OPTIMIZING INDOOR PHOTOVOLTAICS THROUGH SINGLE AND TANDEM PEROVSKITE DESIGNS

BTP Report

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Submission date : 4th December 2025

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<u>Certificate</u>

This is to certify that the report titled **"Optimizing Indoor Photovoltaics Through Single and Tandem Perovskite Designs"**, submitted by **Harsh Vishal and Tanishk Goyal** to the Electrical and Electronics Engineering Department , IIT Patna, is a bona-fide record of the work carried out under the supervision of **Prof. Saurabh Kumar Pandey**.

Prof. Saurabh Kumar Pandey

Assistant Professor IIT Patna

Place: Patna

Date: 4^{th} December 2025

Abstract

This report develops and optimizes **2T all-perovskite tandem solar cells** for indoor white-LED harvesting. Single-junction perovskites show limits from the **Jsc–Voc trade-off**, **thermalization**, and **transmission losses**, motivating a shift to tandems. A **2.1 eV $CsPbBr_3$ top cell** and **1.5–1.6 eV Rb_1MAFA bottom cell** were selected for spectrum splitting and high photovoltage.

SCAPS-1D simulations optimized bandgap, thickness, transport layers, and ICL behavior. The final tandem achieves **~41–42% efficiency**, **Voc ≈ 2.92 V**, **Jsc ≈ 33.6 mA/cm^2**, and **FF ≈ 80%**, clearly outperforming single cells. These results show strong potential for powering **indoor IoT and low-power systems**.

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BACKGROUND ON SINGLE AND TANDEM SOLAR CELLS

1.Normal Solar Cells (Silicon & other single-junction technologies)

- Traditional solar cells (like crystalline Silicon) use **one absorber layer** with a fixed bandgap (≈1.1 eV for Si).
- Designed for **sunlight**, not LED or indoor lighting.

Why we moved away from normal solar cells

- They are **optimized for sunlight**, not white LEDs.
- They can't tune their bandgap to match the indoor spectrum.
- Their efficiency under indoor LEDs is **very low** due to spectrum mismatch.

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2. Perovskite Solar Cells (Single-junction Perovskite)

Why perovskite improved things

- **Bandgap tunability (1.5–2.3 eV)** → we can match the absorber to LED spectrum.
- **High absorption coefficient** → thinner films generate strong current.
- **Low-temperature fabrication** → cheaper, flexible, lightweight.
- **High open-circuit voltage** compared to Silicon.

Benefits over normal solar cells

- You can "choose" the right bandgap for the light source.
- Much better performance under **indoor LED lighting**:
    - Wider bandgap reduces thermalization loss
    - Higher Voc
    - Efficient in the visible region where LEDs emit

But still a limitation

Even with tunability, **one bandgap still can't capture all LED wavelengths efficiently**:

- High bandgap → great Voc, but low Jsc
- Low bandgap → great Jsc, but lower Voc
- Always a trade-off, never optimal across the entire LED spectrum

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3. 2T All-Perovskite Tandem Solar Cells

What they are

- Two perovskite solar cells stacked **monolithically** on one substrate.
- Only **2 external terminals** → behaves like one normal solar cell.
- Top cell = higher bandgap (e.g., 2.1 eV)
- Bottom cell = lower bandgap (e.g., 1.5 eV)

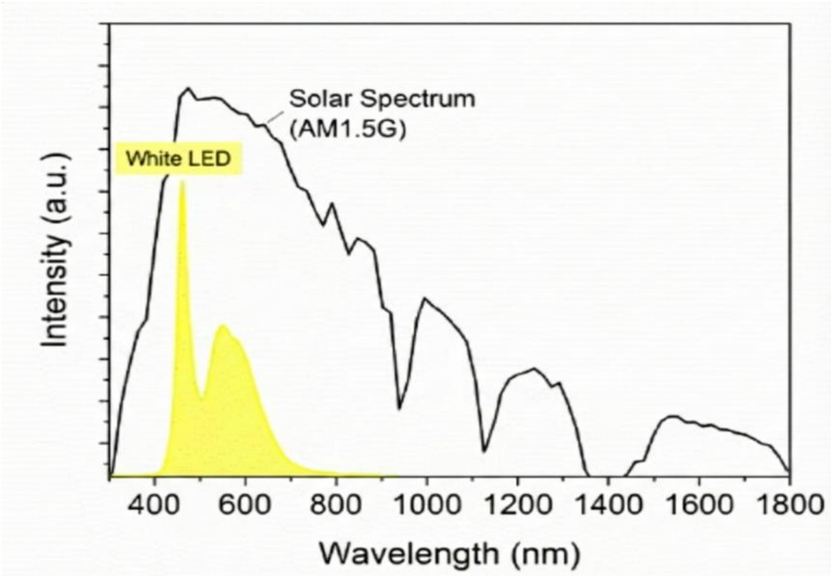
What this architecture solves

- **No thermalization loss:**
  High-energy blue photons are absorbed by the top wide-bandgap cell.
- **No transmission loss:**
  The bottom cell captures the leftover green → red photons.
- **Voltage adds:**

$$V_{oc,total} = V_{oc,top} + V_{oc,bottom}$$

- **Higher efficiency** than any single-junction perovskite.

