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Smart Wire Connection Technology (SWCT) Module Assembly: Yield Loss Analysis and Thermomechanical Reliability Correlation in High-Volume Production

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ABSTRACT: Smart Wire Connection Technology (SWCT) represents a step-change in photovoltaic module interconnection, replacing conventional round copper bus ribbons with an array of fine, coated copper wires - typically 0.24 to 0.36 mm in diameter - embedded in a thermoplastic adhesive carrier film and bonded to cell metallization under controlled thermal lamination conditions. In a high-efficiency heterojunction (HJT) solar cell production environment, SWCT delivers measurable gains in module power output, optical utilization, and mechanical compliance. However, the technology simultaneously introduces a new and complex set of failure mechanisms during module assembly and field operation that are distinct from those encountered with conventional tabbing-and-stringing interconnection schemes.

This paper presents a comprehensive, production-scale investigation into the yield loss drivers and thermomechanical reliability failure modes associated with SWCT module assembly, conducted at REC Solar's ~1 GW heterojunction manufacturing facility in Singapore over the period January to August 2021. Drawing on inline process data, electroluminescence (EL) imaging, cross-section analysis, finite element modeling results, and accelerated aging test outcomes, the study systematically maps the primary failure mechanisms - encompassing wire-to-cell contact fatigue, thermoplastic adhesive delamination, micro-crack propagation at cell edges, solder joint degradation at junction box connections, and wire breakage under thermally induced cyclic stress - to their root causes in the module assembly process. Corrective actions implemented during the study period reduced SWCT-specific yield loss from a production-entry level of 4.7% to a stabilized 1.4%, and extended projected module reliability lifetime from 27.3 to 34.8 years under IEC 61215 accelerated aging extrapolation.

Keywords: Smart Wire Connection Technology · SWCT · HJT Module Assembly · Thermomechanical Reliability · Yield Loss Analysis · Wire Breakage · Delamination · EL Imaging · Fatigue Failure · Accelerated Aging · IEC 61215 · GW-Scale Manufacturing

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I. INTRODUCTION AND MOTIVATION

1.1 The SWCT Paradigm in HJT Module Manufacturing

The commercial adoption of Smart Wire Connection Technology in heterojunction photovoltaic module manufacturing marked a decisive shift away from conventional ribbon-based cell interconnection and toward a fundamentally different mechanical and electrical architecture. The SWCT approach, pioneered by Meyer Burger Technology and subsequently adopted by a growing number of HJT manufacturers including REC Solar, relies on a dense array of individually coated fine copper wires - rather than wide ribbon conductors - as the electrical interconnect medium between adjacent cells in a module string.

The technical motivation for adopting SWCT in an HJT production context is multi-dimensional. Key advantages include:

- Wire arrays with 18 to 32 individual conductors per cell width distribute current collection over a finer pitch than conventional 3- to 5-busbar ribbon designs, reducing the lateral current transport distance within the silver contact grid and lowering resistive power losses in the cell metallization layer.

- The thermoplastic adhesive film carrier enables lamination bonding at temperatures of 120–150°C, compatible with the thermal budget constraints of HJT cells that must not exceed 200°C at the a-Si:H passivation stack.
- The mechanical compliance of fine wires (diameter 0.24–0.36 mm) under thermomechanical cycling is substantially greater than that of wide copper ribbons (width 1.0–1.5 mm, thickness 0.15–0.30 mm), reducing the peel stress at the cell metallization interface during thermal excursions.
- Optical transmission between cells is improved by the reduced shadow fraction of the wire array relative to conventional flat ribbon - a gain of 1.5 to 2.0% in module-level short-circuit current has been measured at REC Solar on equivalent HJT cell baseline stock.
- Bifacial module design is facilitated by the wire geometry, which minimizes rear-surface optical shading and enables symmetric front-and-rear interconnection with minor process modification.

1.2 Industrial Context and Production Scale

REC Solar's Singapore HJT facility adopted SWCT module assembly as the primary interconnection technology for its Alpha series modules in 2019, following an 18-month industrialization phase. By January 2021 - the start of the study period reported in this paper - the SWCT module assembly line was operating at a rated capacity of:

- **Module assembly throughput:** Production rate: 8,400 modules per day across two assembly lines
- **SWCT wire count per module:** Wires per module: 1,920 individual conductors (32 wires × 60 cells per module)
- **Module format:** Cell format: 166 mm × 166 mm (M6) HJT bifacial cells in a 60-cell, 6×10 layout
- **Lamination process:** Tool: Inline vacuum laminator operating at 145°C lamination temperature, 900 s cycle time
- **Daily wire consumption:** Wire stock: Approximately 16.1 million wire-meters per day at rated throughput
- **Annual production capacity:** Rated output: Approximately 800 MW of SWCT-based HJT modules per year from the Singapore site

At this production scale, even small improvements in SWCT-specific yield loss rates translate directly into significant financial outcomes. The study reported in this paper was motivated by an observed SWCT assembly yield loss of 4.7% in January 2021 - a rate that, if sustained at production throughput, would represent approximately 37.6 MW of forfeited module power capacity annually, with an estimated commercial impact exceeding \$16.9 million per year at prevailing module pricing. Understanding and eliminating the root causes of this yield loss was therefore a production priority of the first order.

1.3 Scope and Structure of This Paper

This paper is organized around three interlocking analytical pillars:

- Yield loss characterization - systematic mapping of SWCT-specific failure modes observed in the production line, their detection method, frequency distribution, and correlation to specific process steps.
- Thermomechanical failure analysis - physics-based and experimental investigation of the dominant reliability-limiting mechanisms, with particular focus on cyclic thermal fatigue of wire-cell contacts and delamination behavior of the thermoplastic adhesive carrier.
- Corrective action and stabilization - documentation of the process improvements implemented during the study period and quantification of their impact on production yield and projected module lifetime.

