Photovoltaic Reliability in Transportation Environments

A Technical Benchmark of Failure Physics, Interconnection Architecture, and Field Performance

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MERLIN SOLAR

Executive Summary

Achieving true operational resilience in commercial transportation and mobile or remote operations remains fundamentally constrained by the lack of reliable onboard energy. Assets operating in these environments are subject to constant vibration, mechanical shock, thermal cycling, and limited or nonexistent access to grid infrastructure—conditions that routinely push conventional power systems beyond their design limits. Incremental increases in battery capacity have emerged as a common mitigation strategy, but this approach adds weight, complexity, and cost without addressing the underlying systemic issue.

For decades, solar technology has been optimized for static rooftops, confined to rigid glass-and-aluminum constructions ill-suited to the vibration, impact, and thermal cycling of mobile environments. As a result, conventional systems cannot reliably deliver continuous energy generation in motion. True operational resilience therefore requires solar energy generation at the point of consumption, engineered specifically to withstand the mechanical and environmental realities of mobile and remote applications.

Merlin Solar Technologies was founded to address this challenge directly: enabling reliable power generation at the point of consumption. The company's approach is centered on delivering energy independence and onboard power in environments where traditional solutions cannot survive. By moving energy generation directly to where it is used, Merlin Solar reduces dependence on static infrastructure, minimizes mechanical strain on vehicle electrical systems, and maximizes overall asset uptime.

This white paper examines the commercial applications enabled by Merlin Solar's technology—from liftgate maintenance and battery preservation to remote energy systems—and details how the company has addressed the fundamental failure modes of legacy solar architectures, including back contact and thin film, through a patented, military-grade interconnection design.

Aggregated across commercial trucking, trailer, and specialty deployments since 2016, including long-haul, regional, and off-road duty cycles, Merlin Solar systems have accumulated **more than 100,000 vehicle installations** and over **10 billion cumulative fleet road miles.**

The sections that follow separate the physics of failure, architectural solution, laboratory validation, and operational field evidence to enable objective technical evaluation.

What This Paper Is Not Claiming

This paper does not claim that:

- Solar replaces propulsion energy for transportation assets.
- All thin film technologies are unsuitable for all applications.
- Battery life extension is universal across all chemistries and duty cycles.
- Solar alone eliminates the need for alternators, shore power, or generators.
- Static rooftop performance metrics directly translate to mobile environments.

The purpose of this paper is to define the architectural requirements for reliable photovoltaic energy generation under mechanically dynamic, vibration-dominated, and infrastructure-limited operating conditions.

Contents

1. Engineering Context: Mobile Energy Resilience

Commercial transportation and mobile or off-grid operations present environmental and mechanical challenges that conventional photovoltaic (PV) technologies were not designed to withstand.

Continuous vibration, mechanical shock, surface flexing, extreme temperature swings, and dynamic shading create operating conditions that fundamentally differ from static rooftop installations.

To operate reliably in these environments, solar technology must be engineered from the cell interconnection architecture upward, rather than adapted from designs optimized for fixed structures.

Merlin Solar's mission extends beyond incremental power generation. The company focuses on engineering **mobile energy resilience**: the ability to deliver continuous, dependable energy under real-world operating conditions. By decoupling PV performance from the structural assumptions of rigid modules, Merlin Solar enables solar deployment in environments previously considered incompatible with high-efficiency crystalline silicon.

Key objectives include:

- **Electrifying Transportation Systems:** Providing reliable auxiliary power to reduce alternator load, minimize idling, stabilize battery state of charge (SoC), preserve battery state of health (SoH), and extend overall asset life.
- **Enabling Renewable Energy on Nontraditional Surfaces:** Integrating solar onto curved, flexible, and vibration-prone platforms, including cab fairings, trailer roofs, deployable shelters, and maritime assets, where rigid glass modules routinely fail under sustained vibration and dynamic loading.
- **Supporting Sustainability at Scale:** Converting passive surfaces into active energy-generating assets to reduce fuel consumption and emissions across logistics, defense, and remote operations.

Sections 2 and 3 describe the underlying physical and architectural mechanisms governing photovoltaic durability in mobile environments.

Sections 4 and 5 present laboratory validation and field evidence supporting these principles.

2. Physics of Failure in Legacy PV

Understanding Merlin Solar's architecture requires examining the failure mechanisms of legacy PV technologies when deployed beyond static installations. Mobile assets impose mechanical and environmental stresses, continuous vibration, surface flexing, thermal cycling, and dynamic shading, that differ fundamentally from rooftop conditions.

The two most common legacy approaches, back contact (BC) crystalline silicon and thin film technologies, most notably copper indium gallium selenide (CIGS), were optimized for static installations and exhibit critical limitations under mobile operating conditions.

2.1 Thermal Expansion Mismatch and Mechanical Fatigue in Back Contact Cells

BC cells rely on thick copper metallization and soldered copper interconnects bonded directly to silicon wafers. While this architecture performs effectively in rigid, glass-framed modules, it introduces significant reliability challenges in mobile applications due to coefficient-of-thermal-expansion (CTE) mismatch among constituent materials.

Representative CTE values include:

- Copper: ~17 ppm/°C
- Silicon: ~2 ppm/°C
- Polymers: >100 ppm/°C
- Fiberglass (vehicle body material): ~13 ppm/°C
- Aluminum (vehicle body material): ~23 ppm/°C

In mobile deployments, temperature swings from –40°C to +80°C or higher are common on vehicle roofs and fairings. Under these conditions, copper and polymer layers expand nearly **8.5 times** faster than silicon. This mismatch induces repeated mechanical stress, leading to cell cracking and interconnect fatigue, commonly described as the "tired wire" effect.

While BC architectures can be fabricated at larger wafer sizes, mechanical yield and fatigue reliability degrade rapidly as copper thickness and wafer area increase. The thick electroplated copper required at larger cell formats introduces non-linear wafer warpage, elevating interconnect strain and accelerating fatigue failure. As a result, large-format BC cells remain impractical for vibration-dominated environments due to compounded yield loss and long-term reliability risk.

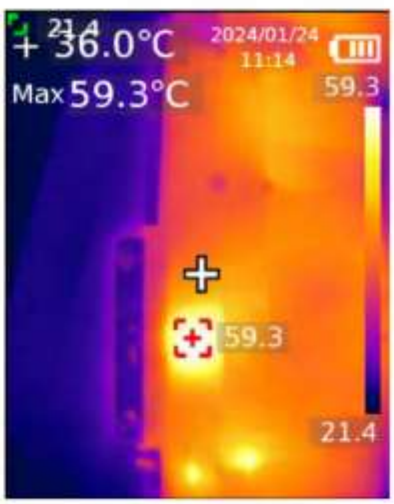
As the solar industry has transitioned to 182 mm wafer formats to improve power density and cost efficiency, a global supply base, including domestic U.S. manufacturing, has formed around these standardized cells. Because Merlin Solar's interconnection architecture does not rely on thick copper backplanes or rigid soldered busbars, it remains compatible with evolving wafer formats, enabling the use of contemporary large-format crystalline silicon cells while preserving the mechanical compliance required for mobile applications.

2.2 Interconnection Failure in Back Contact Architectures

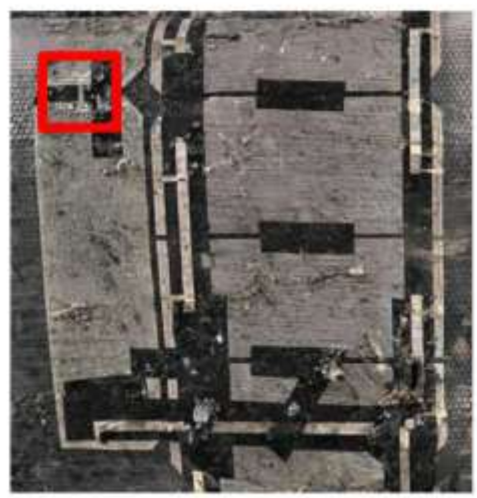
In mobile environments, BC module degradation is driven primarily by interconnection fatigue rather than intrinsic silicon degradation. Repeated thermal cycling and vibration cause solder joints to fracture, creating localized regions of elevated electrical resistance.

As resistance increases, current is forced through progressively smaller conductive pathways, generating localized thermal hotspots. These hotspots accelerate metallization damage, increase resistive losses, and initiate a self-reinforcing degradation process that ultimately results in measurable power loss and elevated safety risk.

Field observations on mobile assets, including refrigerated trailers and commercial transport platforms, consistently demonstrate this failure mode under real-world operating conditions. This failure mechanism is illustrated in **Figure 2.1**.