SUNLIGHT VS WHITE LED & THEIR IMPACT ON SOLAR CELL DESIGN



1. Sunlight (AM1.5G Spectrum)

Sunlight provides a **broad, continuous spectrum**:

- UV (300–400 nm)
- Visible (400–700 nm)
- **Infrared (700–2500 nm)** — a huge portion of the total energy

Silicon is designed specifically for this:

- Silicon bandgap = **1.1 eV**, which perfectly matches **infrared-rich** sunlight.
- That's why silicon generates **very high Jsc outdoors** — because it absorbs both visible and IR photons efficiently.
- Outdoors, silicon is unbeatable for current generation.

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2. White LED Spectrum (Typical Indoor Lighting)

White LED light is completely different:

- A **strong blue spike** at ~450 nm (from the LED chip)
- A **broad yellow-green hump** around 550–650 nm (from phosphor)

- **No infrared photons** (almost zero intensity above 700 nm)

This is a disaster for silicon:

- Silicon relies heavily on IR to generate current
- Under LEDs, its absorption is limited to only a small part of visible light
- Therefore, **silicon Jsc collapses indoors**

PERFORMANCE PARAMETERS

1) Short-Circuit Current (Jsc)

$$J_{sc} \approx \text{Photon absorption} \times \text{Conversion efficiency}$$

- How well the cell converts available light into charge.

2) Open-Circuit Voltage (Voc)

$$V_{oc} \propto E_g - \Delta E_{\text{loss}}$$

What it tells you:

- Bandgap suitability
- Recombination losses
- Maximum voltage available to electronics

3) Fill Factor (FF)

$$FF = \frac{P_{\max}}{V_{oc} J_{sc}}$$

What it tells you:

- Quality of charge transport
- Series and shunt resistance
- How close the I–V curve approaches ideal performance

4) Power Conversion Efficiency (PCE)

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

What it tells you:

- Overall ability to convert LED light into usable electricity.
- **Most important KPI** in indoor PV.

How these four parameters guide our design

- **Jsc** → thickness tuning, optical matching

- **Voc** → bandgap selection, defect reduction
- **FF** → interface engineering, transport layers
- **PCE** → final benchmark for material & architecture selection

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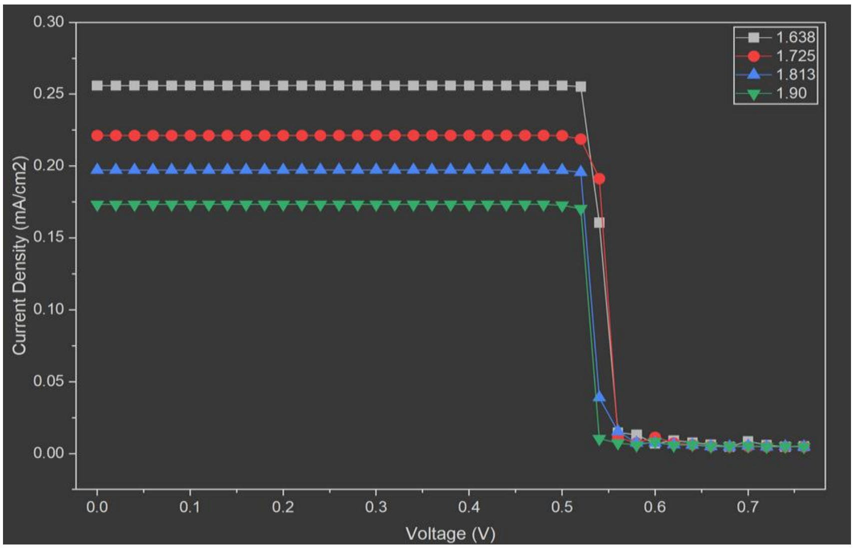
Thermalisation Loss

- Some photons have **more energy than the bandgap (E > Eg)**.
- The solar cell only needs **Eg** to create one electron–hole pair.
- The **extra energy (E − Eg)** from the photon cannot be used.
- This extra energy is quickly released as **heat**, not electricity.
- So high-energy photons give **no extra power**, only **extra heat**, reducing efficiency.

I–V CHARACTERISTIC BASELINE(FOR SINGLE PEROVSKITE SOLAR CELL)



Band Gap (Eg)	Jsc (mA/cm²)	Vmpp (V)	Jmpp (mA/cm²)	Pmax (mW/cm²)	Efficiency (η)
1.638 eV	0.256	0.52	0.255	0.133	8.85%
1.725 eV	0.221	0.52	0.219	0.114	7.58%
1.812 eV	0.197	0.52	0.196	0.102	6.78%
1.900 eV	0.173	0.52	0.17	0.089	5.90%

Band Gap (Eg)	Jsc (mA/cm²)	Pmax (mW/cm²)	Fill Factor (FF)
1.638 eV	0.256	0.133	79.90%
1.725 eV	0.221	0.114	79.40%
1.812 eV	0.197	0.102	79.70%
1.900 eV	0.173	0.089	79.10%

• Eg ↑ ⇒ LED absorption window shrinks ⇒ Jsc ↓

Higher bandgap cell cannot absorb the full LED spectrum (especially 550–650 nm), so **Jsc drops sharply** from 0.256 → 0.173 mA/cm².

