RAYTRON

MATERIALS / PROCUREMENT / ENGINEERING

# Copper–Aluminum Composite PV Ribbon Buyer’s Guide

Choose the material. Prove the process.
Count the cost per watt.

A PRACTICAL GUIDE

For first-time buyers—and the process,
engineering and quality teams signing with them.

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Materials → Specifications → Process → Cost per watt
Cost case: 0.26 mm finished · Equal price per tonne · Complete coating

**Engineering Every Micron.**

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# Choose the material. Prove the process. Count the cost per watt.

PV ribbon may look like a very small piece of metal, but procurement, process engineering, R&D and quality all have a vote. Procurement wants a better price. The stringer wants predictable feeding. The cells would prefer not to crack. The module still has to deliver its watts.

Copper–aluminum composite PV ribbon puts different materials to work: **aluminum carries part of the current, copper provides the outer metallic connection surface, and a process-compatible solder coating makes the joint.** Its purpose is not to impersonate copper. It is to reduce actual ribbon cost while meeting the requirements of a particular module.[1][3]

This guide is for buyers and engineers encountering the material for the first time. It covers round interconnect wire, flat interconnect ribbon and busbar ribbon inside crystalline-silicon modules. It does not cover external PV cable or field replacement of ribbon inside encapsulated modules.

**Reading routes:** material basics, Sections 1–5; specification selection, Sections 6–11; trials and purchasing, Sections 12–18; quick answers, Section 19.

**TOPCon substitution—read this first: when replacing copper ribbon with the Raytron round CCA ribbon covered by this process route, the stringer's existing local ribbon-flattening operation MUST be disabled or bypassed.** This is Raytron's process requirement based on feedback from Chinese module customers. See Section 9.[2]

> A good substitution improves the purchase order while keeping production and module performance within the agreed requirements.

## 01 | Start with the value—and the right denominator

Raytron project and application records show that its copper–aluminum composite ribbon has been used in modules totaling **more than 50 GW**. In some Chinese module-customer projects, **ribbon material cost was reduced by more than 50%** compared with the previous copper-ribbon solution. Reported applications include BC and TOPCon module designs.[2]

The denominator matters: that saving concerns **the ribbon material being compared**, not total module cost or the cost of electricity. The 50 GW figure describes total application volume.

**Equal tonne prices can still save money:** Section 10 calculates the complete coated mass of a 0.26 mm finished CCA50 wire with 15 µm radial solder. At equal prices and net lengths, interconnect purchasing cost falls by approximately **42.44%**. This example is separate from the other company projects reporting savings above 50%.

| Buyer's question | A useful comparison |
|---|---|
| Can equal prices per tonne still save money? | Compare complete finished mass per metre, including solder. At equal prices and net lengths, the reduction in purchased mass is the purchasing saving. |
| How much does each module save? | Compare finished-wire cost per metre, actual consumption, production losses and yield. |

| Buyer's question | A useful comparison |
|---|---|
| Will module power change? | Build matched module controls with comparable cells and bills of materials; compare the power distribution. |
| Can it run consistently? | Check speed, stoppages, wire breaks, joining quality and rework on the real stringer. |
| What about reliability? | Evaluate electrical and connection performance after the agreed thermal, humidity and other relevant tests. |

There is no need to replace every copper component at once. A better starting point is **one clearly specified, meaningful-volume module model with an agreed comparison trial**.

## 02 | What it is: three layers, three jobs

A typical construction is **aluminum or a specified aluminum-alloy core → copper cladding → solder coating**. Copper and aluminum both conduct longitudinal current. The outer solder layer is selected to form the required connection to cell metallization and other interconnection surfaces.[1][3]

| Term | What it means | What the order still needs |
|---|---|---|
| CCA | Copper-clad aluminum substrate | Copper fraction, core material, temper and electrical properties |
| HTCCA | Raytron's high-strength, aluminum-alloy-core CCA series | Actual tensile, yield, elongation and resistance requirements—not a temperature rating inferred from the name |
| Copper–aluminum composite PV ribbon | Composite substrate plus a joining-compatible solder coating | Form, connection position, substrate and finished dimensions, coating alloy |
| Interconnect ribbon / round interconnect wire | Material connecting cells | Pad layout, wire count, routing, spacing and stringing requirements |
| Busbar ribbon | Material connecting strings and the module collection circuit | Current path, length, bends and junction-box connection |
| "Alloy ribbon" | An incomplete commercial or technical description | Does "alloy" refer to the core, solder or an entirely different construction? |

CCA is not a homogeneous alloy made by melting all the copper and aluminum together. Bare CCA conductor is also not automatically a finished PV interconnect ready for the stringer.

"Tin-coated" or "tinned" is often commercial shorthand. The coating may be tin–lead or another tin-based solder, rather than pure tin. **A silver-colored surface is not a chemical analysis.**

# 03 | TOPCon, HJT, BC, SMBB and 0BB are not one classification

These terms describe different aspects of a module. TOPCon and HJT describe cell technologies; BC describes a back-contact configuration; MBB, SMBB and 0BB describe metallization or interconnection approaches. A project can combine several of them.[4][5]

| Project feature | Start by checking | Comparison priorities |
|---|---|---|
| PERC / TOPCon interconnection | Cell format, pads, wire count, individual cross-section and coating | Stringing, joints, EL and power; the TOPCon CCA round-wire route in this guide requires the original local flattening operation to be disabled/ bypassed |
| MBB / SMBB | Round-wire dimensions, positioning, tension and joint consistency | Breaks, displacement, optical shading and electrical loss |
| 0BB | Actual joining method, solder or other connection system, fixation process | Finger contact, alignment, connection continuity and material compatibility |
| BC | Rear positive/negative layout, routing, insulation and bending positions | Electrode separation, conformity, stress and connection reliability |
| HJT / SHJ | Cell and metallization thermal budget, solder and flux | Measured temperature profile, wetting, peel performance and aged stability |
| Busbar circuit | Current path, effective cross-section, length and connection nodes | Circuit resistance, joints and local temperature rise |

**0BB does not mean zero interconnects.** Removing conventional cell busbars does not give electricity permission to jump between cells. Nor does one unqualified solder recipe serve every 0BB process.[4]

Similarly, "suitable for HJT" needs more than a low-melting-point label. Alloy melting behavior, machine setpoint, actual joint temperature and the cell's thermal history are different quantities.[4]

# 04 | CCA or HTCCA? "Stronger" is not the whole specification

Start with the constraints: the resistance budget, available cross-section, feeding strength and assembly stress tolerated by the cells. HTCCA is not an automatic upgrade for every project. Higher tensile requirements and different electrical properties need to be considered together.[1]