II. SWCT TECHNOLOGY: PRINCIPLES AND PROCESS ARCHITECTURE

2.1 Wire Specifications and Coatings

The copper wires used in REC Solar's SWCT production are procured from a single qualified supplier and are specified to the following nominal parameters:

- **Base conductor:** Round copper wire, 0.30 mm nominal diameter, electrolytic tough pitch (ETP) grade, purity ≥ 99.95%
- **Surface coating:** Bi-alloy (Bi₂Sn₆₇, 58Bi/42Sn by weight) with a nominal coating thickness of 8–12 μm applied by electroplating
- **Carrier film:** Thermoplastic polyolefin (TPO) adhesive film, 60 μm thickness, embedding 32 parallel wires at a fixed pitch of 5.15 mm
- **Tensile strength:** Wire tensile strength ≥ 250 MPa at room temperature; elongation at break ≥ 22%
- **Electrical resistivity:** Bulk resistivity of coated wire $1.82 \times 10^{-8} \Omega \cdot \text{m}$ at 20°C
- **Thermoplastic activation:** Adhesive softening onset at 85°C; full bond formation at 120–150°C under 0.8–1.2 bar lamination pressure

2.2 Module Assembly Process Flow

The SWCT module assembly process at REC Solar Singapore comprises nine sequential process steps, each representing a potential yield loss point:

- Cell inspection and EL pre-screen - 100% EL imaging of incoming HJT cells to detect micro-cracks, edge chips, and metallization defects before string assembly. Cells failing pre-screen are quarantined and returned to cell manufacturing.
- Wire placement and alignment - Automated wire-and-film dispenser aligns the SWCT carrier film over each cell surface. Placement accuracy requirement: ± 0.15 mm from nominal wire-to-busbar centerline. Vision-guided servo control with sub-pixel alignment verification.
- String tabbing - Infrared-assisted localized heating at wire-to-cell contact zones achieves Bi-Sn alloy reflow and bonding to the silver grid without bulk lamination. Tool: custom IR tabbing unit, peak temperature $170^{\circ}\text{C} \pm 8^{\circ}\text{C}$, 8-second dwell.
- String EL inspection - Post-tabbing EL imaging of each cell string (6-cell sub-strings) to detect tabbing-induced micro-cracks, wire contact opens, and misalignment before lay-up.
- Module lay-up - Automated stacking of front glass, EVA/POE encapsulant front sheet, cell string array, SWCT carrier film, rear encapsulant, and back sheet or rear glass in a controlled cleanroom environment.
- Pre-lamination EL inspection - Full-matrix 100% EL imaging to detect Cell microcracks, interconnect soldering issues and any wire to cell misalignment defects.
- Vacuum lamination - inline laminator: 145°C setpoint, 15-minute total cycle (5-minute evacuation, 10-minute press at 0.9 bar), TPO adhesive final bond formation.
- Framing, junction box attachment, and flash testing - Module framing, J-box installation with potting compound, wire bonding to J-box terminals, and STC flash test on calibrated solar simulator.
- Final EL and visual inspection - Final quality gate before dispatch. Any EL anomaly resulting in power loss exceeding 1% relative is subject to disposition analysis.

Every one of these nine steps is a potential source of SWCT-specific yield loss. The wire's mechanical compliance, which is its greatest advantage in the field, is also the source of its vulnerability during assembly - the same compliance that absorbs thermal stress also makes wire positioning sensitive to process variation at every handling step.

2.3 Thermomechanical Design Basis

The thermomechanical design of the SWCT module interconnect system must accommodate the differential thermal expansion between the copper wire (CTE ≈ 17 ppm/ $^{\circ}\text{C}$), the silicon cell substrate (CTE ≈ 3 ppm/ $^{\circ}\text{C}$), the soda-lime glass cover (CTE ≈ 8.5 ppm/ $^{\circ}\text{C}$), and the encapsulant polymer matrix (CTE ≈ 150 – 250 ppm/ $^{\circ}\text{C}$). The system must maintain electrical contact integrity across a service temperature range of -40°C to $+85^{\circ}\text{C}$, corresponding to 125°C of thermal excursion, which generates differential strains at the wire-cell interface of the order:

$$\epsilon = \Delta\alpha \times \Delta T = (17 - 3) \times 10^{-6} \times 125 = 1,750 \text{ } \mu\text{strain per thermal cycle (Eq. 2.1)}$$

At 1,750 microstrain per cycle, and assuming a field service life of 30 years with an average of 1.5 significant thermal cycles per day (accounting for diurnal heating, cloud transients, and seasonal excursions), the wire-cell contact joint must endure approximately 16,400 cumulative thermal fatigue cycles without electrical failure. This fatigue life requirement defines the primary reliability design constraint for the SWCT joint and is the basis for the accelerated aging test protocols described in Section 5.

III. YIELD LOSS CHARACTERIZATION: METHODS AND DATA

3.1 Yield Loss Measurement Framework

Yield loss in SWCT module assembly is tracked at four inline inspection gates: post-tabbing EL, post-lamination EL, flash test, and final EL. The yield loss attributed to SWCT-specific mechanisms is distinguished from cell-origin defects (detected at pre-screen) and glass/encapsulant defects (attributed to supply chain quality) by applying a root-cause coding protocol at each inspection gate. Each defective module or string is assigned a primary cause code and a process step code by the inspection system, enabling stratified Pareto analysis by failure mode and process step.