• Voc & FF stay nearly constant

Under low-intensity indoor LEDs, **Voc is recombination-limited**, not Eg-limited, and the device structure is unchanged ⇒ **Voc ≈ constant** and **FF ≈ 80%** for all bandgaps.

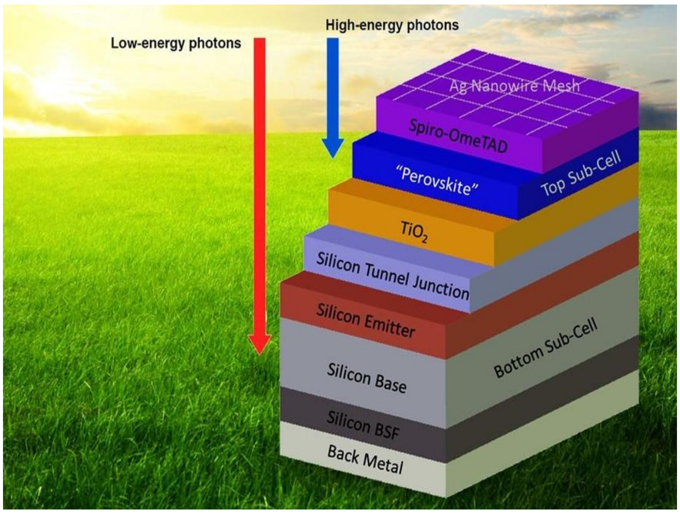
• Pmax and efficiency fall with Jsc

Since **η ∝ (Voc × Jsc × FF)** and Voc/FF do not improve, the **drop in Jsc directly pulls efficiency down** (8.85% → 5.90%).

• Final takeaway

The **lowest Eg (1.638 eV)** performs best for single-junction operation because it harvests more photons from the indoor LED spectrum, while higher Eg cells lose too much current.

Why Move to Tandem?



Problem With Single-Junction Perovskites

1)Single-junction = one Eg → forced trade-off:

High Eg → ↑Voc, ↓Jsc (misses yellow/red),

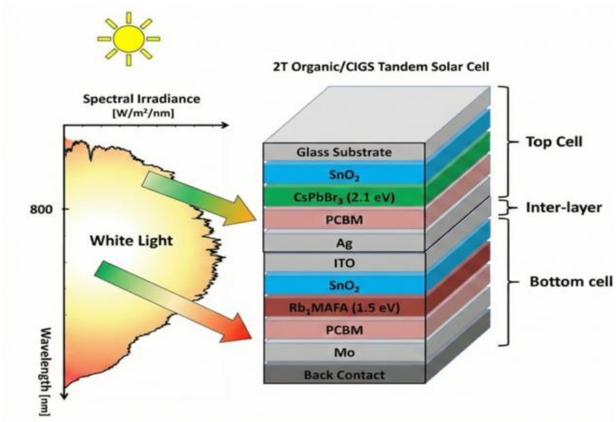
Low Eg → ↑Jsc, ↓Voc (thermalization loss).

2)LED spectrum has two energy regions (blue + green/red) → no single Eg can harvest both efficiently.

2T Tandem Breaks the Limit

1. Top cell (Eg ≈ 2.1 eV): absorbs blue (~450 nm) → ↓thermalization, ↑Voc.
2. Bottom cell (Eg ≈ 1.5 eV): absorbs green–red (500–700 nm) → ↓transmission loss, ↑Jsc.
3. Voc,total=Voc,top+Voc,bottom → ↑Voc
4. J,tandem=J,top=J,bottom
5. Trade-off removed:
6. Top = voltage contributor, Bottom = current contributor, eliminating the Jsc–Voc compromise.

2T Tandem Structure



1. Glass / FTO (Front Electrode)

- **Glass** acts as the mechanical support and allows all incoming LED light to pass.
- **FTO (Fluorine-doped Tin Oxide)** is a **transparent conducting oxide (TCO)** that collects electrons and maintains high optical transmission.
- It provides the **front contact** for the entire tandem stack.

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2. ETL (SnO_2) — Electron Transport Layer

- **SnO_2** has a **wide bandgap (~3.6–4.0 eV)** → it does not absorb visible light, so **no parasitic optical loss**.
- It efficiently extracts electrons from both perovskite absorbers while blocking holes, reducing recombination.
- SnO_2 is also **chemically stable** and can be deposited at low temperatures, ideal for perovskite integration.

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3. Top Cell — $CsPbBr_3$ (2.1 eV)

- **All-inorganic composition (Cs instead of MA/FA)** gives:
    - High thermal stability
    - Better resistance to humidity
    - Lower ion migration
- Bandgap **Eg ≈ 2.1 eV** perfectly matches the **blue-rich LED peak (440–480 nm)**.
- Because it filters out only the high-energy photons, it:
    - **Minimizes thermalization loss**
    - Delivers **high Voc (~1.5 V)**
    - Shows **high tolerance to defects**, which is crucial under low indoor photon flux.
- It also allows the **remaining green/yellow/red photons** to reach the bottom cell.