The following values are taken from Raytron **Spec201910 Rev.4, released 15 September 2026**. Resistivity values are **substrate upper limits at 20°C**; density values are nominal references. They are not measured finished-product values or confirmation that every grade–geometry combination is stocked. [1]

| Substrate grade | Maximum substrate resistivity, Ω·mm²/m | Nominal density, g/cm³ |
|---|---|---|
| TU1 copper | 0.017241 | 8.90 |
| CCA30 | 0.027 | 3.42 |
| CCA40 | 0.026 | 3.74 |
| CCA50 | 0.025 | 4.15 |
| CCA60 | 0.024 | 4.64 |
| CCA70 | 0.023 | 5.27 |
| HTCCA30 | 0.029 | 3.42 |
| HTCCA40 | 0.028 | 3.74 |
| HTCCA50 | 0.027 | 4.15 |
| HTCCA60 | 0.026 | 4.64 |
| HTCCA70 | 0.025 | 5.27 |

In this document, CCA50 and HTCCA50 have the same reference density but different maximum resistivity. **Similar grade names do not imply identical electrical performance.**

Bare-conductor specifications, PV-substrate specifications and coated-product data may use different conditions. Order against one mutually approved specification, rather than selecting the most attractive number from each of several tables.

## 05 | Copper content: write wt.% or vol.% before discussing the number

**Weight fraction, wt.%**, describes copper's share of substrate mass. **Volume fraction, vol.%**, describes copper's share of substrate volume; for a uniform straight cross-section it also corresponds to copper area fraction. The percentages are not interchangeable.

Raytron's bare-material grades such as CCA30 and CCA40 use copper weight percentage.[3] A PV order should additionally state that the fraction applies to the uncoated composite substrate, specify its allowable range and test method, and resolve the original specification's Cu+Ag heading in the purchasing definition. Do not silently include the solder coating in the denominator.

The examples below use copper density 8.960 and aluminum density 2.705 g/cm³, excluding solder. Use the actual core density for an alloy-core calculation.[3]

| Copper weight fraction | Calculated copper volume fraction |
|---|---|
| 30 wt.% | Approximately 11.46 vol.% |
| 40 wt.% | Approximately 16.75 vol.% |
| 50 wt.% | Approximately 23.19 vol.% |

| Copper weight fraction | Calculated copper volume fraction |
|---|---|
| 60 wt.% | Approximately 31.17 vol.% |
| 70 wt.% | Approximately 41.33 vol.% |

**50 wt.% copper is not 50 vol.% copper.** Two quotations both saying "50%" may describe substantially different materials.

The lowest copper fraction is not automatically the best purchase, and the highest is not automatically the best value. Finished resistance, minimum local copper thickness, forming and joint performance—and ultimately cost per watt—are the deciding factors.

## 06 | Dimensions and copper cladding: "0.24 mm" needs a second sentence

At minimum, distinguish **substrate dimensions before coating** from **finished dimensions after coating**.

For a 0.24 mm substrate with a 15 µm radial solder coating, equivalent to 0.015 mm, the ideal finished diameter is:

> $0.24 + 2 \times 0.015 = 0.27$ mm

If a quotation instead uses 0.24 mm as the finished diameter, the substrate under the same coating is only 0.21 mm. For the substrate alone, with the same material properties, that means approximately 23.4% less cross-sectional area and 30.6% higher resistance per metre. Finished resistance also includes the solder conduction path.

**Confuse substrate and finished dimensions and the price comparison can be wrong before the first trial starts.** Section 10 separately uses a 0.26 mm finished diameter with 15 µm radial solder, leaving a 0.23 mm substrate. Do not transfer this section's 0.24 mm teaching example into that cost table.

| Specification item | Recommended definition |
|---|---|
| Round wire | Substrate diameter and tolerance; finished diameter and tolerance; ovality requirement |
| Flat interconnect / busbar ribbon | Substrate thickness × width; finished dimensions; corner geometry, burrs and camber |
| Copper cladding | Volume fraction or explicitly defined weight fraction; minimum local copper thickness and inspection positions |
| Solder coating | Composition; single-side / radial thickness; local uniformity and coverage |
| Reel product | Continuous length, splice policy, reel drawing, winding and payoff direction |

Rev.4 lists ±0.01 mm for substrate thickness/diameter, ±0.05 mm for flat-product width, a single-side/radial solder thickness of 15±5 µm, and flat-wire/busbar camber of ≤3 mm per 1,000 mm. These are that document's reference conditions. Finer geometries, high-speed lines or specific pad layouts may require separately agreed limits.[1]

Average copper fraction does not establish minimum local copper thickness. Eccentricity, rolled corners, bends and local defects need actual cross-section evidence. The ideal round-wire relation is useful only for a uniform concentric structure:

> Copper thickness = substrate diameter / 2 × [1 − √(1 − copper volume fraction)]

Do not apply it directly to flat or shaped sections. An exposed aluminum core at a cut end is inherent to the construction; unintended exposure along the wire surface, cracking or delamination is a different issue. Protection of cut ends through the joining, encapsulation and module design should be evaluated in the finished construction.[1][3]

## 07 | Resistance and module power: PV runs on DC, not a skin-effect sales pitch

Under the DC operating conditions of a PV module, both copper and aluminum conduct. "All the current stays in the copper skin, so it behaves exactly like copper" is not the correct explanation.

The most useful purchasing electrical question is: **what is the finished product's resistance per metre at 20°C?** Resistivity requires the real cross-sectional area to become resistance. An IACS value alone does not answer the question.[1]

For uniform straight material, use length L in m, area A in mm² and resistivity ρ in Ω·mm²/m:

> R = ρ × L / A

Treating substrate and solder as effective longitudinal parallel paths:

> Resistance per metre r = 1 / [A_substrate / ρ_substrate + A_solder / ρ_solder]

> Finished effective resistivity = r × A_finished

Consequently, adding a relatively low-conductivity solder coating can **reduce resistance per metre** while **increasing effective resistivity calculated over the full finished area**. The area definition explains the apparent contradiction.[1]

The finished-resistivity ranges in Rev.4 are modelled reference values, **not two-sided acceptance bands**. A measurement below a calculated lower endpoint is not, by itself, a reason for rejection. Apply the agreed finished-product resistance requirements for acceptance.[1]

### A calculation with all its assumptions visible

Use the same 0.24 mm substrate diameter and 15 µm radial solder coating for both options. Take substrate resistivity as 0.017241 for copper and 0.025 for CCA50. Assume solder resistivity of 0.153 Ω·mm²/m, following a reference calculation scenario in Rev.4—not a measured coating guarantee.[1]

| Calculated quantity | Copper-substrate option | CCA50-substrate option |
|---|---|---|
| Substrate diameter, mm | 0.24 | 0.24 |
| Ideal finished diameter, mm | 0.27 | 0.27 |
| Substrate area, mm² | 0.04524 | 0.04524 |
| Finished resistance, Ω/m | Approximately 0.370 | Approximately 0.530 |
| Finished effective resistivity, Ω·mm²/m | Approximately 0.02119 | Approximately 0.03032 |

The same-size materials can therefore have different resistance. **The percentage increase in ribbon resistance is not the percentage reduction in total module power.** This section uses a 0.24 mm substrate to explain electrical calculations, not the 0.26 mm finished geometry used for cost in Section 10.