(a) Thermal Imaging of Failure Location



(b) Solder Joint Failure Analysis

Figure 2.1. *Infrared thermal imaging (a) and post-failure inspection (b) of a back-contact photovoltaic module interconnect. The thermal image identifies a localized electrical hotspot caused by increased resistance at a fractured solder joint. Physical inspection confirms interconnect fatigue at the corresponding location, illustrating a common failure mechanism in mobile solar applications.*

2.3 Back Contact Shade Intolerance

In addition to mechanical fatigue, BC architectures exhibit fundamental durability limitations under partial shading in mobile environments. BC cells collect current through defined rear-side metallization networks with limited lateral redundancy. Under uniform illumination, this architecture performs efficiently. However, under non-uniform illumination, current cannot redistribute evenly and is forced into a reduced number of conductive pathways, concentrating electrical stress.

In transportation environments, partial shading occurs continuously due to trees, bridges, vehicle structures, cargo, rooftop accessories, and surrounding infrastructure. These events are dynamic, frequent, and unavoidable.

Electrical Survivability vs. Long-Term Durability

While BC modules often remain electrically functional under partial shading, the dominant concern is long-term durability. Partial shading introduces localized reverse-bias conditions that elevate junction temperatures and accelerate metallization and interconnect degradation. Over repeated exposure cycles, this produces irreversible damage including localized hotspot formation[1], progressive interconnect fatigue, metallization degradation, and permanent power loss. Partial shading therefore acts as a cumulative damage accelerator rather than a purely transient performance loss mechanism.

Compounding Effect in Mobile Environments

In mobile deployments, shading-induced electrical stress occurs simultaneously with vibration and thermal cycling. Electrically weakened interconnects become more susceptible to vibration-driven fatigue, while mechanically strained joints exhibit increased resistive heating under non-uniform current flow. These coupled stressors significantly accelerate degradation rates.

Measured Performance Under Non-Ideal Illumination

Controlled testing demonstrates that Merlin Solar modules maintain significantly higher relative power output than BC modules when sunlight is not directly overhead.

When the sun is positioned to the side or rear of the panel, conditions representative of real vehicle operation, BC modules exhibit rapid power loss as tilt angle increases. By contrast, Merlin Solar modules retain substantially higher usable output across the same illumination angles.

Time-of-day performance data further confirms this effect. Merlin Solar consistently outperforms BC modules during morning and late-afternoon periods, when low sun angles and environmental shading dominate real-world energy capture.

[1] **NREL:** *Impact of Partial Shading on Photovoltaic Module Performance*
https://docs.nrel.gov/docs/fy15osti/62596.pdf

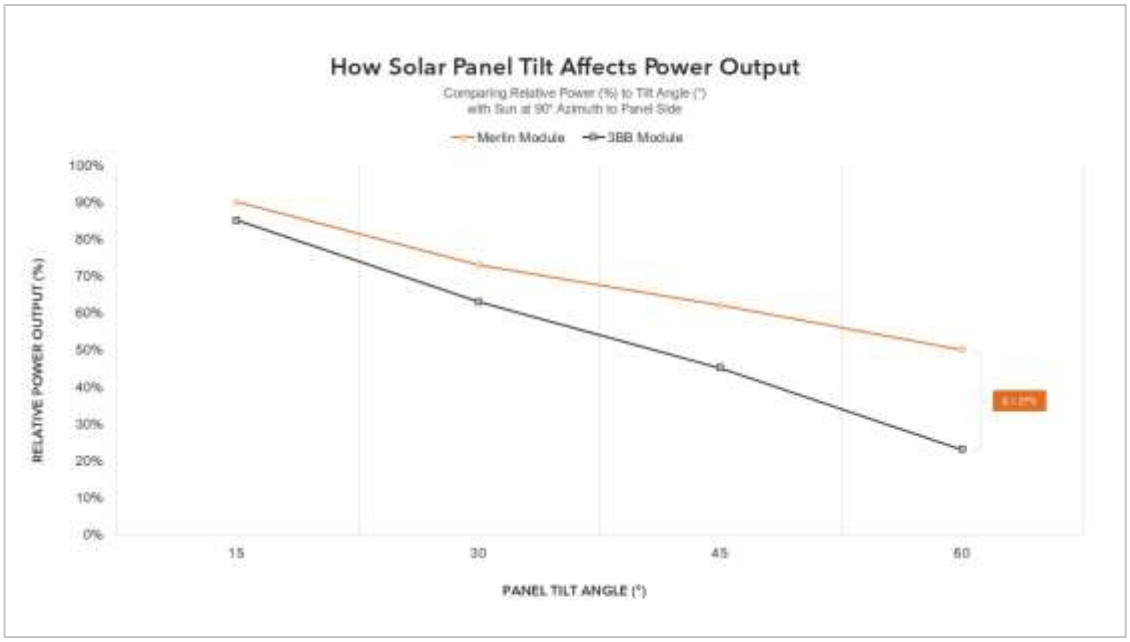


Figure 2.3a. *Relative power output versus panel tilt angle under side illumination (sun at 90° azimuth relative to panel normal) for Merlin Solar and a conventional 3-busbar (3BB) crystalline silicon module. Merlin Solar exhibits a relative output advantage of approximately* ***27% at 60° tilt,*** *with sustained separation across increasing tilt angles.*

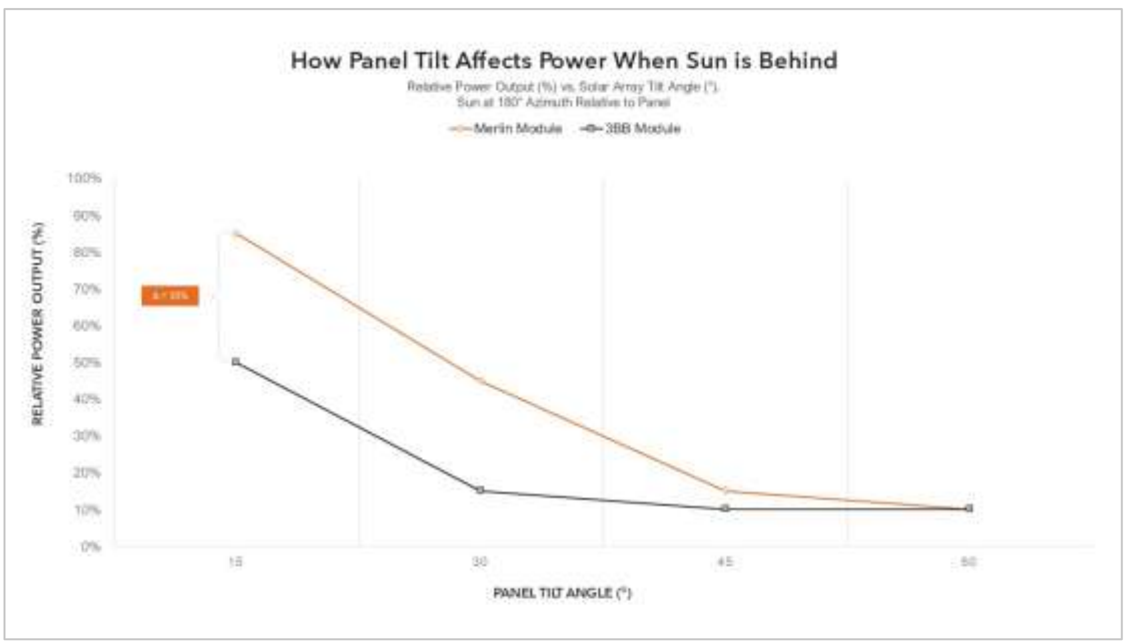


Figure 2.3b. *Relative power output versus panel tilt angle under rear illumination (sun at 180° azimuth relative to panel normal) for Merlin Solar and a conventional 3-busbar (3BB) crystalline silicon module. Merlin Solar exhibits a relative output advantage of approximately* ***35% at 15° tilt****, with consistent separation across higher tilt angles.*

Architectural Root Cause

The observed performance and durability differences are not driven by intrinsic cell efficiency, but by current-collection architecture. BC modules rely on a limited number of rear-side conductive pathways, preventing efficient current rerouting under partial shading and leading to localized heating.

Merlin Solar's grid-based architecture provides thousands of parallel conductive pathways across each module. Under partial shading, current redistributes automatically around shaded or degraded regions, limiting stress concentration, reducing hotspot formation, and preserving electrical continuity.

Long-Term Impact

In BC modules, partial shading accelerates long-term degradation through repeated cycles of localized electrical and thermal stress, resulting in progressive power loss, increased hotspot risk, accelerated interconnect fatigue, and reduced lifetime energy yield[2]. In mobile environments, these degradation mechanisms compound.