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4. HTL (Hole Transport Layer)

- Extracts holes from the perovskite and transports them to the contact.
- Must provide:
    - Good energy alignment with the perovskite valence band
    - Low recombination
    - High transparency (for upper layers)

- Commonly Spiro-OMeTAD or inorganic HTLs for stability.

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5. ICL (Interconnecting Layer) — Heart of the 2T Tandem

This layer connects the top and bottom cells in **series**.

To work correctly, the ICL must satisfy all three conditions:

1. **Transparent** → so light can reach the bottom cell
2. **Ohmic recombination layer** → electrons from top + holes from bottom recombine without voltage loss
3. **Does not block charge transfer** → must allow:
   - electrons to exit top cell
   - holes to enter bottom cell

- Proper ICL design ensures **Voc_addition** and **current matching**.

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6. ETL (for Bottom Cell)

- Another SnO_2 or similar wide-bandgap layer that collects electrons from the bottom absorber.
- Ensures band alignment between bottom perovskite and metal contact.

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7. Bottom Cell — Rb_1MAFA (1.5 eV)

- **Bandgap 1.5 eV** targets the **550–700 nm LED phosphor hump**, producing **high Jsc (~46.4 mA/cm²)**.
- Rb^+ doping stabilizes the mixed-cation perovskite lattice:
   - Reduces phase segregation
   - Improves crystallinity
   - Increases Voc and FF
- This absorber captures all the **longer-wavelength photons** that pass through the top cell.

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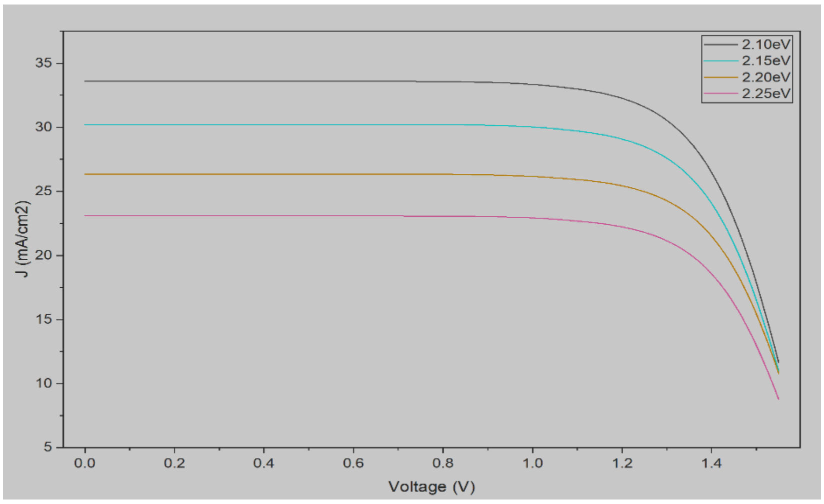
8. Bottom HTL / Metal Electrode

- Extracts holes and forms the rear contact.
- High work-function metal (Au, Ag) ensures efficient hole collection.
- Must maintain stability and good interfacial properties over time.

Tandem Results:

1) Optimization of Top cell

Bandgap Tuning



Eg (eV)	Voc (V)	Jsc (mA/cm²)	FF (%)	n (%)
2.1	1.555	33.58	72.9	30.37
2.15	1.5508	30.22	73.29	27.41
2.2	1.5445	26.34	73.78	23.95
2.25	1.5382	23.08	74.19	21.01

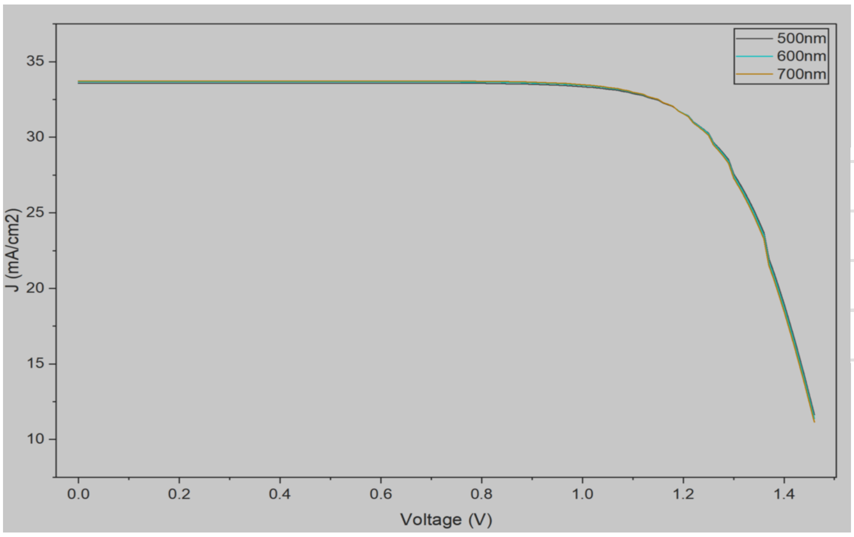
1)↑Eg (2.10 → 2.25 eV) ⇒ ↓Jsc↓↓, ↓η

- while Voc ≈ const and FF ≈ const
- higher Eg cuts LED (550–650 nm) photons ⇒ performance collapse.