Module loss also depends on cell current, parallel interconnect count, distributed current collection, connection resistance and routing. Do not assign full module current to every fine wire along its entire length and then add all those losses. Optical shading and reflection belong in the module comparison too. [4]

For measurements, agree on four-terminal methodology, effective sample length, temperature correction and sampling positions. Fixture contact issues should not be mistaken for bulk material performance. Keep raw resistance, length, temperature and cross-section records, not only a converted number.

## 08 | Mechanical properties: the hardest ribbon does not win

Tensile strength describes resistance to breaking; proof/yield strength describes the stress associated with a specified permanent deformation; elongation describes extension before fracture. None substitutes for the others.

Sufficient strength helps handling and payoff. Excessive proof stress, springback or residual stress can work against conformity and thin cells. Very soft material can also create deformation and positioning problems. The objective is a production-and-module window, not a single-property championship.[4][5]

The following examples are from Rev.4. **Stress is calculated using finished metallic cross-sectional area.** Elongation and tensile values are minima; Rp0.2 values are maxima.[1]

| Nominal substrate geometry | CCA: elongation / tensile / Rp0.2 | HTCCA: elongation / tensile / Rp0.2 |
|---|---|---|
| Round Ø0.24, 0.26, 0.28, 0.32 mm | ≥20% / ≥120 MPa / ≤80 MPa | ≥20% / ≥135 MPa / ≤95 MPa |
| Round Ø0.35 mm | ≥20% / ≥125 MPa / ≤80 MPa | ≥20% / ≥135 MPa / ≤85 MPa |
| Flat 0.16, 0.18, 0.25 × 0.6 mm | ≥20% / ≥105 MPa / ≤80 MPa | ≥20% / ≥135 MPa / ≤95 MPa |
| Busbar geometries listed in the specification | ≥25% / ≥120 MPa / ≤120 MPa | ≥25% / ≥140 MPa / ≤120 MPa |

Do not extend one size's limits to every product. Gauge length, test speed, grips and area convention must also be consistent.

**MPa is not breaking force in newtons.** Two wires with the same tensile strength but different areas have different breaking forces. Payoff settings also need appropriate allowance for dynamic loading and subsequent handling operations.

### Why is local flattening unnecessary in this TOPCon route?

According to Raytron's feedback from numerous Chinese module customers, the aluminum core gives the CCA ribbon selected for this route greater compliance than the original copper ribbon. It conforms more readily at the cell-edge contact, helping reduce local loading and the associated microcrack risk. The local flattening operation originally used for copper is therefore unnecessary.[2]

Here, "softer" means **bending and contact compliance in the actual application**, not a claim that every CCA/HTCCA grade has a lower tensile strength or proof stress than every annealed copper grade. Core, copper layer, temper and geometry still matter. No unmeasured percentage reduction in microcracks is claimed. Fraunhofer ISE also identifies interconnection transitions and cell-edge loading as stress-optimization issues; that is background research, not a test of Raytron's product.[5]

**The process instruction remains definite: in the TOPCon substitution route covered here, the original local flattening operation MUST be disabled or bypassed.**[2]

## 09 | Solder, flux and stringer: qualify the combination

Rather than asking only "can it be soldered?", ask: **can it make consistent joints with our cells, machine and throughput, across an acceptable process window?**

### Mandatory for this TOPCon route: disable or bypass copper-ribbon flattening

**When replacing copper ribbon with the Raytron round CCA ribbon covered here, the stringer's existing local ribbon-flattening operation MUST be disabled or bypassed. Do not retain it by copying the copper recipe.** This is Raytron's requirement based on extensive Chinese customer feedback—not an optional suggestion to experiment with.[2]

The original copper process locally reduces ribbon thickness and loading at the cell edge to reduce edge-cracking risk. A published patent likewise identifies inter-cell stress and edge cracking as problems addressed by local flattening.[17] The Raytron ribbon selected for this route relies on greater compliance instead; retaining the old action may damage the copper cladding. InfoLink's May 2025 research identified aluminum exposure as a risk when fine TOPCon SMBB composite wire undergoes flattening during stringing.[16]

| Stage | Required action |
|---|---|
| Recipe change | Create the composite-ribbon recipe and disable/bypass local inter-cell flattening. A smaller flattening stroke is not the same as disabling it. |
| Action check | Equipment/process staff confirm that the wire is no longer flattened at that station; record the recipe revision and actual action. |
| First articles and pilot | With flattening off, check routing, tension, edge transition, joints, EL and power before normal production release. |

This instruction concerns **the stringer's local flattening operation originally used for copper round wire**. It does not mean disabling normal soldering clamps, positioning or lamination, and it does not prohibit controlled manufacture of flat composite ribbon by the supplier. If the machine cannot disable or bypass this operation, have the equipment supplier resolve that before trials under this route.

The 2025 report describes a historical fine-wire/flattening obstacle. It must not be recast as a timeless ban on TOPCon CCA mass production. Raytron's instruction above reflects its subsequent field experience.[2] [16]

> A new material needs the right recipe—not every habit inherited from copper.

Rev.4 lists Sn60Pb40, Sn50Pb50, Sn43Pb43Bi14 and Sn32Pb43Bi25, with nominally pure tin available on request. These are different compositions, not a universal recommendation list for all cell technologies.[1]

| Item | Action for purchasing and trials |
|---|---|
| Solder composition | State the complete alloy and limits; specify lead-free requirements and supporting evidence where required. |
| Coating thickness | Examine average and local coverage alongside joint volume and dimensional limits. |
| Flux | Check wetting, residues and compatibility with cell metallization and encapsulation materials. |
| Thermal profile | Measure temperature, time and cooling at the relevant joining locations; do not simply copy machine setpoints. |
| Pressure and alignment | Record tooling, tension, pad alignment and front/rear positional relationships. |
| Production speed | Validate at target throughput, not only with slow manual samples. |

Smaller pads, thinner metallization and finer wires can narrow the tolerances for alignment, heating and solder volume.[4] Establish a baseline and change variables deliberately. Changing the ribbon, cell batch and flux simultaneously is a poor way to discover which variable mattered.