Practical Implication

Shading cannot be eliminated in transportation and off-grid deployments. Consequently, any solar architecture that concentrates electrical stress under partial shading will exhibit reduced reliability and lower lifetime energy production.

Merlin Solar's architecture is engineered specifically for these conditions. By enabling current to reroute freely across the module, Merlin Solar preserves both instantaneous power output and long-term durability under real-world shading environments.

2.4 Thin Film Technologies: Flexibility Without Mechanical Reliability

Thin film PV technologies, including CIGS, are often positioned as flexible alternatives. However, they present several fundamental limitations in mobile environments:

- **Low Power Density:** Requiring substantially more surface area to achieve equivalent power output, limiting feasibility on space-constrained assets.
- **Shade Intolerance:** Partial shading in thin film modules, when combined with series device structures and non-uniform degradation, induces adverse bias conditions that accelerate irreversible absorber damage and localized hotspot formation. While thin film modules may remain electrically operational under shading, long-term durability in mobile environments is significantly compromised.
- **Moisture Vulnerability:** Thin film PV technologies are highly sensitive to moisture ingress, creating a fundamental trade-off between environmental protection and

[2] **NREL:** *PV Module Degradation and Failure Modes*
https://docs.nrel.gov/docs/fy15osti/63765.pdfe

mechanical flexibility. Commercial approaches that improve moisture resistance typically rely on rigid, glass-glass module constructions, limiting suitability for mobile applications.

These degradation mechanisms often develop internally before complete electrical failure is observed. Electroluminescence (EL) imaging provides a direct method for visualizing early electrical discontinuities, absorber damage, and hotspot formation that result from these coupled stressors in mobile operation. **Figure 2.4** presents a field EL comparison illustrating how these architectural limitations manifest in real transportation deployments.

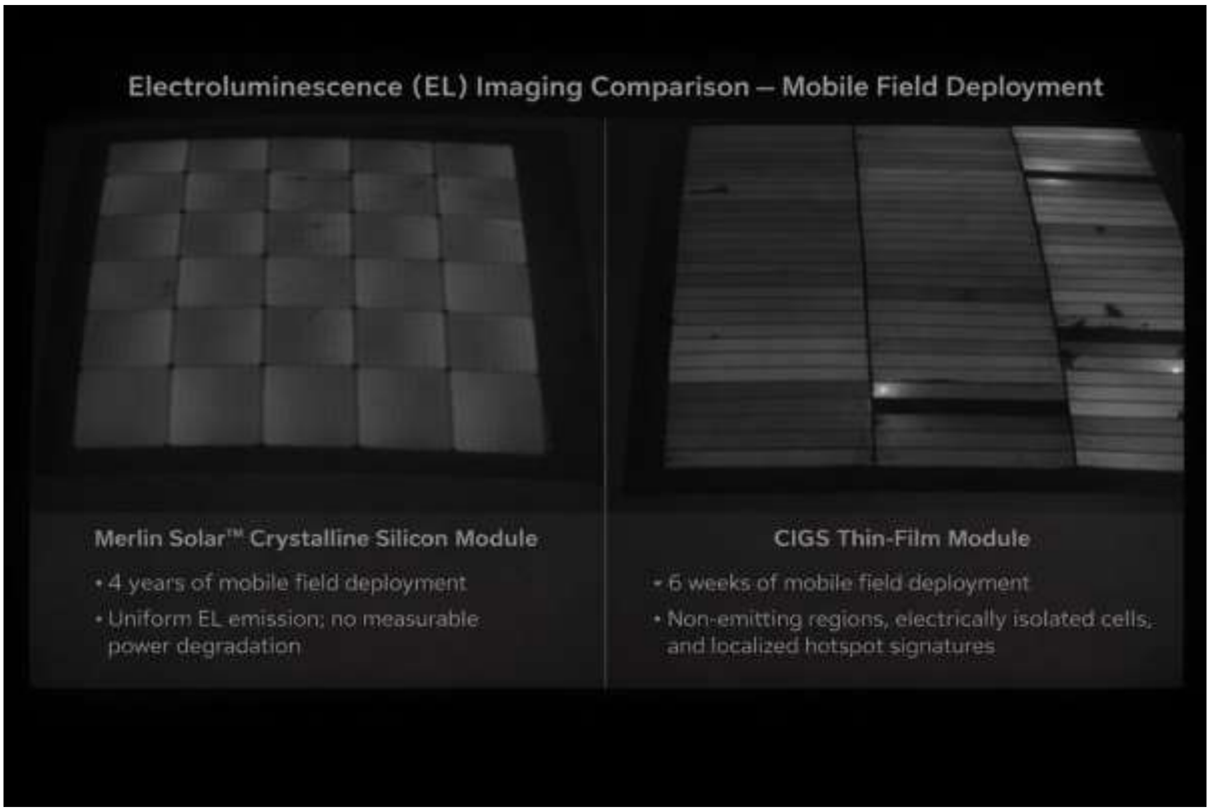


Figure 2.4. *Electroluminescence (EL) imaging comparison of photovoltaic modules following mobile field deployment on a Freightliner Cascadia cab fairing. The Merlin Solar crystalline silicon module (left) retains uniform emission after approximately four years of service, indicating preserved electrical continuity and stable performance. The CIGS thin-film module (right) exhibits non-emitting regions, electrically isolated cells, and localized hotspot signatures after approximately six weeks, illustrating the limited electrical and structural durability of thin-film architectures under mobile operating conditions.*

3. Merlin Solar's Patented Architectural Solution

Rather than incrementally reinforcing legacy module designs, Merlin Solar developed a patented interconnection architecture that fundamentally decouples electrical performance from mechanical stress. This approach allows high-efficiency crystalline silicon cells to operate reliably without reliance on rigid glass, heavy framing, or soldered stress-bearing interconnects.

By eliminating these structural dependencies, Merlin Solar remains cell-agnostic, enabling rapid adoption of future high-efficiency crystalline silicon technologies without requiring redesign of the module architecture.

3.1 Micro-Spring Interconnect Architecture

Merlin Solar replaces traditional soldered busbars with a patented copper grid incorporating a Micro-Spring interconnect architecture. These compliant interconnects maintain continuous electrical contact while remaining thermo-mechanically decoupled from the silicon cell.

This design allows the module to flex, expand, and contract independently of the silicon substrate, minimizing stress transfer that leads to cell cracking, solder joint fatigue, and electrical discontinuities in conventional module architectures.

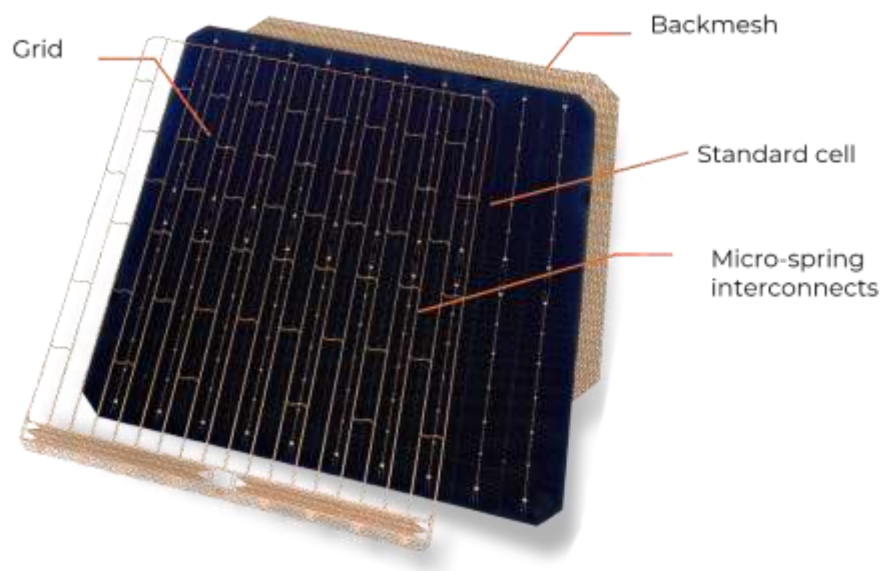


Figure 3.1. Merlin Solar redundant grid and interconnect architecture. *The Merlin Grid distributes current through 2,100+ independent grid connections, reducing sensitivity to microcracking, while 180+ compliant Micro-Spring interconnects maintain electrical continuity without transferring mechanical stress to the silicon. This architecture eliminates solder fatigue and preserves performance under vibration, flexing, and thermal cycling.*