2)Eg = 2.1 eV

- max Jsc, max η, good blue absorption, good green transmission
- best current-matching + top-cell performance.

Thickness Tuning



t (µm)	Voc (V)	Jsc (mA/cm^2)	FF (%)	n (%)
0.5	1.555	33.58	72.9	30.37
0.6	1.5544	33.67	72.71	30.36
0.7	1.5537	33.72	72.53	30.32

Increasing thickness from 0.5 → 0.7 µm **does NOT increase absorption** for the top cell.

- The LED blue peak (~450 nm) is absorbed **very strongly** by $CsPbBr_3$.
- Even 0.5 µm is **already thick enough** to absorb almost all usable photons.
- Adding more thickness gives **no performance gain** because the top cell is already at **absorption saturation** for the LED spectrum.

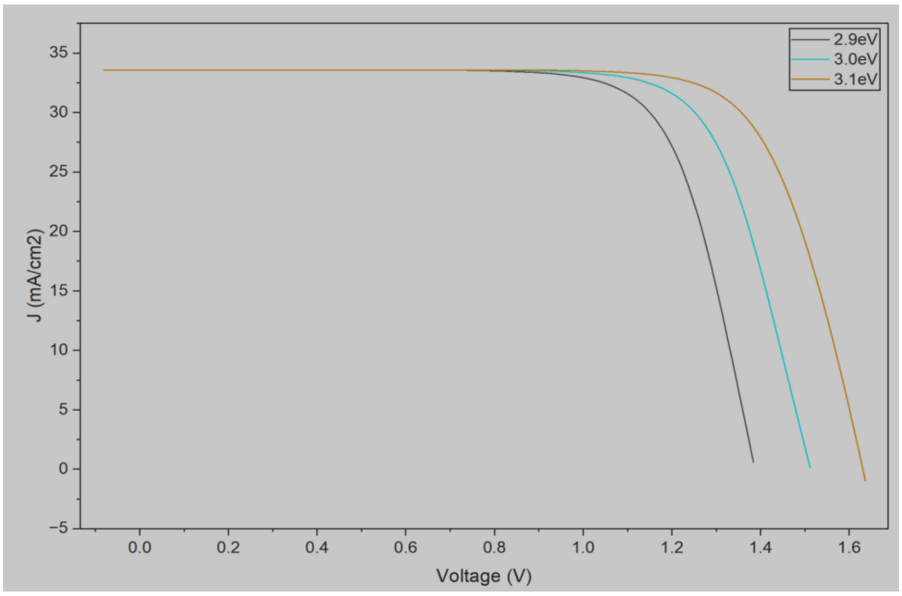
This is exactly why the curves are nearly identical.

A thicker top cell =

- More absorption for itself
- Less transmission to the bottom cell
- Worse current matching
- Lower tandem efficiency

So **Use the thinnest layer that already gives maximum performance.**

Spiro Bandgap varying



Spiro Eg(eV)	Voc (V)	Jsc (mA/cm^2)	FF (%)	n (%)
2.9	1.4559	33.58	71.49	27.89
3	1.5544	33.58	72.71	30.36
3.1	1.6306	33.58	75.2	32.85

1) Jsc constant → absorber and optical generation unchanged (Spiro is HTL, not absorber).

2) Voc increase → improved energetic alignment / larger built-in potential and reduced interfacial recombination when Spiro's electronic levels shift with effective Eg/work-function change.

3) FF increase → reduced recombination and improved charge extraction (better hole extraction / lower interfacial losses) at higher Spiro Eg.

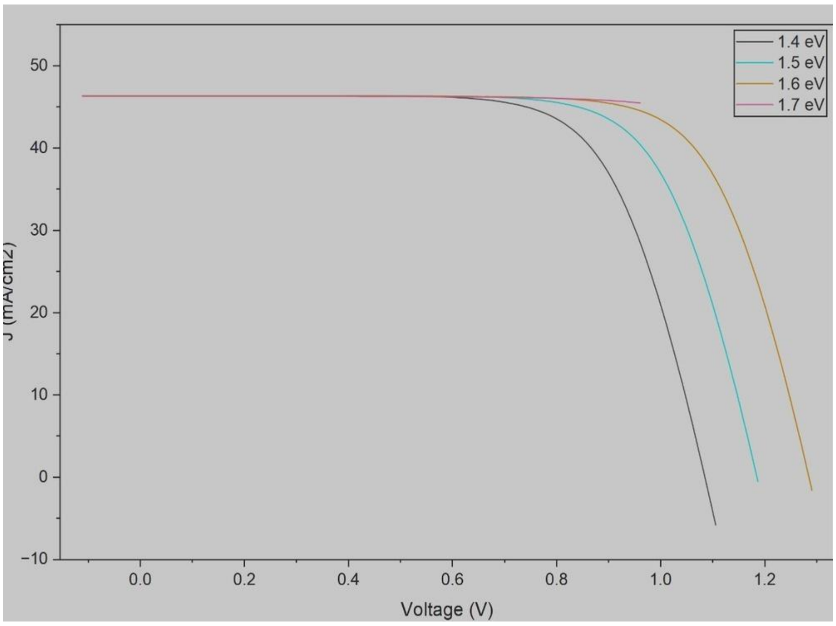
4) Net effect: Voc × Jsc × FF rises → efficiency increases substantially.