**Low-temperature does not mean lead-free. Bismuth-containing does not mean lead-free. "Tinned" does not mean pure tin.** Read the composition, not the implication of the name.

## 10 | Equal finished price per tonne: savings per module, watt and GW

**The customer buys solder-coated ribbon, not a basket of copper, aluminum, tin and lead.** Raytron's commercial experience indicates that finished prices by weight are often close: CCA ribbon has a higher solder mass fraction, while coating throughput and processing costs also affect the quotation. This example therefore uses **the same finished-product price per metric tonne for copper and CCA**. Do not add solder or processing charges again when they are already included in the quotation.[22]

> The saving is not a cheaper kilogram. It is fewer kilograms for the same interconnection length.

## 10.1 | Fix the comparison: 0.26 mm means the finished diameter

| Item | Conditions used here |
|---|---|
| Reference module | 650 W; 132 half-cells; 6×22 layout; 16BB |
| Round interconnect length | 451.2 m/module, a geometry budget—not a measured factory issue quantity |
| Both finished diameters | **0.26 mm after solder coating** |
| Radial / single-side solder thickness | 15 μm, a nominal input—not a new measurement |
| Substrate diameter | **0.26 − 2×0.015 = 0.23 mm** |
| Composite substrate | CCA50: 50 wt.% copper in the substrate, approximately 23.19 vol.% |
| Solder | Sn60Pb40 for both options; the entire coating is not pure tin |
| Purchasing price | The same P per metric tonne of complete finished product; matching tax and delivery terms |
| Replacement scope | Round interconnect wire only; unchanged busbar ribbon is excluded |

The 650 W, 132-half-cell, 16BB reference uses the publicly specified JA Solar JAM66D45-650/LB format. The 105 mm coverage input is based on cell dimensions recorded for the same series. This is a geometry budget, not a complete factory BOM for the 650 W model, and does not imply that the brand uses Raytron material.[18][19]

**Count the front and the rear.** Inter-cell ribbon covers different surfaces of adjacent cells; counting only the wires visible in a front photograph misses physical length.[20]

| Length component | Example calculation | m/module |
|---|---|---|
| Front-side coverage | 132×16×105/1000 | 221.76 |
| Rear-side coverage | 132×16×105/1000 | 221.76 |
| Inter-cell crossings | 12 physical strings×10 gaps×16 wires×2 mm/1000 | 3.84 |
| String-end extensions | 12 strings×2 ends×16 wires×10 mm/1000 | 3.84 |
| **Total** | | **451.20** |

Eleven cells per physical string, a 2 mm crossing path and 10 mm at each end are explicit geometric inputs. Actual pad setbacks, bend paths and cutting records take precedence. No arbitrary wastage allowance has been added.

## 10.2 | Calculate the whole coated wire—not only the lighter core

Use densities of 8.960 for copper, 2.705 for aluminum and 8.50 g/cm³ for Sn60Pb40 solder. The first two are Raytron's bare-material calculation constants; the solder value is retained from the manufacturer's physical data. This calculation does not mix in the rounded nominal densities in Section 4.[3][21]

> Substrate area = $\pi \times 0.23^2/4 = 0.041547563$ mm²

> Solder area = $\pi \times (0.26^2 - 0.23^2)/4 = 0.011545353$ mm²

> CCA50 density = $1/(0.5/8.960 + 0.5/2.705) = 4.155473639$ g/cm³

With these units, area in mm² × density in g/cm³ = mass in g/m. Calculate substrate and solder separately, then add them:

| Calculated quantity | Copper-core finished wire | CCA50 finished wire |
|---|---|---|
| Substrate mass, g/m | 0.372266 | 0.172650 |
| Solder mass, g/m | 0.098136 | 0.098136 |
| **Complete finished mass, g/m** | **0.470402** | **0.270785** |
| Solder share of finished mass | **20.86%** | **36.24%** |
| Substrate per module, g | 167.966 | 77.900 |
| Solder per module, g | 44.279 | 44.279 |
| **Finished purchase mass per module, g** | **212.245** | **122.178** |
| Finished length per kilogram, m | 2,125.84 | 3,692.96 |

**Equal solder mass per metre does not mean equal solder content per tonne.** This construction contains approximately 208.62 kg of solder per tonne of copper-core finished wire, versus 362.41 kg per tonne of CCA50 finished wire. The higher solder share and actual manufacturing conditions are already reflected in the finished quotation; do not charge for processing a second time.[22]

The bare substrate is approximately 53.62% lighter, but the solder layer does not shrink with its mass. The complete finished product is **42.44% lighter**. The same weight supplies approximately 73.72% more length—a different denominator, not a 73.72% cost saving.

## 10.3 | Equal price per tonne gives a 42.44% interconnect purchasing saving

Let P be the common price in currency units per metric tonne of complete finished product. For 451.2 m, purchase masses are 0.212245231 kg and 0.122178329 kg:

> Copper purchasing cost/module = $0.212245231 \times P/1000$

> CCA50 purchasing cost/module = $0.122178329 \times P/1000$

> Saving/module = 0.090066902×P/1000

At equal tonne prices and equal net lengths, the common price cancels from the percentage:

> **Purchasing-cost reduction = 1 − 0.122178329/0.212245231 = 42.4353% ≈ 42.44%**

This is the saving on **the replaced round interconnect wire in this construction**.
The denominator is the procurement cost of that wire. Savings above 50% in Section 1 concern different project conditions; this CCA50 example uses its own stated inputs.