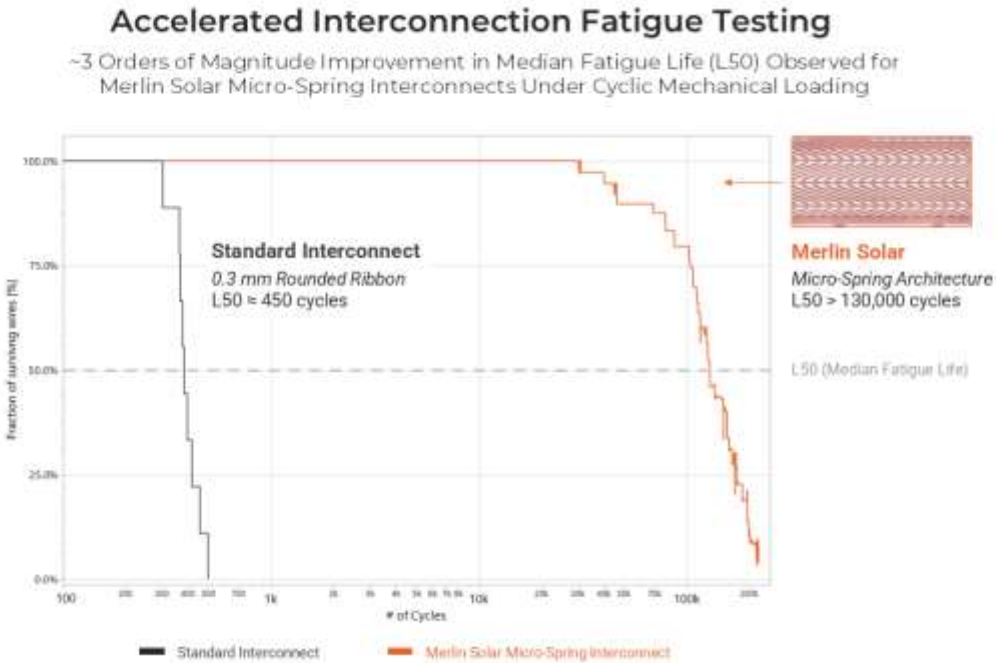


Figure 3.2. Accelerated interconnection fatigue testing under cyclic mechanical loading. *Survival curves compare a standard soldered copper ribbon interconnect (0.3 mm rounded ribbon) with Merlin Solar's Micro-Spring interconnect architecture. The standard interconnect exhibits a median fatigue life (L50) of approximately 450 cycles, while the Merlin Solar Micro-Spring architecture achieves an L50 exceeding 130,000 cycles, representing an improvement of approximately three orders of magnitude in fatigue resistance under identical test conditions.*

3.2 Redundancy and the "Rebar Effect"

Merlin Solar incorporates redundant conductive grid networks on both the front and back surfaces of each crystalline silicon cell. This dual-layer architecture functions analogously to structural rebar in reinforced concrete, distributing mechanical stress while preserving electrical continuity.

- **Structural Integrity:** The grid network reinforces the silicon substrate and limits crack initiation and propagation under mechanical loading.
- **Electrical Redundancy:** With more than 2,100 independent conductive pathways per module, electrical current automatically reroutes around damaged regions, preserving power output following localized impacts or cell fractures.

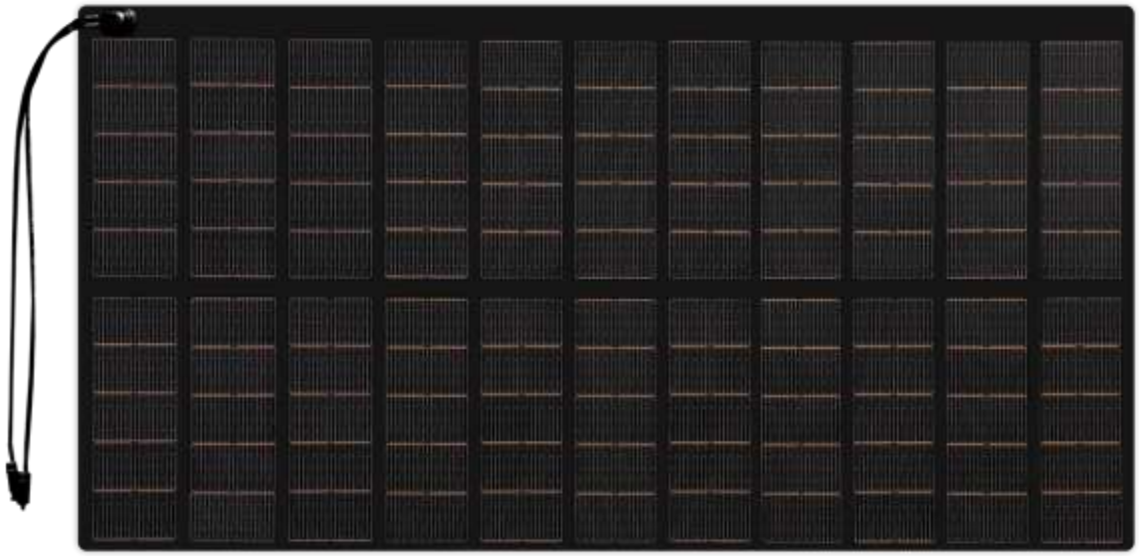


Figure 3.3. *Redundant grid architecture in a flexible Merlin Solar™ module, enabling structural crack control and electrical current rerouting.*

3.3 Technology Comparison Matrix

The following table summarizes the comparative performance and architectural characteristics of Merlin Solar relative to legacy PV technologies under mobile operating conditions.

Module Type	Merlin Solar Flex	Back Contact Crystalline Silicon	Thin-Film (e.g., CIGS)
Power Density	Comparable to rigid crystalline silicon depending on configuration	Comparable to Merlin Solar depending on configuration	Lower power density, requiring significantly more surface area
Energy Yield	Higher real-world yield due to grid architecture, particularly under low light angles and partial shading	Reduced yield in diffuse and non-ideal illumination	Similar instantaneous response, but lower total energy yield due to power density limitations
Cell Technology Compatibility	Grid architecture compatible with N-type and agnostic to future high-efficiency crystalline silicon cells	Limited to specialized back contact cell formats with constrained supply chains	Typically limited to CIGS thin film architectures with constrained material sourcing
Surface and Encapsulation	Matte, UV-stable, and moisture-resistant surface with architecture agnostic to future cell technologies	Glass-based construction with limited UV and moisture barrier flexibility	Often glossy or textured polymer or glass surfaces that increase glare, dust accumulation, or weight
Mechanical Robustness	Flexible and mechanically compliant architecture with high fatigue resistance when properly supported	Susceptible to cell cracking and interconnect fatigue under vibration and thermal cycling	Flexible in bending but highly susceptible to mechanical damage and coating fatigue
Hotspot Tolerance	Grid redundancy and current rerouting minimize localized heating under non-uniform conditions	Localized cell defects can lead to uncontrolled hotspot formation	Highly sensitive to hotspot formation, which accelerates irreversible degradation
Shading Resistance	Maintains electrical continuity and current flow under high shading percentages	Partial shading can induce damaging electrical bias and thermal stress	Partial shading rapidly induces hotspot formation and accelerated failure

3.4 Operational and Supply-Chain Constraints of Legacy Technologies

Beyond inherent performance differences, legacy PV architectures introduce operational and supply-chain risks that become significant when deployed at scale in transportation and mobile applications. These risks can affect fleet reliability, maintenance costs, and long-term program scalability.

Back Contact

Supply Chain Fragility

Back contact architectures depend on a **narrow and specialized manufacturing** base. Historically, technology leaders in this segment have faced significant business continuity challenges. For example, the original pioneer of a leading BC cell design exited the market in 2024 due to bankruptcy and subsequent asset transfers, resulting in further fragmentation of the supply base[3].

This concentration of suppliers introduces single-source dependencies, which can:

- Increase exposure to regulatory and customs delays (e.g., import holds[4] related to supply-chain transparency and compliance requirements).
- Reduce availability of replacement modules and spare parts.
- Elevate risk for long-term support commitments for large fleets.

These dynamics contrast with the broader supply chains of conventional crystalline silicon technologies, which benefit from multiple global manufacturers and diversified fabrication nodes.

Thin Film

Performance and Structural Constraints

Thin film PV technologies, including copper indium gallium selenide (CIGS), are frequently promoted for mechanical flexibility. However, as discussed in Section 3.4, they exhibit operational and environmental limitations that restrict their suitability for mobile applications.

- **Low energy density:** Thin film requires substantially more surface area to achieve equivalent power output compared with crystalline silicon, reducing feasibility on space-constrained assets.
- **Shade sensitivity:** Thin film modules subjected to dynamic partial shading in transportation environments experience localized bias stress that accelerates hotspot formation and long-term absorber degradation, reducing durability despite continued short-term power output.
- **Moisture vulnerability and rigidity trade-off:** The inherent moisture sensitivity of thin film absorbers has driven commercial implementations toward rigid, glass-glass hermetically sealed module constructions, in which the PV stack is encapsulated between two glass sheets to limit moisture ingress. While these structures improve moisture protection, they:
    - Eliminate mechanical compliance needed to withstand vibration and thermal cycling on mobile platforms.
    - Increase module weight and installation complexity.