<u>why 3.1ev?</u>

3.1 eV ⇒ highest Voc + best FF + same Jsc ⇒ η(max)

2) Optimization of Bottom Cell

Bandgap Tuning



Eg (eV)	Voc (V)	Jsc (mA/cm^2)	FF (%)	n (%)
1.4	1.0849	46.36	69.77	28
1.5	1.1849	46.36	71.59	31.38
1.6	1.2848	46.35	73.07	34.72
1.7	7.759	46.29	12.16	34.86

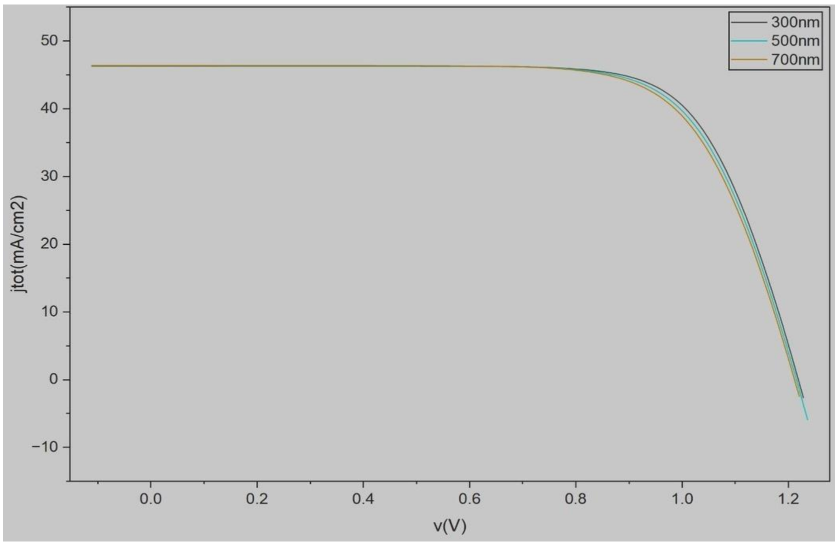
What the table shows:

Eg (bottom) 1.4 → 1.6 eV → Voc ↑ (1.085 → 1.284 V), Jsc ≈ 46.3 mA/cm^2 (constant), FF ↑ (≈70 → 73%), so η rises.

- **Eg_bottom↑ (1.4→1.6 eV) ⇒ Voc↑, FF↑, Jsc ≈ constant**, because the bottom absorber still captures the same 500–700 nm LED photons.
- **η_bottom peaks at Eg ≈ 1.60 eV**, since the increase in **Voc × FF** dominates while Jsc remains nearly unchanged.
- **Eg = 1.7 eV gives non-physical Voc (≈7.7 V)** → clear SCAPS convergence error → discarded.
- In a **2-terminal tandem**, the operating current is constrained by **J_tandem = J_top = 33.6 mA/cm^2**, not by the standalone bottom Jsc.
- For **tandem current-matching**, Eg ≈ **1.53 eV** provides the correct JV-touch under the filtered spectrum, aligning the bottom cell's operating current with the top cell.
- **Eg = 1.6 eV gives highest standalone η**, but slightly reduces tandem current-matching, so its benefit depends on whether standalone-bottom optimization or full-tandem optimization is prioritized.
- **Final decision:** Eg_bottom = **1.60 eV** chosen because it delivers the **highest standalone efficiency** (max Voc·FF with Jsc ≈ const), making it the best-performing bottom absorber in your dataset.

- **Summary:** Eg_bottom = **1.60 eV** ⇒ **max η_bottom**, strong Voc, high FF, and stable Jsc → optimal bottom-cell bandgap.

Thickness Tuning



t (nm)	Voc (V)	Jsc (mA/cm²)	FF (%)	n (%)
300	1.2186	46.31	72.91	32.83
500	1.2149	46.36	72.07	32.39
700	1.2114	46.39	71.34	31.99

What the curves show (short)

- J–V curves for t = 300, 500, 700 nm almost overlap → **Jsc ≈ 46.3 mA/cm² (constant), Voc/FF/η fall slightly as t increases** (Voc: 1.2186 → 1.2114; FF: 72.9 → 71.3; η: 32.83 → 31.99).