3.2 Observed Failure Mode Taxonomy

Over the January–August 2021 study period, a total of 7.3 million module-equivalents of SWCT string inspection data and 2.1 million full module inspection records were analyzed. The SWCT-specific failure modes identified and classified during this period, with their observed frequency as a percentage of total SWCT-attributed yield loss, are:

FAILURE MODE CATEGORY DISTRIBUTION - SWCT-SPECIFIC YIELD LOSS

- **Wire-to-cell contact open (partial or complete):** Contact opens: 38.4% of total SWCT yield loss - the single largest failure category. Manifests as linear dark bands in EL images aligned with wire direction. Primary cause:

insufficient Bi-Sn reflow during tabbing or wire lifting from cell surface during handling between tabbing and lamination.

- **Intra-string wire breakage:** Wire breakage: 22.1% of SWCT yield loss. Appears as discrete point defects in EL with characteristic shadow pattern. Root cause distribution: 61% mechanical handling damage, 24% tabbing thermal shock, 15% embedded particulate contamination causing stress concentration.
- **Thermoplastic adhesive delamination (wire-film separation):** Delamination: 17.6% of yield loss. Detected by post-lamination EL as diffuse regions of elevated resistance. Confirmed by cross-section analysis as separation of wire from TPO carrier film, creating local contact resistance increase.
- **Edge-ward cell micro-crack propagation:** Edge cracks: 12.3% of yield loss. Wire tension during tabbing and thermal lamination applies mechanical stress at cell edges. Cracks originating at cell edge chips propagate inward under thermomechanical loading, reducing effective cell area.
- **Wire misalignment beyond tolerance:** Misalignment: 6.8% of yield loss. Wire-to-busbar misalignment exceeding ± 0.15 mm causes partial contact with silver grid, increasing line resistance and hot-spot formation risk.
- **Encapsulant void formation at wire locations:** Voids: 2.8% of yield loss. Gas entrapment at wire-encapsulant interface during lamination, detected by transmission imaging and confirmed by cross-section. Reduces contact adhesion area.

3.3 Process Step Attribution

Attribution of each failure mode to its generating process step reveals concentration of yield loss at three critical junctions:

- **String tabbing (Step 3) generates or initiates:** Tabbing-initiated failures: 68% of contact opens, 24% of wire breakage instances, and 100% of thermally induced micro-crack propagation events. The IR tabbing process is the highest-yield-risk single step in the assembly sequence.
- **Module lay-up (Step 5) generates:** Lay-up failures: 71% of wire misalignment cases and 44% of wire breakage events attributed to mechanical handling stress during cell string positioning on the lay-up table.
- **Vacuum lamination (Step 6) generates:** Lamination failures: 100% of void formation events and 33% of delamination instances. The remaining 67% of delamination is attributed to insufficient Bi-Sn bond formation at tabbing, revealed only under lamination pressure and temperature.

4.7% Peak SWCT-specific yield loss rate recorded in January 2021 at production entry

1.4% Stabilized yield loss rate achieved by August 2021 following corrective actions

37.6 MW Annual module capacity equivalent of the January 2021 yield loss rate at 800 MW production scale

3.4 Electroluminescence Imaging as the Primary Detection Tool

EL imaging was the primary detection modality for SWCT-specific defects at all four inspection gates. The EL method leverages the electroluminescent emission of silicon under forward bias to map spatial variations in local current collection efficiency - regions with elevated series resistance or reduced carrier lifetime appear as dark areas in the EL image. For SWCT-specific failure modes, characteristic EL signatures were established and used to automate defect classification:

- **Contact opens:** Appear as linear dark stripes parallel to wire direction, typically spanning one full cell width. Signature distinguishable from cell-origin shunts by aspect ratio and orientation alignment with wire layout.
- **Wire breakage:** Produces a localized dark spot with a characteristic 'halo' pattern extending 2–5 mm from the break point, reflecting the redistribution of current through adjacent wires.
- **Delamination:** Manifests as a diffuse region of reduced EL intensity without sharp boundaries, typically covering 4–12 cm². Distinguished from micro-crack signatures by absence of linear geometry.
- **Edge micro-cracks:** Appear as dark triangular or fan-shaped regions extending inward from cell edges, consistent with crack propagation geometry confirmed by cross-section optical microscopy.
- **Wire misalignment:** Produces asymmetric reduction in EL intensity across the wire pitch, with alternating bright and dark bands reflecting differential contact resistance between adjacent wires.

IV. THERMOMECHANICAL FAILURE ANALYSIS

4.1 Wire-to-Cell Contact Fatigue Mechanism

The dominant failure mode - wire-to-cell contact opens at 38.4% of yield loss - was investigated through a combination of cross-section metallographic analysis, scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX), and finite element analysis (FEA) of the wire-cell contact stress field. The analysis revealed a two-stage failure mechanism:

WIRE-CELL CONTACT FATIGUE: TWO-STAGE FAILURE MECHANISM

Stage 1 - Bi-Sn alloy microstructure coarsening: The bismuth-tin eutectic coating undergoes progressive grain growth under thermomechanical cycling. Individual Bi-rich and Sn-rich grains, initially 2–4 μm in diameter at the as-deposited state, coarsen to 15–28 μm after thermal cycling equivalent to 5–10 years of field service. Grain boundary sliding under cyclic shear stress is the microstructurally active deformation mechanism. EDX mapping confirmed preferential bismuth segregation to grain boundaries after cycling, forming a bismuth-rich continuous grain boundary network that is mechanically weaker than the bulk alloy.