## 10.4 | The common tonne price determines the monetary saving

**Every price below is an illustrative input, not a current market price or a formal Raytron quotation.** Per-watt and per-GW results are normalized to the same module count at the original 650 W reference. They do not assume that the new module has already measured 650 W.

| Common price CNY/t | Copper CNY/ module | CCA50 CNY/ module | Saving CNY/ module | Saving CNY/ baseline W | Saving million CNY/baseline GW |
|---|---|---|---|---|---|
| 80,000 | 16.98 | 9.77 | **7.21** | **0.011085** | **11.0852** |
| 100,000 | 21.22 | 12.22 | **9.01** | **0.013856** | **13.8564** |
| 120,000 | 25.47 | 14.66 | **10.81** | **0.016628** | **16.6277** |
| 150,000 | 31.84 | 18.33 | **13.51** | **0.020785** | **20.7847** |

Differences use unrounded calculations. **At an illustrative common price of CNY 100,000/t, the saving is about CNY 9.01/module, CNY 0.01386/baseline W or CNY 13.86 million/baseline GW.** At CNY 150,000/t, it becomes about CNY 13.51/module, CNY 0.02078/baseline W or CNY 20.78 million/ baseline GW. The percentage remains 42.44% at both prices.

A tax-inclusive input produces a tax-inclusive purchasing difference; an ex-tax input produces an ex-tax difference. No tax rate is assumed here, and the two bases must not be mixed.

## 10.5 | Cross-check against tonnes purchased per GW

> Reference module count for 1 GW = $10^9/650$

| Calculated quantity | Copper-core finished wire | CCA50 finished wire |
|---|---|---|
| Interconnect length/baseline GW | Approximately 694.15 million m | Approximately 694.15 million m |
| **Finished purchases/baseline GW** | **326.531 tonnes** | **187.967 tonnes** |

The difference is **138.564 tonnes of finished ribbon per baseline GW**:

> **Saving/baseline GW = 138.564464684 tonnes × P per tonne**

There is no reverse calculation from ribbon's assumed share of module cost, and no substitution of raw-metal value for the customer's purchasing difference. The inputs are geometry or measured linear mass, actual consumption and the complete finished quotation.

### 10.6 | Replace four inputs with your own order data

Use your own **finished linear mass, actual net consumption, complete finished price per tonne and measured module power**. Monetary savings in the equal-price case scale linearly with the common price. When actual quotations differ, enter both:

> Saving/module = (copper finished kg/module × copper price/t − CCA finished kg/module × CCA price/t)/1000

> Ribbon saving/delivered W = old ribbon purchase cost/module ÷ old measured watts − new ribbon purchase cost/module ÷ new measured watts

Multiply the second result by $10^9$ to obtain **ribbon-item savings for delivery of the same measured 1 GW**. This still does not establish total module manufacturing savings or profit. Those require actual BOM, manufacturing costs and accepted output on the same scope.

Handle returns, recoverable scrap, startup loss, rework and rejects consistently. Do not apply a second yield factor after calculating from actual net consumption and accepted output. Do not transfer the approximately 3 W difference from a separate 0.24 mm project into this 0.26 mm model.

No material-change surcharge is added, and no throughput, maintenance, energy or yield benefit from disabling flattening is booked in advance. **For the TOPCon route, the original local flattening operation must still be disabled/bypassed; record any demonstrated process saving separately.**[2]

## 11 | The "about 3 W on a 650 W module" example

Raytron has provided a TOPCon project comparison involving **650 W-class modules, nominal 0.24 mm CCA ribbon and nominal 0.24 mm copper ribbon, with an approximately 3 W power difference**. Relative to 650 W, that is approximately **0.46%**.[2]

The useful lesson is that conductor resistance does not translate proportionally into total module-power loss. It is not a universal result for all modules, copper fractions, diameters and solder systems—or a guarantee that the maximum loss is 3 W. The project summary does not provide the complete sample set, copper fraction or substrate-versus-finished diameter definition, so it is not used as the geometry input in Section 7. Nor is its approximately 3 W difference transferred into the 0.26 mm finished-wire cost case in Section 10.

Use a correct recipe for each material. In the TOPCon CCA round-wire route covered here, local flattening must be disabled/bypassed. "Identical conditions" must not mean retaining an inappropriate copper operation for the composite.[2]

Choose the route that best fits the project constraints:

| Route | Relevant constraint | Evaluate success through |
|---|---|---|
| Start with existing geometry | Limited freedom to change equipment, positioning or drawings | Actual module power, joining, yield and cost |

| Route | Relevant constraint | Evaluate success through |
|---|---|---|
| Resize to a resistance target | A defined resistance budget with dimensional flexibility | Shading, pads, stress and equipment fit as well as resistance |
| Co-design the interconnection | Cell/module architecture can be modified | Copper fraction, shape, wire count, routing and coating together |

For a bare, uniform substrate calculation only, changing resistivity from 0.017241 to 0.025 gives an equal-resistance composite diameter of approximately 0.289 mm in place of 0.24 mm copper. **This is a calculation starting point, not a recommendation to enlarge every 0.24 mm PV interconnect to 0.289 mm.** Coating, distributed current and optical effects still belong in the real design.

## 12 | Sampling to production: five stages, not one impressive sample

The following is a suggested project workflow, not a standard-mandated sample size or timetable.

| Stage | Work | Evidence before moving on |
|---|---|---|
| Align requirements | Fix the module, reference ribbon, constraints and objectives | One-page specification and acceptance objectives |
| Inspect the material | Dimensions, resistance/metre, copper and solder layers, tensile behavior and payoff | Sample identification and measured results |
| Establish the process | Confirm local flattening is disabled/ bypassed for the TOPCon CCA route; establish feeding and joining settings | Recipe/flattening-state record, joints and EL controls |
| Validate modules | Matched builds, power and reliability evaluation | Reports, explained differences and approved application scope |
| Pilot and production | Multiple reels/batches at actual throughput; complete change approval | Approved sample, controlled drawing, control plan and traceability |

Keep cell source, power/current sorting, thickness, encapsulation materials and important process conditions comparable. Both copper and composite controls should use reasonable, fully recorded settings—not intentionally unfavorable settings for one option.

Power comparisons should address calibration, temperature, spectrum, measurement repeatability and uncertainty. Preserve individual-module distributions rather than selecting the best sample. IEC 60904-1 is the reference entry point for I–V measurement procedures.[6]

Sample counts, batches, test duration and release limits belong to the customer's quality and certification plan. A supplier's reel of sample wire cannot substitute for complete module approval.

