuse fraction and weather. Second, the study is energy-based and does not include capital cost, operation and maintenance cost or levelised cost of electricity (LCOE), all of which must be considered before an investment decision. Third, the loss factors are held constant across configurations, whereas soiling and degradation could differ in practice, for example with water-borne dust or bird droppings on floating plants [17]. The model should therefore be regarded as a screening tool, to be followed by detailed simulation with measured weather data.

VI. Challenges and Future Scope

Economics and finance. Bifacial modules and trackers add cost, floating structures add balance-of-system cost, and agrivoltaic structures must be taller and stronger. Detailed LCOE studies using local prices are needed to confirm which options pay back fastest.

Reliability and standards. Perovskite devices must show 20–25-year outdoor stability under heat, humidity and ultraviolet exposure before they can compete with silicon [6]. Standards for floating and agrivoltaic installations are still evolving and need to be harmonised with electrical safety and land-use regulations.

Grid integration and storage. Higher-yield plants still produce power only in daytime. Pairing solar plants with battery storage, pumped hydro or green-hydrogen production will be needed to supply round-the-clock renewable power.

End-of-life and sustainability. As the first generation of large plants nears retirement, recycling of silicon, silver, glass and, for perovskites, lead must be planned from the start, together with environmental assessments of floating plants on water bodies.

Policy and market context. In India, schemes such as PM-KUSUM for solar pumps and farm-based solar plants, production-linked incentives for domestic module manufacturing, and the International Solar Alliance promoted by India and France provide an enabling environment for several of the technologies discussed here [1]. Agrivoltaic and floating pilots can benefit from these programmes, but clear guidelines on land classification, water-body leasing and tariff treatment are still needed.

Future scope. Useful extensions of this work include simulation with hourly weather files, field measurement of floating and agrivoltaic pilots, economic optimisation using LCOE, the use of artificial-intelligence-based tracking and predictive maintenance, and the development of low-cost small-scale solar thermal systems for rural India.

VII. Conclusion

This paper reviewed six unique solar energy technologies—perovskite and tandem cells, bifacial modules with trackers, floating PV, agrivoltaics, BIPV and the solar updraft tower—and compared four of them with a baseline plant through an analytical yield model for Indian conditions. The model predicted 1,680 kWh/kWp per year for a conventional fixed-tilt plant and 2,177 kWh/kWp for a bifacial plant with single-axis tracking, a 29.6% increase. Floating PV improved yield by 3.2% while saving land, and an agrivoltaic layout cost about 3% of energy but allowed continued farming. No single technology is best everywhere: tracker-based bifacial plants suit land-rich, high-irradiation sites; floating and agrivoltaic systems suit land-scarce locations; and perovskite tandems promise higher efficiency once their durability is proven. Selecting the right technology for each site, supported by economic analysis and field data, will be essential to meet India's solar targets.

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