Stage 2 - Interfacial delamination initiation and propagation: Shear stress concentration at the perimeter of the wire-cell contact zone - driven by the CTE mismatch between copper wire and silicon cell - initiates interfacial crack nucleation at the Bi-Sn/silver-grid interface. Once nucleated, cracks propagate along the weakest path: the Bi-Sn grain boundary network established in Stage 1. Electrical failure (contact open) occurs when the crack propagation front extends across the full contact width, severing the current path.

FEA results for the wire-cell contact zone under a single -40°C to $+85^{\circ}\text{C}$ thermal cycle yielded the following stress field characteristics:

- **Maximum shear stress at the Bi-Sn/Ag interface:** Peak shear: 28.4 MPa, located at the wire edge contact perimeter (2.1 mm from wire centerline)
- **Equivalent von Mises stress at wire centerline:** Center stress: 9.7 MPa - well below the Bi-Sn alloy yield strength of approximately 18 MPa, confirming elastic response at the contact center
- **Calculated fatigue crack initiation life:** Initiation cycles: 4,200 cycles to crack nucleation at the contact perimeter using a Coffin-Manson fatigue model calibrated to Bi-Sn alloy properties
- **Crack propagation rate:** Propagation rate: Approximately 8–15 μm per cycle in the grain boundary-dominated regime, yielding a complete contact separation life of 11,000–16,000 cycles
- **Field life correlation:** Field service projection: 11,000–16,000 cycles corresponds to 20–29 years of field service at the 1.5 cycles/day thermal fatigue rate - marginally compliant with the 30-year design life target at the lower bound.

4.2 Thermoplastic Adhesive Delamination

Delamination of the SWCT thermoplastic adhesive film - the second largest reliability concern at 17.6% of yield loss - was investigated through peel strength measurement, differential scanning calorimetry (DSC), and post-lamination cross-section analysis. Key findings are summarized as follows:

- **Peel strength baseline:** As-laminated adhesive peel strength (wire-to-film) measured at 8.2–12.4 N/cm across 60 production modules sampled at the start of the study period
- **Post-cycling peel strength:** After 200 thermal cycles (-40 to $+85^{\circ}\text{C}$), peel strength dropped to 4.1–6.8 N/cm - a reduction of 45–50% relative to baseline
- **DSC analysis:** Glass transition temperature (T_g) of the TPO adhesive measured at 62°C by DSC. At module operating temperatures above T_g (common in tropical Singapore climates where module temperatures routinely exceed 65°C), the adhesive transitions to a viscoelastic state with substantially reduced peel and shear strength
- **Crystallization-induced stress:** On cooling below T_g , partial crystallization of the polyolefin matrix introduces volumetric shrinkage of 1.8–2.4%, generating tensile stress at the wire-to-film bond interface. This mechanism is identified as the primary driver of the observed 45–50% peel strength reduction after thermal cycling
- **Film thickness sensitivity:** Modules assembled with adhesive film lots at the lower thickness tolerance (58 μm vs. nominal 60 μm) showed delamination rates $2.3\times$ higher than those at nominal thickness, establishing incoming material thickness uniformity as a critical quality parameter.

4.3 Micro-Crack Propagation at Cell Edges

Cell edge micro-crack propagation, contributing 12.3% of SWCT-specific yield loss, was analyzed through a combination of EL image time-series tracking, optical microscopy of cross-sections, and mechanical modeling of wire tension-induced stress at cell edges.

EDGE MICRO-CRACK ROOT CAUSE ANALYSIS - CRITICAL FINDINGS

- **Wire tension during tabbing:** The IR tabbing process applies a wire tension of 0.18–0.24 N per wire at the cell edge contact zone. For a 32-wire module layout, cumulative edge tension reaches 5.8–7.7 N along the full cell edge width - sufficient to initiate crack propagation from pre-existing edge chips of depth $\geq 80 \mu\text{m}$
- **Pre-existing edge chip size distribution:** Statistical sampling of incoming HJT cells prior to SWCT assembly revealed that 6.2% of cells contained at least one edge chip with depth $\geq 80 \mu\text{m}$ - the threshold above which propagation risk under SWCT tabbing tension is confirmed by finite element stress intensity factor analysis

- **Fracture toughness of M6 silicon wafers:** Critical stress intensity factor K_{Ic} for (100) silicon in the (011) crack propagation direction: $0.89 \text{ MPa}\cdot\text{m}^{1/2}$. At a pre-existing chip of $80 \mu\text{m}$ depth, the stress intensity factor K under wire tabbing tension reaches $0.83 \text{ MPa}\cdot\text{m}^{1/2}$ - approaching K_{Ic} , confirming crack propagation risk
- **Propagation rate under thermal cycling:** Once initiated during tabbing, cracks propagate at $2\text{--}8 \mu\text{m}$ per thermal cycle under the thermomechanical stress field of the assembled module. A crack reaching 3 mm inward from the cell edge reduces the effective photovoltaic area by approximately 3.6% , exceeding the 1% power loss gate for module rejection
- **Seasonal dependence:** EL inspection data showed crack propagation events to be $1.7\times$ more frequent during May–August 2021 (tropical summer, average ambient 32°C) versus January–March 2021 (cooler months, average ambient 25°C), consistent with increased thermomechanical cycling amplitude in higher ambient conditions

4.4 Wire Breakage Failure Analysis

Wire breakage was the second most frequent single failure mode at 22.1% of SWCT yield loss. Failure analysis of broken wire specimens retrieved from post-lamination EL-rejected modules identified three distinct fracture morphologies:

- **Ductile overload fracture:** Accounts for 61% of breakage events. Characterized by cup-and-cone fracture surface, high reduction in area ($\geq 40\%$), and dimpled fracture morphology under SEM. Root cause: mechanical overload during automated string handling between tabbing and lay-up. Primary fix: wire tension control algorithm update and string gripper pressure reduction.
- **Fatigue fracture:** Accounts for 24% of breakage events. Characterized by beach-mark fatigue striations on fracture surface under SEM, with a smooth crack propagation zone occupying $60\text{--}80\%$ of the cross-section and a final fast-fracture zone of only $20\text{--}40\%$. Root cause: thermally induced cyclic stress at wire bend points where wire crosses cell gap. Wire bending radius at cell gap was $1.2\text{--}1.4 \text{ mm}$ - below the 1.8 mm minimum recommended by wire supplier for fatigue life compliance.
- **Brittle intergranular fracture:** Accounts for 15% of breakage events. Smooth, faceted fracture surface with no visible plastic deformation. SEM/EDX confirms bismuth segregation to fracture surface - consistent with bismuth liquid metal embrittlement (LME) at the tabbing temperature of 170°C , where bismuth approaches its melting point (271°C) and grain boundary diffusion is accelerated. Wire samples from this failure mode showed elevated bismuth content at grain boundaries ($14.2 \text{ wt}\%$ versus $3.8 \text{ wt}\%$ in unaffected regions by EDX quantification).

IV. ACCELERATED AGING AND RELIABILITY TESTING

5.1 Test Protocol and Standards Basis

Accelerated reliability testing was conducted in accordance with IEC 61215-2:2021 and IEC 61730-2:2021, supplemented by internal REC Solar reliability test protocols developed during the SWCT industrialization phase. The test matrix was designed to accelerate the three primary life-limiting mechanisms identified in Section 4: wire-cell contact fatigue, adhesive delamination, and wire breakage under cyclic thermal loading.

Test specimens were drawn from three distinct cohorts:

- **Cohort A:** Modules assembled with the pre-corrective-action process (January 2021 baseline conditions) - 48 modules
- **Cohort B:** Modules assembled with interim corrective actions (April 2021 process state) - 48 modules
- **Cohort C:** Modules assembled with fully implemented corrective actions (August 2021 process state) - 48 modules

5.2 Thermal Cycling (TC) Results

Thermal cycling was performed per IEC 61215-2 TC200 and extended to TC400 and TC800 to generate lifetime projection data. All modules were characterized by flash test, EL imaging, and IR thermography before and after each TC checkpoint. The key outcomes were:

- **TC200 checkpoint (200 cycles, -40 to $+85^\circ\text{C}$):** Cohort A: Average power degradation of 2.8% P_{max} relative; 6 modules (12.5%) exceeded the 5% power loss gate; EL images showed delamination progression in 23% of cells across the cohort
- **TC200 checkpoint:** Cohort B: Average power degradation of 1.9% P_{max} relative; 2 modules (4.2%) exceeded the 5% loss gate
- **TC200 checkpoint:** Cohort C: Average power degradation of 0.9% P_{max} relative; 0 modules exceeded the 5% loss gate
- **TC400 checkpoint:** Cohort A: Average degradation 5.7% P_{max} ; 19 modules (39.6%) failed the 5% gate; widespread wire-cell delamination in EL confirmed by cross-section
- **TC400 checkpoint:** Cohort B: Average degradation 3.4% P_{max} ; 7 modules (14.6%) failed the 5% gate
- **TC400 checkpoint:** Cohort C: Average degradation 1.8% P_{max} ; 1 module (2.1%) failed the 5% gate

- **TC800 checkpoint:** Cohort A: Average degradation 9.2% Pmax; 34 modules (70.8%) failed the gate - module population not suitable for 30-year service life extrapolation
- **TC800 checkpoint:** Cohort B: Average degradation 5.8% Pmax; 18 modules (37.5%) failed the gate
- **TC800 checkpoint:** Cohort C: Average degradation 3.1% Pmax; 3 modules (6.3%) failed the gate - acceptable performance consistent with 30+ year reliability projection

5.3 Damp Heat (DH) and Combined Stress Testing

Damp heat testing (85°C / 85% relative humidity, 1000 hours per IEC 61215-2 DH1000) was conducted in parallel with TC testing to evaluate adhesive delamination under humidity conditions. Key observations:

- **Cohort A DH1000:** Delamination at wire-to-film interface progressed in 31% of cells across the cohort, detected by post-DH EL imaging. Average peel strength reduction after DH1000: 58% relative to pre-test baseline. Moisture ingress path confirmed by FTIR spectroscopy showing hydroxyl absorption band growth in TPO adhesive samples.
- **Cohort C DH1000:** Delamination detected in 7% of cells. Average peel strength reduction: 19%. FTIR confirmed reduced moisture uptake in the reformulated adhesive primer layer implemented as part of Corrective Action 4 (Section 6).
- **Combined TC + DH:** A subset of 12 modules per cohort underwent combined TC200 followed by DH500 to simulate the sequential stress environment of real field service. Cohort A showed synergistic degradation - power loss after combined stress was 1.4× greater than the linear sum of TC-only and DH-only losses, confirming moisture-assisted delamination is accelerated by prior fatigue cracking at the wire-film interface.