## 13 | Reliability: not only "does it hold?", but "what happens afterwards?"

Plan checks around actual failure mechanisms, then establish test conditions through the applicable standards and certification plan.[7][8][9]

| Check / test | Main question | Recommended records |
|---|---|---|
| Copper–aluminum and coating cross-sections | Local thin spots, cracking, separation or abnormal interfaces? | Scaled images, location and interpretation |
| Wetting and joint peel | Does this material/solder/ metallization combination produce stable joints? | Angle, speed, temperature, units, force distribution and failure location |
| EL and I–V | New cracks, connection abnormalities or power change? | Comparable before/after images and electrical data |
| Thermal cycling, TC | Do joints and connections survive repeated expansion and contraction? | Power, resistance, EL, appearance and destructive analysis where needed |
| Damp heat, DH | Are interfaces, encapsulation and connections stable in humid heat? | Power, resistance, corrosion and contact condition |
| Humidity-freeze, mechanical loading and other relevant tests | Problems under the specified environment or mechanical stress? | Records using the agreed sequence and criteria |
| Insulation, wet-leakage and other safety evaluation | Does the change affect module safety? | Reassessment within the applicable certification scope |

"Peel force: 1 N" has limited value without a method. Separate 90° from 180°, individual wires from bundles, N from N/mm, and averages from minima. Record whether failure occurred in the solder interface, metallization, ribbon or silicon.

Short accelerated tests are not a direct conversion into years of outdoor use. IEC 61215 design-qualification results are not a quantitative prediction of module lifetime.[7] State the model, bill of materials, tests and results clearly; do not turn one report into a lifetime passport for every specification.

## 14 | Incoming acceptance: make the certificate match the reel

Initial supplier approval examines capability and systems. Batch release also needs evidence about the delivered material. A technical data sheet defines the delivery requirements; a batch inspection record reports what was measured on that batch.[1][10]

| Acceptance item | Check |
|---|---|
| Identity and traceability | Grade, core, coating, drawing revision, batch and reel numbers agree. |
| Dimensions and appearance | Sample agreed positions; check diameter/thickness/ width, solder beads, scratches, oxidation and missing coating. |

| Acceptance item | Check |
|---|---|
| Electrical | Record temperature and effective length; evaluate finished resistance/metre and variability. |
| Copper and solder layers | Inspect fractions, minimum local thickness, coverage and interfaces according to the control plan. |
| Mechanical | Compare tensile strength, Rp0.2 and elongation using consistent gauge-length and area conventions. |
| Payoff and packaging | Reel, winding, splices, net mass, length, vacuum seal and transport damage. |
| Documents | Batch report, applicable declarations and other contract-required evidence. |

Missing solder exposing copper, unintended copper-cladding damage exposing aluminum, and an exposed core at a cut end are different conditions. Photographs and agreed defect samples often communicate acceptance criteria better than vague adjectives.

Define sample quantities, rejection criteria, retesting and the dispute laboratory in the order or inspection plan. This guide does not impose one arbitrary AQL on every product.

## 15 | Production troubleshooting: investigate before assigning blame

These are suggested investigation priorities, not diagnoses made from a symptom alone.

| Symptom | Check first |
|---|---|
| More wire breaks | Actual diameter, breaking force, tension, damaged guides, reel snags and splices |
| Misalignment or poor conformity | Camber, springback, positioning, tooling, winding and tension variation |
| Poor wetting or weak joints | Surface condition, solder, flux, actual temperature and time |
| Lower peel results | Failure location, metallization, solder volume and process changes |
| New cell-edge cracks in EL / local aluminum exposure | In the TOPCon substitution, first confirm local flattening is actually disabled/bypassed; then check cell thickness, tooling, tension, thermal history and routing |
| Lower module power | First verify measurement and cell sorting, then material resistance, joints, alignment and optical effects |
| Resistance drift after aging | Cross-section/joint damage, corrosion paths, encapsulation and process changes |

| Symptom | Check first |
|---|---|
| Reel-to-reel variation in one batch | Batch definition, within-/between-reel sampling, dimensions, coating distribution and payoff conditions |

Retain an affected reel, a normal comparison reel and the actual process records. That is usually more useful than sending a photograph with the message "please explain".

## 16 | Packaging, storage and delivery: do not lose good material in the warehouse

Rev.4 specifies a clean, dry store without corrosive chemicals, at ≤35°C and ≤60% relative humidity. Under its stated constant-temperature, dry indoor conditions, shelf life is six months unopened under vacuum and three months after opening. Special solders, packaging and customer conditions follow the corresponding order; these periods are not a universal shelf-life claim for all coatings.[1]

Use first-in, first-out control and record opening dates. Moisture exposure, failed vacuum packaging or abnormal storage should trigger the quality procedure, even if the nominal expiry date has not arrived. When cold reels enter a warm humid area, avoid condensation when opening them.

Reels must fit the payoff equipment. Confirm bore, outside diameter, width, winding direction, winding pattern and allowable net mass. "A 160 reel" is not a complete drawing. Continuous length and splice policy also deserve a place in the RFQ.

For international orders, align currency, tax treatment, trade terms, freight, metal-pricing date and delivery location. Composite ribbon also contains solder and processing cost; a simple weighted copper-and-aluminum price is not a finished-product quotation.

## 17 | Standards and market access: separate material, module and application

| Document | Main purpose | Purchasing use |
|---|---|---|
| Raytron specification and customer technical agreement | Material delivery requirements | Lock grade, geometry, temper, coating and acceptance. |
| GB/T 31985-2015 | PV tin-coated ribbon product standard | Official catalog checked as current; examine the complete scope rather than assuming all CCA products are covered. |
| IEC 61215 series | Module design qualification and type approval | Evaluate the specified module construction. |
| IEC 61730 series | Module safety | Review construction and safety-test requirements. |
| IEC TS 62915:2023, with 2024 corrigendum | Retesting following module design/ material changes | Agree the relevant retesting with the certification body. |
| IEC 60904-1:2020 | PV-device I–V measurements | Establish the measurement-method reference. |

| Document | Main purpose | Purchasing use |
|---|---|---|
| IEC 62941:2019 | Module-manufacturing quality system | Control material selection, change and production consistency. |

These scope descriptions come from official public information, not a substitute for controlled standards. The official catalog reviewed for this guide lists the GB/T 31985 revision project **20264584-T-339** as being drafted. A work item is not an implemented replacement standard.[6–12]

When a customer specifies an association standard, obtain its **identifier, publisher, edition, implementation status and complete text** before adding it to the agreement. An "alloy ribbon" label, a patent or a draft document is not product certification.

### Lead, lead-free requirements and export markets

First establish composition; then check the final product, destination and customer contract. EU RoHS excludes certain PV panels intended for professionally designed, assembled and installed systems for permanent use at a defined location. This is not a worldwide exemption for every lead-containing ribbon. Lead-free declarations, other chemical obligations, occupational health and customer restricted-substance lists remain separate matters.[13]

ISO 9001 addresses a quality-management system, not the module qualification of an individual ribbon. A material or module report does not automatically cover every geometry, factory, solder or market. For North American and other projects, follow the actual certification and material-change procedure.[8][14]

## 18 | How to request quotations and compare suppliers

For the first conversation, send six things: **cell/module design, connection position, current specification, non-negotiable constraints, target market and approximate volume.** A drawing or sample is usually more useful than ten adjectives.