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[3] SunPower files for Chapter 11 bankruptcy, *Canary Media*, August 6, 2024, https://www.canarymedia.com/articles/solar/sunpower-a-solar-icon-once-valued-in-the-billions-files-for-bankruptcy.
[4] Wesoff, E., *Maxeon's world-leading solar tech faces hard road ahead*, *Canary Media*, 2024, https://www.canarymedia.com/articles/solar/maxeons-world-leading-solar-tech-faces-hard-road-ahead.

4. Laboratory and Field Validation

Merlin Solar validates durability through testing regimes that significantly exceed IEC and UL qualification requirements. These test conditions are designed to reflect the mechanical, thermal, and environmental stresses routinely experienced by mobile and deployable assets. Figures 4.1 through 4.5 summarize Merlin Solar's accelerated environmental and fatigue validation results.

4.1 Accelerated Life Testing

UV Aging

While standard IEC and UL test protocols are primarily intended for static utility-scale installations, Merlin Solar's internal testing replicates the dynamic and fatigue-driven conditions encountered in mobile operation.

- **Vibration and Fatigue:** Merlin Solar interconnects exceed **130,000 fatigue cycles** compared with approximately **450 cycles** for conventional soldered copper interconnects, representing nearly three orders of magnitude improvement in fatigue resistance.
- **UV Exposure:** Testing conducted by a Nationally Recognized Test Laboratory (NRTL) at **19×** standard IEC/UL ultraviolet exposure levels validate long-term electrical performance and structural integrity over the intended service life of up to **20 years**.

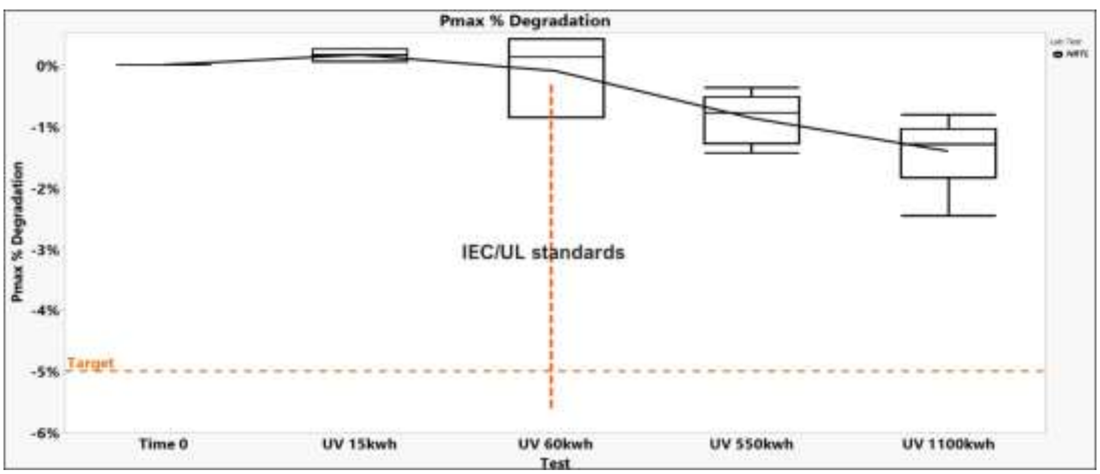

Figure 4.1. *Pmax degradation of Merlin Solar modules under accelerated ultraviolet (UV) exposure testing. Results demonstrate minimal power loss across exposure levels extending well beyond IEC/UL qualification limits, with degradation remaining significantly below the −5% target threshold through 1100 kWh/m² of cumulative UV dose, validating long-term electrical stability under extreme UV stress.*

Thermal Cycling

Merlin Solar panels withstand thermal cycling from **–40°C to 120°C** at **four times standard IEC/UL acceleration**, with minimal performance degradation. Standard thermal cycling protocols do not extend to temperatures commonly encountered in mobile solar deployments, where surface temperatures can routinely exceed **80°C** during normal operation.

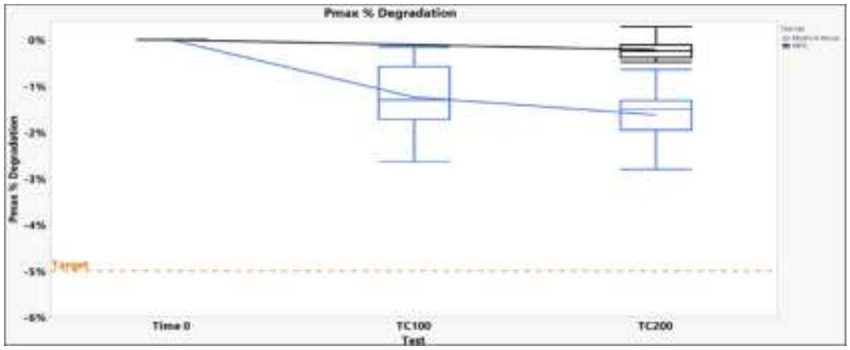

Figure 4.2. *Accelerated thermal cycling results for Merlin Solar modules, showing Pmax degradation remaining well below IEC/UL target thresholds through 200 cycles between −40 °C and 120 °C. Median degradation remains within the low single-digit percentage range, with no samples approaching the −5% performance limit, indicating strong thermal stability under temperature extremes representative of mobile operating environments.*

Humidity Freeze, Dry Heat, and Damp Heat

Merlin Solar subjects modules to extended environmental stress testing that significantly exceeds standard IEC/UL requirements. This includes **Humidity Freeze testing at 70 cycles** (compared to 10 cycles standard) and **Dry Heat exposure for 2,000 hours at 120 °C (248 °F)** versus the standard 200 hours at 105 °C (221 °F).

These tests evaluate long-term resistance to moisture ingress and sustained thermal exposure associated with solar loading, engine heat, and exhaust proximity. Under these conditions, Merlin Solar modules also demonstrate compliance with, and margin beyond, industry Damp Heat performance criteria.

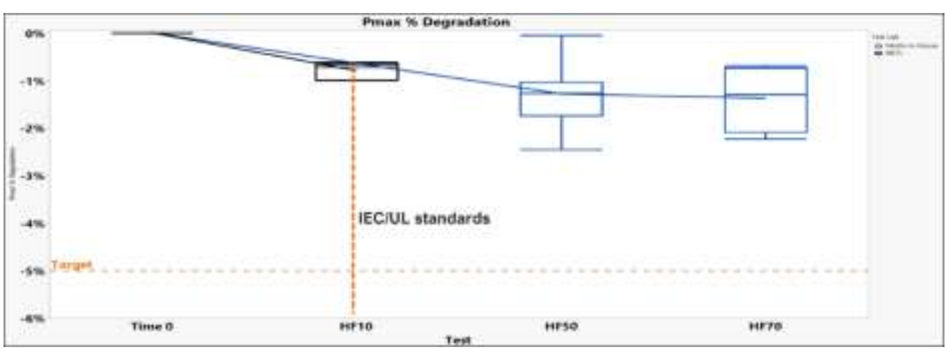

Figure 4.3. Humidity Freeze. *Pmax degradation of Merlin Solar modules after 70 humidity-freeze cycles. IEC/UL standards require 10 cycles, and industry programs typically test up to 30 cycles. Merlin Solar extends testing to evaluate long-term moisture durability of flexible modules, with degradation remaining well below IEC/UL limits.*

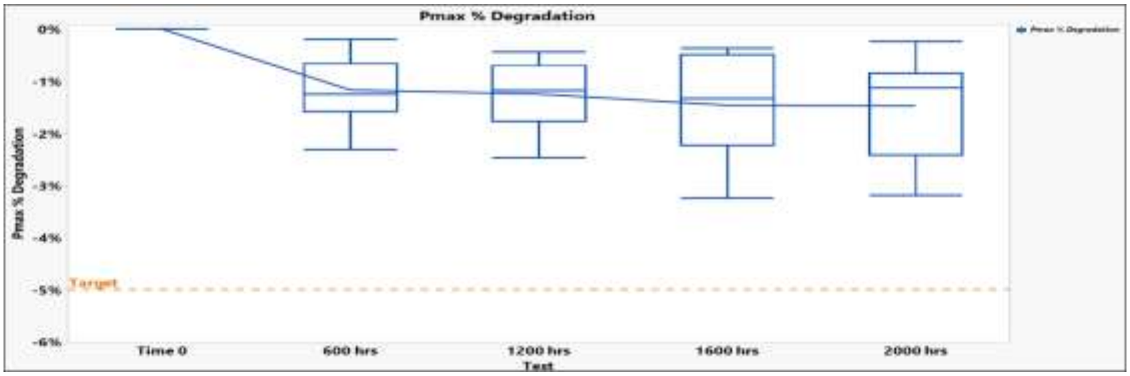

Figure 4.4. Dry Heat. *Pmax degradation of Merlin Solar modules following 2,000 hours of dry heat exposure at 120 °C. IEC/UL standards require 200 hours at 105 °C. Extended testing reflects continuous thermal loading in transportation environments, with degradation remaining within low single-digit percentage levels.*