5.4 Projected Reliability Lifetime

Using the Arrhenius acceleration model for thermal degradation and the Peck model for humidity-accelerated delamination, lifetime projections were computed from the TC800 and DH1000 datasets for all three module cohorts:

- **Cohort A (January 2021 baseline process):** Projected life to 80% power retention (P80 criterion): 27.3 years - non-compliant with 30-year design life warranty requirement
- **Cohort B (April 2021 interim process):** Projected P80 life: 31.7 years - marginally compliant
- **Cohort C (August 2021 fully corrected process):** Projected P80 life: 34.8 years - comfortably compliant with 30-year warranty, providing a 4.8-year reliability margin

VI. CORRECTIVE ACTIONS: DESIGN AND IMPLEMENTATION

6.1 Corrective Action Framework

Corrective actions were prioritized using a risk priority number (RPN) framework from the SWCT process PFMEA, weighting each failure mode by its severity, detection probability, and occurrence frequency. Seven corrective actions were designed, implemented, and validated during the January–August 2021 study period. Each is described below with its specific technical content, implementation timeline, and measured yield impact.

SUMMARY: SEVEN CORRECTIVE ACTIONS IMPLEMENTED JANUARY–AUGUST 2021

- Wire bending radius increase at cell gap - Modified the SWCT carrier film cell gap bridge geometry from a 1.2 mm wire bend radius to 2.1 mm by adjusting the automated wire placement head profile. Implemented February 2021. Reduced fatigue fracture wire breakage events by 78% within three weeks of implementation, eliminating the primary root cause of the 24% fatigue fracture sub-category.
- Tabbing IR profile optimization - Reduced peak tabbing temperature from 170°C to 158°C and extended dwell time from 8 to 12 seconds to achieve equivalent Bi-Sn reflow without reaching the bismuth-embrittlement threshold. Validated by DSC of post-tabbing wire cross-sections confirming complete reflow at the new profile. Implemented March 2021. Eliminated the intergranular fracture breakage sub-category (previously 15% of wire breakage events).
- String gripper pressure reduction - Reduced automated string gripper clamping pressure from 2.4 bar to 1.6 bar during string transfer from tabbing to lay-up station. Combined with a wire tension monitoring system (inline load cell on each string gripper jaw). Implemented February 2021. Reduced ductile overload fracture events by 61%.
- Adhesive carrier film primer reformulation - Worked with TPO film supplier to reformulate the wire-to-film adhesion primer to increase hydroxyl group density at the wire-film interface, improving moisture resistance. New primer formulation showed 34% higher peel strength after DH1000 in qualification testing. Implemented at production scale in May 2021 upon completion of supplier qualification.
- Incoming cell edge chip screening tightening - Tightened cell pre-screen edge chip rejection criterion from 100 µm to 60 µm depth threshold, reducing the population of cells at fracture propagation risk during tabbing. Implemented January 2021. Increased cell pre-screen rejection rate from 2.1% to 5.4%, requiring compensating input quality improvement with cell manufacturing team - achieved by May 2021 through cell dicing process improvement.

- Wire placement vision system upgrade - Replaced the string tabbing alignment camera system with a higher-resolution (5 Mpx vs. previous 1.3 Mpx) system operating at $2\times$ imaging frame rate. Alignment tolerance improved from ± 0.15 mm to ± 0.07 mm. Implemented April 2021. Eliminated wire misalignment as a significant yield loss contributor (reduced from 6.8% to 0.9% of SWCT yield loss).
- Lamination pressure profile optimization - Implemented a two-stage lamination pressure profile (0.4 bar during evacuation, 0.9 bar during press) versus previous single-stage 0.9 bar from start. Reduced void formation at wire-encapsulant interface by 84% by allowing gas evacuation to complete before consolidation pressure traps entrapped air. Implemented June 2021.

6.2 Yield Recovery Timeline

The cumulative effect of the seven corrective actions on production yield loss was tracked on a weekly basis throughout the study period. The yield recovery trajectory reflects the sequential implementation of corrections:

- **January 2021:** Baseline yield loss 4.7%; edge chip screening tightened; immediate impact limited pending cell quality improvement
- **February 2021:** Wire bending radius increased; gripper pressure reduced; yield loss declines to 3.9%
- **March 2021:** Tabbing temperature profile revised; yield loss declines to 3.2%; wire breakage rate halved
- **April 2021:** Vision system upgrade commissioned; alignment-related losses near-eliminated; yield loss at 2.6%
- **May 2021:** Cell edge chip quality improvement from cell manufacturing takes effect; yield loss at 2.1%
- **June 2021:** Lamination pressure profile optimized; void-related rejects eliminated; yield loss at 1.8%
- **July 2021:** Primer reformulation modules enter production; delamination rate declining; yield loss at 1.6%
- **August 2021:** Full corrective action set mature in production; yield loss stabilized at 1.4%

VII. COMMERCIAL AND OPERATIONAL IMPACT

7.1 Direct Yield Improvement Value

The reduction in SWCT-specific yield loss from 4.7% to 1.4% across the study period represents a net yield improvement of 3.3 percentage points at the module assembly level. At the production throughput of the REC Solar Singapore SWCT assembly lines (800 MW annual rated capacity), the commercial value of this improvement is quantified as follows:

- **Recovered module capacity:** 3.3% yield recovery at 800 MW production \equiv 26.4 MW of additional module output per year
- **Revenue impact at average selling price:** 26.4 MW \times \$0.33/W blended ASP \approx \$8.7M incremental annual revenue
- **Scrap and rework cost reduction:** EL-rejected modules reduced from 4.7% to 1.4% of output; rework cost per rejected module approximately \$18; at 800 MW production (assuming 450 W average module power): 59,000 fewer rejected modules annually \times \$18 \approx \$1.1M scrap/rework cost saving
- **Warranty provision reduction:** Projected P80 reliability life extended from 27.3 to 34.8 years; warranty provision rate reduced proportionally from 1.8% to 0.9% of revenue, releasing approximately \$2.4M of annual warranty reserve at the \$8.7M revenue impact level
- **Total estimated annual financial impact:** Aggregate commercial value of the corrective action program: approximately \$12.2M per annum at the 800 MW production scale.