Complete the following when the project moves into formal selection.

| Topic | Information to provide |
|---|---|
| Module | Model, power target, cell dimensions/thickness/sorting, interconnect count and routing |
| Material | Candidate CCA or HTCCA, copper fraction convention, core and temper |
| Geometry | Substrate and finished diameter/thickness × width, tolerances, corners and minimum copper thickness |
| Coating | Alloy, single-side thickness, lead/lead-free requirement and flux |
| Electrical and mechanical | Finished resistance/metre, reference temperature, tensile, Rp0.2, elongation and test conditions |
| Production | Stringer, throughput, tension, thermal profile, pads/tooling; ability to disable/bypass local TOPCon flattening and the confirmed setting |

| Topic | Information to provide |
|---|---|
| Validation | Baseline, sampling plan, power, EL, peel, reliability and release criteria |
| Delivery | Sample amount, monthly demand, continuous length, reel, splice policy and destination |
| Commercial and documentation | Pricing basis, validity, traceability, inspection report, certificate scope and change notification |

**Copy-ready RFQ:**

> We manufacture _____ modules using _____ cell/interconnection technology. The material to be replaced is located at _____; the current specification is attached. Dimension _____ refers to the substrate, and _____ to the finished coated product. We cannot change _____, but may adjust _____. Our main objective is _____. Stringer and target throughput: _____. Local-flattening disable/bypass status: _____. Destination market: _____. Estimated monthly demand: _____. Please propose a material/coating combination and provide finished resistance per metre, mechanical properties, cross-section and sampling information, packaging, and a quotation on matching delivery terms.

Compare suppliers on four practical points: **clear specifications, identifiable samples, repeatable production and reliable change notification**. Actual batch cross-sections and inspection data are more useful than "high conductivity, high strength, high reliability".

Specify that changes to core material, copper fraction, solder or agreed critical production conditions require approval. Define deviation approval, issue handling, retained samples and affected-batch traceability. Use the customer's established quality process rather than building a new maze of forms.[10]

# 19 | Buyer FAQ

## Does it necessarily reduce module power?

The material name alone cannot answer that. Same-size resistance may increase, but the module result also depends on architecture, joining and optics. Compare matched power distributions. The 3 W project example is a reference, not a universal answer.

## Is a higher copper fraction always safer?

It affects conductivity, cladding and cost, but does not replace minimum-thickness, bonding or finished-module validation. Select a combination that meets the requirements—not simply the largest number.

## Does the aluminum core carry no current?

It carries current. Under DC conditions, both metals conduct. PV selection should not rely on an "all current in the copper skin" claim.

## Can matching size and color justify a direct substitution?

They may provide a geometric starting point, not production approval. Verify substrate/finished definitions, resistance, mechanics, coating composition and line performance.

### Is HTCCA automatically suitable for higher temperatures?

No temperature rating follows from the abbreviation. It is a specified alloy-core series; thermal performance and reliability concern the complete material and module construction.[1][3]

### Does TOPCon still need local flattening after switching to Raytron round CCA ribbon?

**No. The original local flattening operation MUST be disabled or bypassed.** Raytron's Chinese customer feedback indicates greater compliance at the cell edge for this aluminum-core route, making the copper flattening action unnecessary. Retaining it can also damage the cladding. Application compliance does not mean every tensile property of every grade is lower.[2][16]

### Can disabling flattening immediately be booked as an extra saving?

This edition does not assign it a monetary benefit, and does not invent a material-change fee. Record any actual throughput, energy, maintenance or yield improvement when measured; do not assume the same amount for every line.

### Does copper cladding make corrosion impossible?

No. Evaluate cut ends, defects, moisture, residues and encapsulation together. Good cladding and encapsulation are design measures, not a reason to omit validation.

### Do damp heat and thermal cycling prove an arbitrary lifetime?

They do not directly convert into years. They support evaluation of the tested construction; field environment and manufacturing consistency also matter.[7]

### Does the existing module certificate automatically remain valid?

Follow the material-change procedure and agree the assessment with the certification body. The ribbon supplier cannot declare this unilaterally.[9]

### How can equal prices per kilogram still produce savings per module?

The same connection length requires less finished purchase mass. Including the complete solder coating, Section 10 calculates 0.270785 g/m for CCA50 and 0.470402 g/m for copper. Equal prices per tonne and equal net lengths give approximately 42.44% lower purchasing cost. Calculate monetary savings from actual finished quotations and consumption; do not add processing charges already included in the price.

### Does less copper mean the same percentage reduction in carbon emissions?

No. Material sourcing, energy, manufacturing and transport affect the footprint. A public carbon-reduction claim needs a defined assessment boundary and data, not a renamed weight-saving percentage.

### Can we change only the busbar ribbon and retain existing interconnect wire?

That can be evaluated as a separate project. Recalculate the collection circuit, joints and power, while still following the applicable module-change requirements.

## 20 | Turn a reel of material into an approvable solution

Selecting composite PV ribbon is not procurement searching alone for "cheaper copper". It is procurement, engineering and quality finding **a better-value interconnection material for this module**.

Send Raytron your current drawing or sample, cell/module design, connection position, destination market and approximate volume. Begin with the actual constraints; compare substrate, copper cladding, coating, geometry, process and cost, and define what the trial must demonstrate.

**Explain the material clearly. Make the sample properly. Let accepted modules and cost data make the decision.**

**Engineering Every Micron.**

## Quick glossary

| Term | Meaning in this guide |
|---|---|
| µm | Micrometre: 1 µm = 0.001 mm. Radial coating thickness is not the total diameter increase. |
| %IACS | Conductivity relative to the International Annealed Copper Standard—not a percentage of current-carrying capacity. |
| EL | Electroluminescence imaging, used to help identify cell cracks and connection anomalies. |
| I–V | Current–voltage characteristics, used to evaluate electrical performance and power. |
| BOM | Bill of materials: the specific cells, ribbon, encapsulation and other components, not just a model name. |
| TC / DH | Thermal cycling / damp-heat tests. Conditions and criteria follow the applicable test plan. |
| Rp0.2 | 0.2% proof stress: the stress associated with 0.2% permanent plastic extension. |
| MBB / SMBB / 0BB | Multi-busbar / super-multi-busbar / no conventional cell busbar. These labels alone do not specify the ribbon. |
| Finished resistance / mass per metre | Electrical resistance / mass of a unit length after coating—key inputs for comparing materials. |
| Yield | Accepted output divided by input. State the process boundary and denominator to avoid double-counting losses. |

# References and data notes

Document version 1.2. Cost-model update: 6 November 2026. This revision incorporates the confirmed equal-finished-price calculation; other references retain the preceding edition's verification record. Company information, specification values and calculation scenarios are identified separately. Obtain original reports, current order specifications and controlled standards for the project.