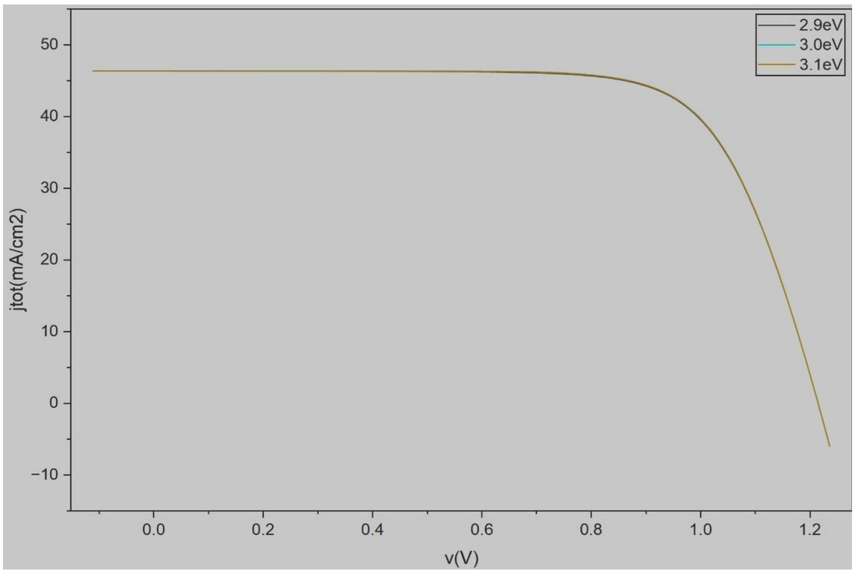
Physical reason / interpretation

- Absorption saturation: the absorber's optical absorption at the bottom-cell wavelengths is strong, so >99% of useful photons are absorbed within ~300 nm → increasing t gives no Jsc gain.
- Thicker ⇒ worse transport/recombination & slight resistive losses: adding thickness increases carrier travel distance and probability of SRH recombination and series resistance → small decreases in Voc and FF (hence η drops).
- Net effect: no Jsc benefit but small electrical penalties as t↑.

Final conclusion:

- Since **performance ≈ identical but material cost & fabrication time ↑ with thickness**, choose **the thinnest film** that already saturates absorption (here 300 nm) — maximizes cost-efficiency while preserving η and leaving more photons available for any optical stack considerations or current-matching.

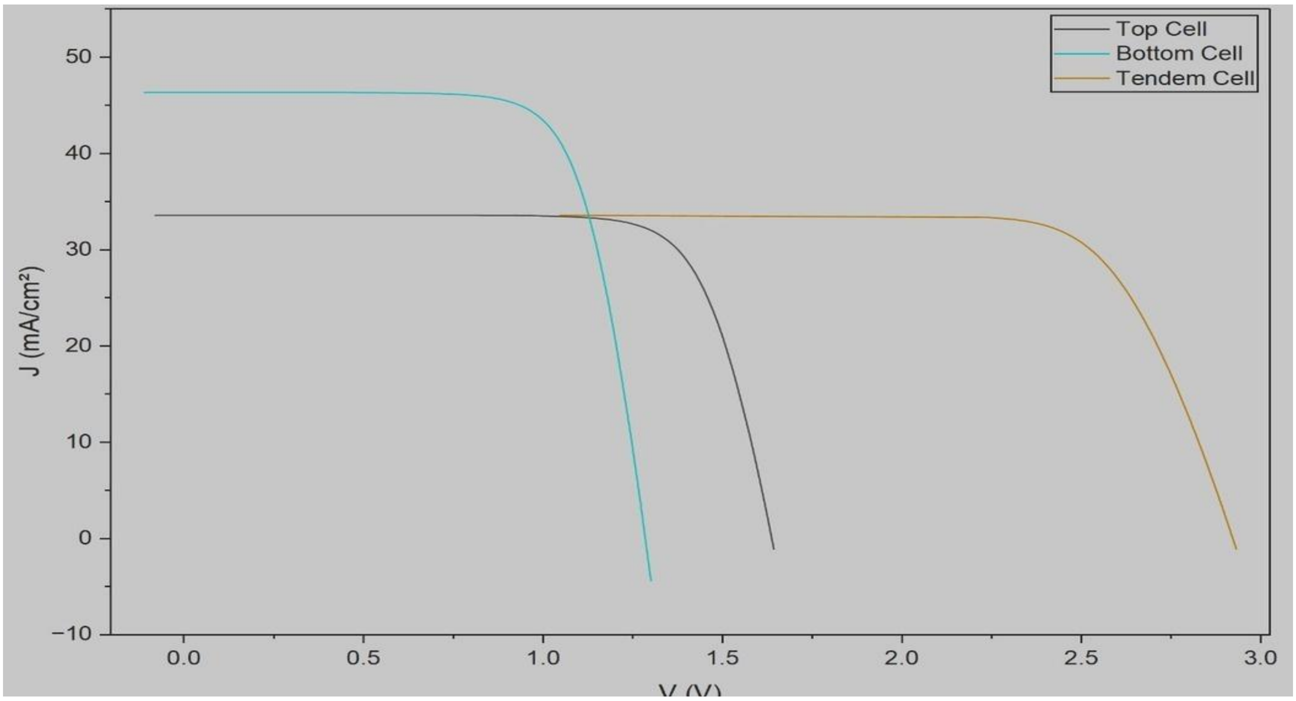
Spiro Bandgap Tuning



Spiro Eg(ev)	Voc (V)	Jsc (mA/cm²)	FF (%)	n (%)
2.9	1.2149	46.36	71.86	32.29
3	1.2149	46.36	72.07	32.39
3.1	1.2149	46.36	72.12	32.41

Spiro Eg change ⇒ Jsc ≈ const (absorption in absorber); small ↑Voc/FF due to better HTL alignment ⇒ slight ↑η.
Pick Spiro Eg = 3.1 eV ⇒ max η (32.41%) — choose highest PCE unless practical constraints override.