7.2 Operational Learning: Key Insights for GW-Scale SWCT Deployment

Beyond the specific corrective actions implemented, the study generated a set of broader operational insights applicable to any manufacturer deploying SWCT at GW scale:

- **Process sensitivity is concentrated in three steps:** String tabbing, string handling to lay-up, and vacuum lamination together account for more than 90% of SWCT-specific yield loss. Process control investment should be disproportionately concentrated at these three gates.
- **Wire geometry at cell gap is a critical design parameter:** The wire bending radius at cell-to-cell gaps is the single most important geometric parameter governing long-term fatigue life. Design rule: minimum 1.8 mm bend radius; target 2.1 mm or greater.
- **EL inspection at 100% coverage at every gate is essential:** The spatial resolution of SWCT failure modes - particularly wire-level contact opens and localized breakage - cannot be adequately sampled by statistical inspection. 100% EL coverage at each gate is a prerequisite for achieving yield loss below 2%.
- **Incoming material variability drives assembly variability:** Both wire lot-to-lot coating thickness variation and adhesive film thickness variation were found to be statistically significant predictors of assembly yield. Tight incoming quality specifications and 100% film thickness verification are required inputs to process control.
- **Thermomechanical analysis must precede process design:** The SWCT wire bending radius failure root cause could have been identified - and the corrective action implemented before production entry - had a detailed FEA model

of the wire-cell-gap stress field been part of the original process design qualification package. This represents the key system learning from the study.

■ **Accelerated aging must be validated to production process state:** TC and DH test results from process qualification modules may not reflect production-state modules if the process has evolved since qualification. Re-testing at each significant process change is essential for reliability assurance integrity.

VIII. COMPARATIVE CONTEXT: SWCT VS. CONVENTIONAL RIBBON INTERCONNECTION

The failure modes and corrective actions documented in this paper must be interpreted in the context of the broader technology choice between SWCT and conventional tabbing-and-stringing (T&S) ribbon interconnection for HJT modules. The comparison is not binary - SWCT's advantages and risks must be weighed against T&S's well-understood strengths and limitations.

8.1 Failure Mode Comparison

The dominant yield loss mechanisms in SWCT assembly (contact opens, wire breakage, delamination) have direct analogues in T&S assembly but manifest differently:

■ **T&S contact opens:** Occur due to insufficient solder wetting at ribbon-to-busbar joints. Detection: visual inspection and EL. Frequency in mature T&S lines: typically 0.5–1.2% yield loss contribution. SWCT equivalent (contact opens): 38.4% of SWCT-specific yield loss, equivalent to approximately 1.8% absolute - substantially higher, driven by the greater number of individual contact points (32 wires vs. 3–5 busbars per cell).

■ **T&S cell cracking:** Caused by ribbon soldering thermal shock and mechanical handling. Crack rate in mature T&S HJT lines: 0.3–0.8% yield loss. SWCT edge crack contribution: 12.3% of SWCT loss (approximately 0.58% absolute) - comparable to T&S once corrective actions are implemented, but with a different failure geometry (edge-initiated vs. center-crack in T&S).

■ **T&S solder joint fatigue:** T&S solder (Sn-Ag or Sn-Pb) joints fatigue at rates comparable to Bi-Sn SWCT contacts under TC testing, but T&S fatigue failure is less frequently an early-life yield loss driver because ribbon geometry provides greater contact area (lower stress per unit area) than wire point contacts.

8.2 Net Technology Assessment

Despite the higher initial yield loss complexity of SWCT, the technology delivers a net performance and cost advantage in the REC Solar HJT production context under the corrected process:

■ **Module power gain:** +8–12 W per module (M6, 60-cell format) versus T&S equivalent, attributable to reduced shadow loss (+5–6 W), reduced resistive loss in metallization (+2–3 W), and improved bifacial utilization (+1–3 W)

■ **Silver paste cost reduction:** –18% silver consumption per cell versus conventional 3-busbar T&S design, due to finer wire pitch reducing required silver grid density

■ **Long-term reliability (post-correction):** Projected P80 life of 34.8 years for Cohort C modules exceeds the 33.2-year P80 projection for equivalent T&S modules tested under the same protocol - a 5% reliability advantage for SWCT once process is stabilized

■ **Manufacturing cost delta:** SWCT wire and carrier film material cost adds approximately \$0.004/W module cost versus T&S; this premium is offset by the silver savings (–0.003/W) and the power premium (+8W/module at 450W baseline = +1.8% power gain × module ASP effect), yielding a net SWCT economic advantage of approximately \$0.006–0.009/W at current material costs.

IX. FUTURE DEVELOPMENT DIRECTIONS

The findings of this study identify several directions for further technical development that would extend the performance and reliability envelope of SWCT module assembly beyond the levels achieved in this work:

9.1 Wire Material and Coating Innovation

■ **Reduced-diameter wire:** Moving from 0.30 mm to 0.24 mm wire diameter would reduce shadow fraction by an additional 20% and improve mechanical compliance under thermal cycling. Preliminary mechanical modeling indicates fatigue life would improve by approximately 35% at the same bend radius, due to the lower bending stiffness of the thinner wire. Production readiness assessment for 0.24 mm wire is underway at REC Solar.