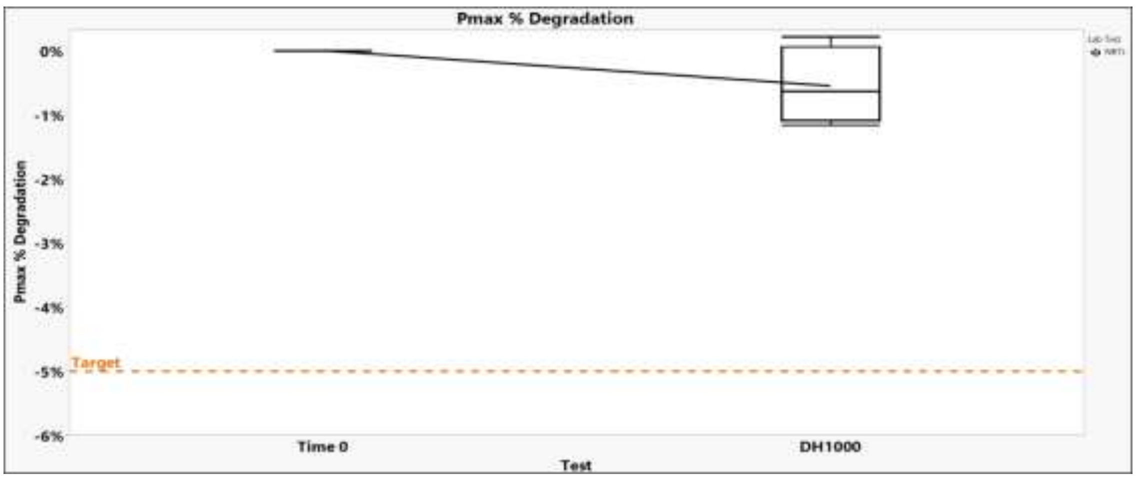

Figure 4.5. Damp Heat. *Pmax degradation of Merlin Solar modules after 1,000 hours of damp heat testing conducted by an NRTL. Results confirm compliance with IEC/UL damp heat criteria, while extended humidity-freeze testing remains Merlin Solar's primary moisture durability benchmark.*

4.2 Field Validation and Durability

In real-world incidents involving severe mechanical impact, Merlin Solar panels have remained both electrically functional and structurally intact.

In one documented event, a truck cab collided with an overbridge, resulting in the destruction of the fiberglass fairing. Despite the severity of the impact, the installed Merlin Solar panel continued to generate power and maintained structural integrity, effectively stabilizing the damaged fairing. Under comparable impact conditions, conventional glass-framed PV modules would be expected to fracture or shatter at substantially lower mechanical loads.

Figure 4.6. Field validation of mechanical durability following severe impact. *A Merlin Solar flexible crystalline silicon module installed on a commercial truck cab fairing remained electrically functional and structurally intact after the vehicle struck an overbridge, resulting in significant damage to the surrounding fiberglass structure. The panel continued to generate power and contributed to stabilizing the damaged fairing. For comparison, conventional glass-framed photovoltaic modules subjected to similar impact or hail events typically exhibit cell fracture, glass breakage, and loss of electrical continuity at substantially lower mechanical loads.*

5. Operational Performance Evidence

In contrast to static PV installations, mobile energy systems are routinely required to operate under diffuse irradiance, low sun angles, intermittent shading, and extended idle periods—conditions that challenge conventional solar performance assumptions[5].

Field results consistently demonstrate approximately 20% higher real-world energy capture compared with legacy rigid and BC systems under equivalent operating conditions.

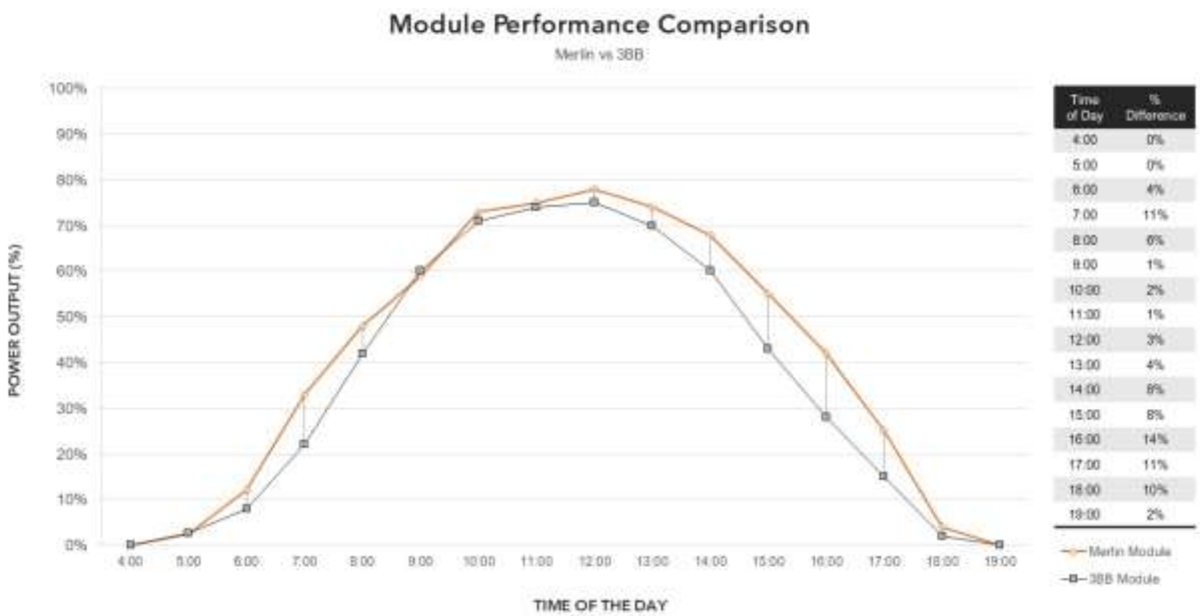

Figure 5.1. *Time-of-day power output comparison between Merlin Solar and a conventional 3-busbar (3BB) crystalline silicon module. Field-measured power output, normalized to peak midday performance, is shown across a full operating day. Merlin Solar maintains consistently higher relative output during morning and late-afternoon periods dominated by low sun angles and diffuse irradiance, with instantaneous performance advantages reaching ~10–15% during off-peak hours. Because these off-peak conditions account for a substantial fraction of daily operating time in mobile and deployable systems, the cumulative effect translates to approximately ~20% higher total daily energy capture compared with conventional rigid silicon architectures under real-world conditions.*

[5] IEEE Xplore: Field performance impacts of shading, mismatch, and operating conditions in photovoltaic modules https://ieeexplore.ieee.org/document/10531621

5.1 Power Availability and Runtime Extension

Extended Runtime Performance

Field data demonstrates that vehicles equipped with Merlin Solar achieve greater than 1.5× runtime for electric HVAC and hotel loads compared to both non-solar and legacy solar configurations. This extended runtime supports continuous operation throughout a standard 10-hour rest period without requiring engine starts, improving driver comfort while reducing idling and associated fuel and maintenance impacts.