Final Optimized Tandem Performance



Parameter	Top Cell	Bottom Cell	Tandem Cell
Power (Pmax)	41.8 mW/cm²	43.5 mW/cm²	78.1 mW/cm²
Efficiency	~33.0 %	~34.0 %	~41.5 %
Voc	1.64 V	1.28 V	2.92 V
Jsc	33.6 mA/cm²	46.4 mA/cm²	33.6 mA/cm²
Fill Factor	76.0 %	73.1 %	79.6 %

Final 2T Tandem Result

1) High Efficiency (~41.5%)

The tandem efficiency is much higher than either sub-cell because the device simultaneously achieves:

- high Voc (adds from both cells),
- high FF (strong electrical quality),
- and a well-matched operating current.

$$\eta_{\text{tandem}} = \frac{V_{oc,\text{top}} + V_{oc,\text{bot}}}{P_{in}} \cdot J_{\text{tandem}} \cdot FF$$

Your numbers maximize this product → **η ≈ 41.5%**, far above the single-junction limit.

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2) High Voc (≈ 2.92 V = 1.64 + 1.28 V)

In a **2-terminal series tandem**, voltages add:

$$V_{oc,\text{tandem}} = V_{oc,\text{top}} + V_{oc,\text{bottom}}$$

So your top cell (1.64 V) + bottom cell (1.28 V) produce **2.92 V**, which is ideal for powering indoor IoT electronics without DC-boosting.
This is one of the biggest advantages of tandem design.

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3) Jsc = min(Jsc_top, Jsc_bottom) = 33.6 mA/cm²

Because the two subcells are connected **in series**, the current flowing through both must be the same:

$$J_{\text{tandem}} = \min\left(J_{\text{top}}, J_{\text{bottom}}\right)$$

Your top cell gives **33.6 mA/cm²**, bottom gives **46.4 mA/cm²**, so the tandem is limited by the **top cell**.

This is why the tandem Jsc equals **33.6 mA/cm²**, not the bottom's 46.4 mA/cm².

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4) High Fill Factor (79.6%)

The tandem FF is higher than either subcell because:

- both subcells operate near their optimal field,
- combined Voc increases the "squareness" of the I–V curve,
- current is well-matched with minimal distortion.

This results in **FF ≈ 79.6%**, which is excellent for indoor perovskite devices.

High FF = low resistive losses + high-quality interfaces + efficient ICL.

Conclusion:

1) Why Single-Junction Perovskites Fail Indoors

A single absorber has only **one Eg**, so it cannot efficiently capture the entire LED spectrum.
This leads to a **Jsc–Voc trade-off**:

- **Eg too high** → Voc↑ but Jsc↓ (green/red photons wasted → transmission loss↑)
- **Eg too low** → Jsc↑ but Voc↓ (blue photons lose energy → thermalization↑)

Under LED lighting, this trade-off becomes severe, dropping η.
Therefore, we shift to 2T tandem, where two bandgaps (**Eg_top + Eg_bottom**) split the LED spectrum efficiently.

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2) Why the 2T All-Perovskite Tandem Works So Well

Top Cell (Eg = 2.1 eV) — Blue Absorber

- Captures **450 nm LED peak** efficiently.
- Minimizes thermalization since blue photons match high Eg.
- Produces high **Voc = 1.64 V**.

Bottom Cell (Eg = 1.53–1.60 eV) — Green–Red Absorber

- Captures the **phosphor hump (550–650 nm)** efficiently.
- Reduces transmission loss since low-energy photons are now absorbed.
- Provides high current potential (Jsc ≈ 46 mA/cm² standalone).

Series Connection Advantages

- **Voltages add:**

$$V_{oc,tandem} = 1.64 + 1.28 = 2.92 \text{ V}$$

This is ideal for powering indoor IoT devices without voltage boosters.

- **Current follows the minimum:**

$$J_{tandem} = J_{top} = 33.6 \text{ mA/cm}^2$$

(Top cell limits the series current — normal and expected.)

Device Quality

- **Strong ICL** (Interconnecting Layer) ensures low-resistance recombination between cells.
- Balanced subcells → **high FF ≈ 80%**.
- Combined improvements give **η ≈ 41–42%**, far higher than any single-junction indoor solar cell.

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3) Future Scope & Opportunities

A. Move Toward 4T Tandems

- A 4-terminal design removes current-matching constraints.
- Each subcell works at its own MPP → **higher maximum achievable η**.
- Suitable for research or high-end indoor applications despite added complexity.

B. Scalable, Low-Cost Fabrication

- The entire stack can be fabricated using **solution-based, low-temperature** processes.
- Enables **roll-to-roll**, **slot-die coating**, and **large-area module** production.
- Makes indoor perovskite tandems cost-effective for mass deployment.

C. High-Impact Applications

- Perfect for **indoor IoT sensors**, **BLE devices**, **smart tags**, **wearables**, and **auxiliary electronics**.
- High V_{oc} + high η under low light makes them ideal for **battery-less** or **battery-assisted systems**.