■ **Low-temperature solder alternatives:** Replacing the Bi-Sn eutectic (melting point 139°C) with an In-Sn alloy (melting point 120°C) would enable tabbing at temperatures below 145°C, eliminating the bismuth grain boundary embrittlement failure mode and reducing tabbing-induced thermal stress on the a-Si:H passivation stack. Adhesion strength and cycling reliability of In-Sn SWCT contacts are under evaluation.

■ **Conductive adhesive bonding:** Research-stage alternatives to solder-based SWCT wire bonding using isotropic conductive adhesives (ICA) or anisotropic conductive films (ACF) operate at even lower temperatures (60–80°C), potentially eliminating thermal shock as a yield loss mechanism entirely. Long-term reliability data for ICA-based SWCT contacts under IEC 61215 conditions is not yet available for production qualification.

9.2 Process Digitalization and AI-Assisted Inspection

■ **AI-powered EL defect classification:** The volume of EL images generated at 100% inspection coverage - approximately 16,800 full-module EL frames per day at production throughput - exceeds practical human review capacity for detailed defect classification. Deployment of convolutional neural network (CNN) defect classifiers trained on the labeled EL dataset accumulated during this study (2.1 million module inspection records) would enable real-time automated root cause coding and Pareto analysis without operator intervention.

■ **Digital twin for thermal stress prediction:** A validated FEA model of the module assembly thermomechanical stress field, parameterized with real-time incoming material property data (wire coating thickness, adhesive film modulus), could serve as a digital twin for predicting the fatigue life of each module as a function of its specific material lot combination - enabling proactive sorting or process adjustment before assembly rather than reactive rejection after EL inspection.

■ **Wire tension real-time monitoring:** Extending the load cell wire tension monitoring system (implemented at string gripper as Corrective Action 3) to the tabbing station and lay-up transfer robot would provide continuous tension data at all high-risk wire handling points, enabling immediate detection of equipment drift before yield loss materializes.

9.3 Module Design Evolution

■ **Cell-gap bridge geometry optimization:** The corrective action implemented in this study increased wire bend radius from 1.2 to 2.1 mm. Parametric FEA analysis of bend radii from 1.5 to 4.0 mm shows that fatigue life scales approximately with radius squared; a further increase to 3.0 mm would extend projected fatigue initiation life from 4,200 to approximately 9,400 cycles - more than doubling the fatigue safety margin with no change in module dimensions.

■ **Asymmetric wire pitch:** The current uniform 5.15 mm wire pitch was selected for manufacturing simplicity. Optimization of wire pitch distribution - with finer pitch in the high-stress cell-edge zones and wider pitch in the center - could reduce peak contact stress by an estimated 15–22% while maintaining the same total wire count and module electrical performance.

X. CONCLUSIONS

This paper has presented a comprehensive production-scale investigation into the yield loss mechanisms and thermomechanical reliability failure modes of Smart Wire Connection Technology module assembly at REC Solar's ~1 GW HJT manufacturing facility in Singapore. The study spans eight months of production data, 2.1 million module inspection records, a full accelerated aging test campaign across three process cohorts, and a structured seven-corrective-action improvement program.

PRINCIPAL CONCLUSIONS

- The SWCT module assembly yield loss at production entry (January 2021) was 4.7%, with contact opens (38.4%), wire breakage (22.1%), adhesive delamination (17.6%), and edge micro-crack propagation (12.3%) as the primary failure categories. String tabbing alone initiates 68% of the contact open failure population.
- Wire-to-cell contact fatigue operates through a two-stage mechanism: Bi-Sn grain coarsening followed by grain boundary crack propagation. FEA confirmed peak shear stresses of 28.4 MPa at the contact perimeter, with fatigue crack initiation predicted at 4,200 cycles - establishing a lower-bound field life of 20 years that is non-compliant with the 30-year design target under baseline process conditions.
- Adhesive delamination is driven by three synergistic mechanisms: polyolefin crystallization shrinkage on cooling (1.8–2.4% volumetric), glass transition temperature exceedance during tropical field operation, and moisture-assisted weakening of the wire-film interface. Combined TC+DH stress produces 1.4× synergistic degradation versus linear superposition of individual stresses.
- Wire breakage occurs via three morphologically distinct fracture types: ductile overload (61%), fatigue fracture (24%), and bismuth-embrittlement intergranular fracture (15%). The intergranular mode is unique to SWCT and is driven by bismuth grain boundary segregation at tabbing temperatures approaching the bismuth melting point.
- Seven corrective actions, implemented sequentially from January through August 2021, reduced SWCT-specific yield loss from 4.7% to 1.4% - a 70% reduction in 8 months. The most impactful single action was increasing wire bend radius at cell gaps from 1.2 to 2.1 mm (fatigue breakage reduced 78%).

- Accelerated aging of August 2021 process-state modules (Cohort C) yielded a projected P80 reliability life of 34.8 years - a 27% improvement over the January 2021 baseline of 27.3 years, and 4.8 years of margin above the 30-year warranty design life.
- The total estimated annual commercial value of the yield and reliability improvements is approximately \$12.2M at 800 MW production scale, comprising recovered module revenue, scrap cost savings, and reduced warranty provision.
- The key systemic learning from this study is that thermomechanical FEA of the SWCT wire geometry must be a mandatory input to process design qualification - the wire bending radius failure root cause that dominated early production yield loss was predictable from first principles and preventable had the FEA model been applied at the design stage.

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