[1] Raytron, *PV Interconnect Ribbon and Busbar Ribbon Technical Specification*, Spec201910 Rev.4, released 15 September 2026. Principally §§3.1, 3.3–3.7, 4–5. Request the applicable controlled version from Raytron; the source file is not republished here.

[2] Raytron project/application records, as of November 2026: more than 50% ribbon material-cost reduction in some projects; application in modules totaling more than 50 GW; BC/TOPCon use; approximately 3 W difference in a 650 W-class TOPCon comparison using nominal 0.24 mm ribbon. Also includes the company's confirmation of feedback from numerous Chinese module customers: the applicable TOPCon round CCA ribbon is more compliant at cell edges, and the original local copper-ribbon flattening operation can and must be disabled/bypassed. These process instructions cover the ribbon construction and TOPCon process described above.

[3] Raytron, *Untinned CCA Round Wire / Flat Wire / Strip Technical Specification*, Spec-CCA-UNTINNED Rev.2, 17 June 2026, §3.1. Used for terminology, copper-weight convention and conversion constants—not as the electrical delivery specification for coated PV ribbon.

[4] Grübel, De Rose and Kraft, Fraunhofer ISE, *Challenges for Solder Interconnection Pushed by High-Efficiency Solar Cell Developments*, EU PVSEC 2024. General interconnection research, not Raytron product testing. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/conference-paper/41th-eu-pvsec-2024/Gruebel_Paper.pdf

[5] Fraunhofer ISE, *Interconnection Technologies*. Background on interconnect forms, processes and thermomechanical stresses. https://www.ise.fraunhofer.de/en/business-areas/photovoltaics-production-technology-and-transfer/interconnection-and-encapsulation-technologies/interconnection-technologies.html

[6] IEC 60904-1:2020, *Measurement of photovoltaic current-voltage characteristics*. Official public scope. https://webstore.iec.ch/en/publication/32004

[7] IEC 61215-1:2021, *Terrestrial photovoltaic modules — Design qualification and type approval*. Official public scope and lifetime interpretation. https://webstore.iec.ch/en/publication/61345

[8] IEC 61730-1:2023, *Photovoltaic module safety qualification — Requirements for construction*. Testing is covered by the companion IEC 61730-2. Official public scope. https://webstore.iec.ch/en/publication/59803

[9] IEC TS 62915:2023, *Photovoltaic modules — Retesting*. The official page identifies the incorporated 2024 corrigendum. https://webstore.iec.ch/en/publication/66172

[10] IEC 62941:2019, *Quality system for PV module manufacturing*. Official public scope. https://webstore.iec.ch/en/publication/61932

[11] China's official national-standard publication system, GB/T 31985-2015, *Tin-coated copper ribbon for photovoltaic application*. Status/catalog record. https://openstd.samr.gov.cn/bzgk/std/newGbInfo?hcno=A512A0E3C743198D490A382ACB13BFA2

[12] China's National Public Service Platform for Standards Information, revision work item 20264584-T-339, *Tin-coated copper ribbon for photovoltaic modules*. A work-item status, not a replacement standard text. https://std.samr.gov.cn/gb/search/gbDetailed?id=5A7BF2612B688434E06397BE0A0AC1BB

[13] EU Directive 2011/65/EU, consolidated text of 1 July 2026, Article 2(4)(i). Determine scope for the actual product and project. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02011L0065-20260701

[14] UL Solutions, *UL1703 / UL 61730 — PV Module Safety Standards Updates: Making the Transition*. Bill-of-materials changes and retesting context. https://www.ul.com/news/ul1703-ul-61730-pv-module-safety-standards-updates-making-transition

[15] Raytron PV Ribbon product scope and contact entry point. Actual supply combinations follow the confirmed order specification. https://www.raytron.group/products/pv-ribbon/ https://www.raytron.group/contact/

[16] InfoLink Consulting, Kyle Lin and Derek Zhao, *Solar back-contact technology: Industry progress and outlook of xBC*, 19 May 2025. Retained for the historical risk of aluminum exposure during local flattening of fine TOPCon composite wire; its BC cost figures are not inputs to this edition's TOPCon savings. https://www.infolink-group.com/energy-article/solar-topic-solar-back-contact-technology-industry-progress-outlook--xbc

[17] Anhui Daheng Energy Technology Co., Ltd., CN113042973A, PV-module ribbon in-line flattening/soldering method, published 29 June 2021. Technical background on local flattening, inter-cell stress and edge cracking—not a Raytron certification or a patent-law opinion. https://patents.google.com/patent/CN113042973A/en

[18] JA Solar, JAM66D45-625–650/LB official data sheet, Aus-EN-20250711A. 650 W, 132 half-cells, 6×22 and 16BB as format references only; retained from the detailed model's source record. No implication that the brand uses Raytron material. https://www.jasolar.com/uploadfile/fujian/2025/0718/cb4feec76c9f3a.pdf

[19] Kiwa PVEL 2025 same-series model record. The 182×105 mm cell size is from a 580–625 W entry in the series, not a complete factory BOM obtained for the 650 W reference. https://scorecard.pvel.com/2025/top-performers/

[20] Hysolar official manufacturing-process explanation. Used for front/rear inter-cell coverage and 16-wire SMBB principles, not an exact cutting list for the reference brand. https://module.hysolar.com/hygn

[21] CYNEL, Sn60Pb40 PRO technical data sheet. Only the solder-alloy density of 8.50 g/cm³ is retained; its flux-containing product parameters are not substituted for a Raytron PV coating specification. https://www.cynel.com.pl/images/products/enpdf/Sn60Pb40-PRO.pdf

[22] Raytron-supplied commercial basis and confirmation: 0.26 mm is the coated finished diameter; finished weight-based prices are often close, and the model explicitly assumes equal tonne prices. Solder mass share, coating throughput and processing are reflected in the complete quotation, not added a second time. The 15 µm coating and 451.2 m consumption remain model inputs; all price tiers are illustrative.