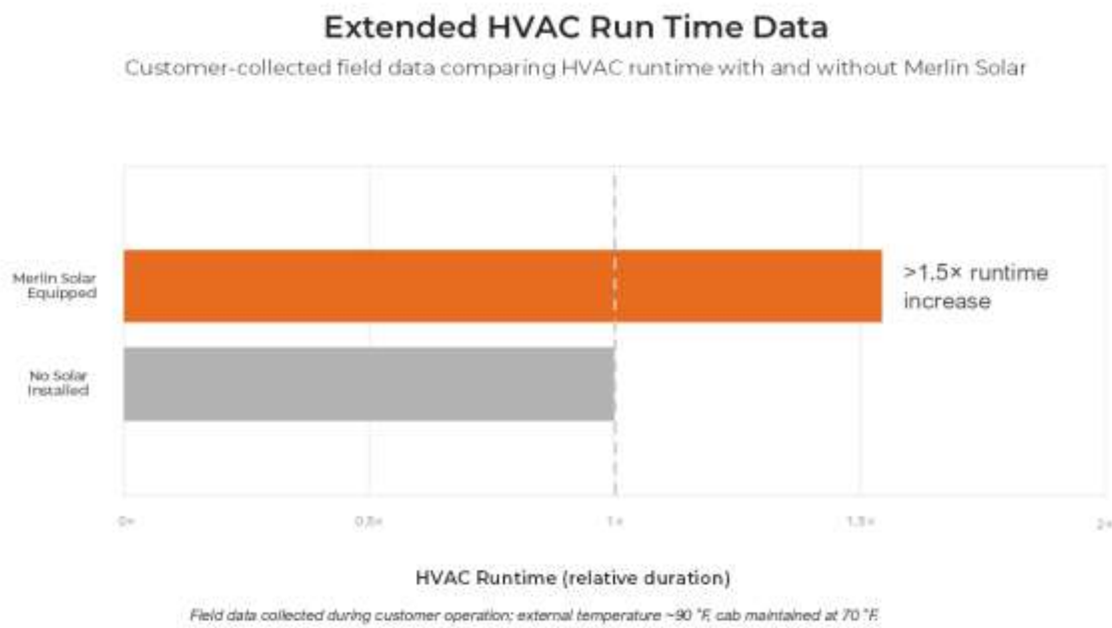

Figure 5.2. Customer-collected field data comparing HVAC runtime with and without Merlin Solar. *Vehicles equipped with Merlin Solar achieved greater than 1.5× HVAC runtime while maintaining a 70°F cab temperature during external temperatures peaking at 90°F, enabling extended climate control operation without engine idling.*

5.2 Real-World Energy Capture Under Low-Angle and Diffuse Irradiance

Merlin Solar's grid architecture enables effective energy harvesting across a broader range of irradiance conditions. In contrast to legacy PV modules that rely on direct, overhead sunlight to produce meaningful current, Merlin Solar systems begin generating power at lower sun angles and continue harvesting energy later into the day, increasing total daily energy yield under real-world operating conditions.

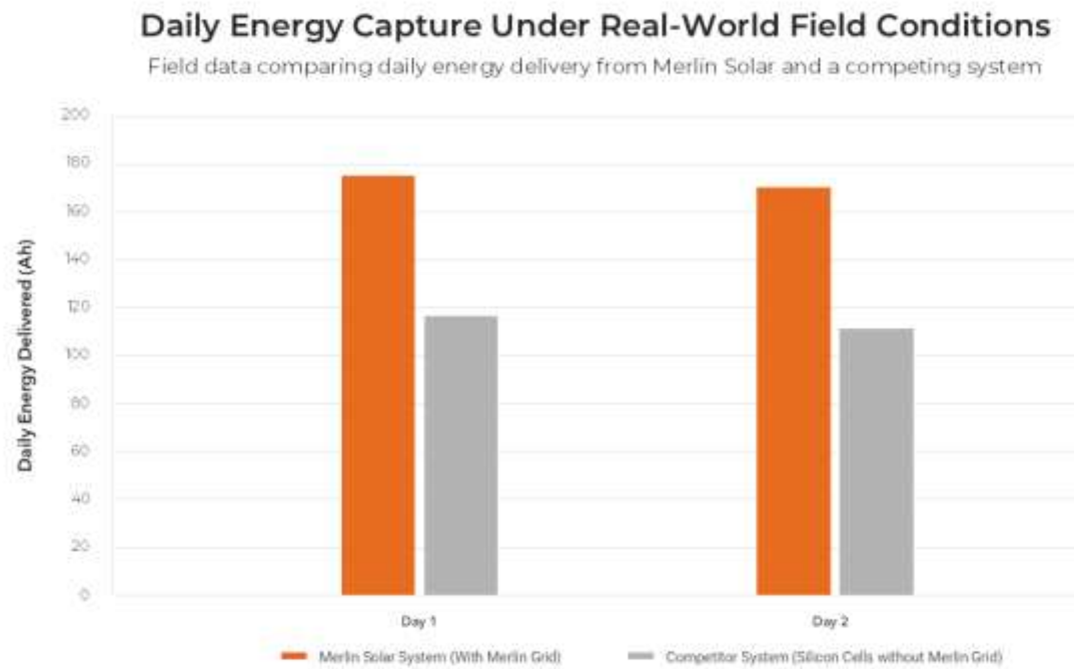

Figure 5.3. *Field data comparing daily amp-hour energy delivery from a Merlin Solar 400-series system incorporating the Merlin Grid architecture and a competing 300-series system using conventional silicon cells without Merlin Grid. Under real-world operating conditions, the Merlin system consistently delivered higher daily energy to the battery pack, achieving approximately 178 Ah (≈2.6 kWh) in a single day—representing roughly a 53% increase in daily energy yield despite comparable STC ratings.*

5.3 Battery Life Extension: Rationale and Field Validation

Battery degradation in transportation energy systems is most often driven not by battery defects, but by repeated deep discharge events. When battery voltage falls below critical thresholds, sulfation initiates, permanently reducing usable capacity and shortening service life.

Rationale

Merlin Solar provides continuous supplemental charging that prevents batteries from entering deep discharge conditions. By maintaining a consistently higher state of charge (SoC), the system mitigates the electrochemical degradation mechanisms that typically limit commercial battery service life to approximately **18–24 months**.

Field Validation

In a pilot deployment involving **10 heavy-duty trucks**, Merlin Solar's Jump Start Avoidance system was evaluated under conditions representative of real-world operational errors, including extended key-on states and auxiliary loads operating continuously over a **48-hour weekend period**.

Results

Even under low-light conditions, the Merlin Solar system maintained sufficient battery charge to start the vehicle or sustain auxiliary loads, with **zero jump-start events** recorded during the pilot.

Figure 5.4. *Field-recorded battery voltage traces from a multi-vehicle pilot deployment illustrating Merlin Solar's ability to prevent deep-discharge events under extended auxiliary load conditions. (Top) Aggregate battery voltage profiles across multiple trucks over a multi-day period. (Bottom) Representative vehicle trace highlighting voltage stabilization above the deep-discharge threshold (~8.1 V) and recovery toward full charge levels (~13.2 V) enabled by continuous solar charging. Results demonstrate improved battery protection, reduced jump-start risk, and enhanced operational reliability.*

5.4 Real-Time Visibility: Telematics and Performance Monitoring

Merlin Solar integrates telematics to provide continuous, objective visibility into system performance and battery health, enabling fleet operators to evaluate outcomes based on measured data rather than anecdotal observation.

In the absence of supplemental charging, starter batteries in commercial vehicles typically discharge within three to four days during extended idle periods. Using real-time voltage and energy-harvest monitoring, field data shows that Merlin-equipped fleets maintain average battery voltages above 13.2 V, even during prolonged inactivity. This data-driven approach allows battery voltage to serve as a consistent, repeatable indicator of system effectiveness across diverse operating conditions.

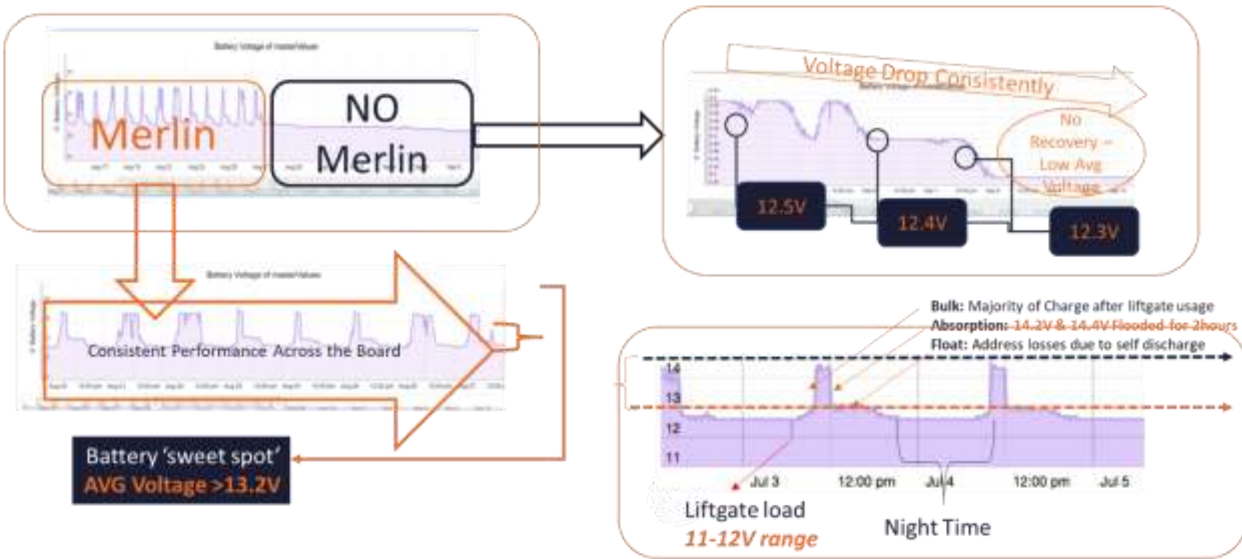

Figure 5.5. Telematics-derived battery voltage profiles comparing vehicles with and without Merlin Solar. *Merlin-equipped vehicles maintain consistent voltage recovery and average battery levels above 13.2 V during extended idle and auxiliary load periods, while non-solar configurations exhibit progressive voltage decline without recovery. Real-time monitoring enables objective, repeatable evaluation of battery health and system performance across operating conditions.*

6. Applications and Case Studies

Merlin Solar is not limited to a single vehicle type or industry. Our technology powers a vast ecosystem of mobile assets, ranging from Class 8 tractors and refrigerated trailers to last-mile delivery vans, ocean drones, and stratospheric balloons.

We support all vehicle powertrains (Gasoline, Diesel, CNG, Hybrid, and All-Electric), providing critical energy resilience across five primary categories:

1. **Connectivity & Securities:** Telematics, smart sensors, and cameras
2. **Freight & Logistics:** Battery maintenance for starter batteries, liftgates, pallet jacks, and reefers.
3. **Commercial Transport:** Idle reduction (APU) and Battery maintenance.
4. **Electric Mobility:** EV range extension and auxiliary load support.
5. **Specialty & Tactical:** Disaster relief, military, and maritime surveillance.

Figure 6.1. *Merlin Solar application scalability across vehicle classes and auxiliary power loads, supporting functions from telematics and battery maintenance for liftgate operation, HVAC loads, and hybrid TRU systems across gasoline, diesel, hybrid, and electric platforms.*

6.1 Commercial Trucking: Idle Mitigation & Battery Recovery

Figure 6.2. *Merlin Solar direct-fit panels installed on a Freightliner Cascadia cab fairing.*

Application

Class 8 Tractors (Sleeper Cabs).

Challenge

High idling requirements to support hotel loads (HVAC, refrigeration, onboard electronics) and frequent starter battery failures driven by repeated deep discharge events.

Merlin Solar Solution

Merlin Solar systems installed on sleeper cab fairings to supply auxiliary power for electric APUs and continuously maintain start battery state of charge.

Results

- **Idle Reduction:** Idle time reduced to <1%.
- **Battery Health:** In fleets where deep-discharge events are the dominant battery failure mode, starter battery service life has been extended from approximately 18 months to 3–4 years.
- **Return on Investment (ROI):** Full system ROI achieved within 15 months through fuel savings and reduced battery replacement and maintenance costs

6.2 Refrigerated Transport: eTRU Efficiency

Figure 6.3. *Fleet of AEM refrigerated trailers equipped with Merlin Solar panels.*

Application

Refrigerated Trailers (Reefers).

Challenge

The transition to electric Transport Refrigeration Units (eTRUs) has increased reliance on shore power and onboard battery capacity, introducing range limitations, added weight, and operational constraints for long-haul refrigerated transport.

Merlin Solar Solution

Installation of a 6 kW Merlin Solar system across the roof of a 48-foot refrigerated trailer to provide continuous supplemental energy generation during operation.

Results

- **Range Extension:** Enabled continuous operation from Miami to Phoenix on a single shore power charge under summer irradiance conditions, moderate refrigeration duty cycles, and continuous solar exposure.
- **Reduced Shore Power Dependency:** Shore power requirement reduced from approximately 200 kWh (baseline) to 48 kWh with Merlin-assisted operation

6.3 Liftgates & Material Handling: Plug-and-Play Battery Maintenance

In last-mile delivery operations, liftgate reliability directly impacts fleet uptime. Battery failures quickly translate into missed deliveries, vehicle downtime, and increased operating costs. To address this, Merlin Solar developed modular, plug-and-play charging kits designed to sustain liftgate and auxiliary batteries in high-cycle delivery environments, now adopted by major commercial fleets.

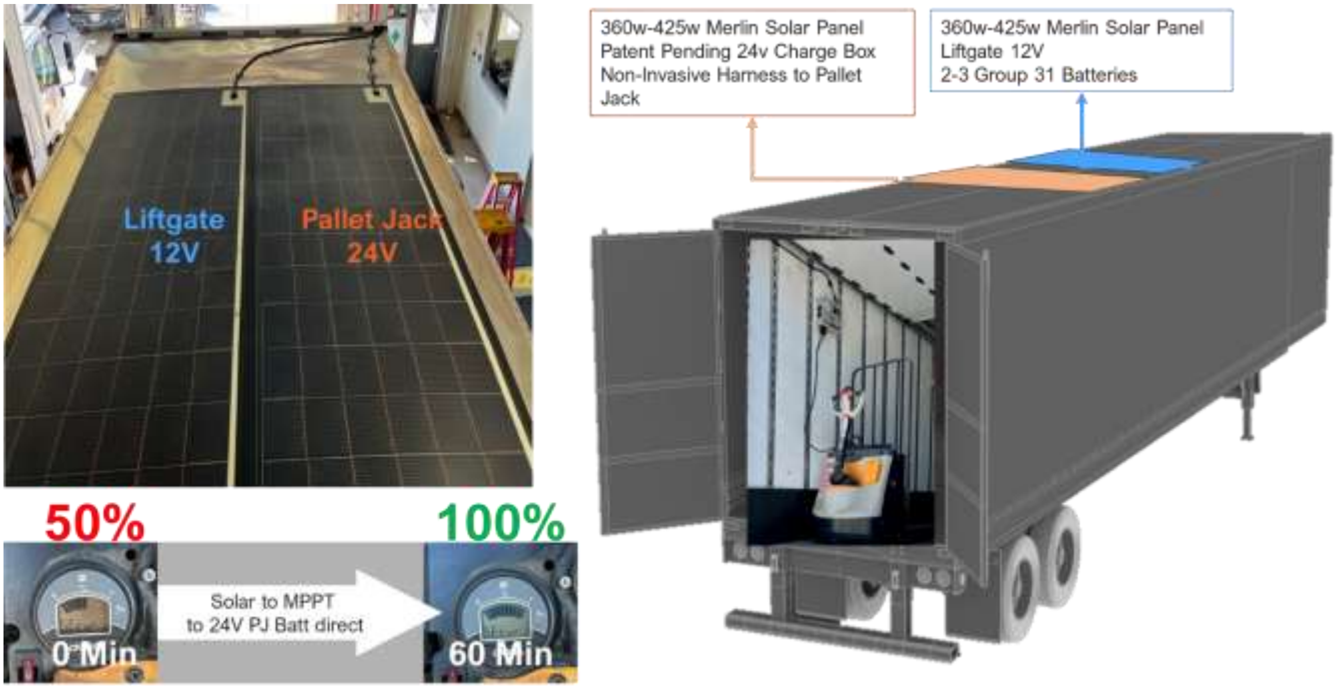

Figure 6.4. Dual-voltage Merlin Solar liftgate and pallet jack charging system on a delivery trailer. *Independent solar arrays and charge controllers simultaneously maintain 12 V liftgate batteries and 24 V pallet jack batteries through non-invasive harness connections, enabling autonomous charging and rapid state-of-charge recovery during daily delivery operations.*

Application

Regional food-service delivery trucks equipped with hydraulic liftgates and electric pallet jacks supporting high-frequency, multi-stop routes.

Challenge

A regional fleet operating along the Seattle–Portland corridor experienced recurring liftgate battery failures driven by aggressive daily cycling and limited alternator charging time between delivery stops. Battery depletion routinely caused liftgate downtime, forcing service interruptions, delayed deliveries, and increased maintenance intervention. Conventional charging strategies proved insufficient to sustain battery state of charge under real-world operating conditions.

Merlin Solar Solution

The fleet deployed Merlin Solar’s modular plug-and-play charging system integrating a proprietary charge controller capable of simultaneously maintaining 12 V liftgate batteries and 24 V pallet jack batteries. The system provided continuous supplemental charging throughout daily operation without requiring changes to driver behavior or vehicle electrical architecture.

Results

- **Sustained Battery State of Charge:** Average battery charge remained at approximately 100% over a three-year operating period despite heavy daily cycling.
- **Zero Battery Failures:** No liftgate battery failures were recorded during the pilot, with projected service life extending beyond six years.
- **Improved Operational Efficiency:** Drivers eliminated the need to idle vehicles to recover battery charge at delivery stops, reducing fuel consumption and operational disruption.

6.4 Electrical Reefer Load Support

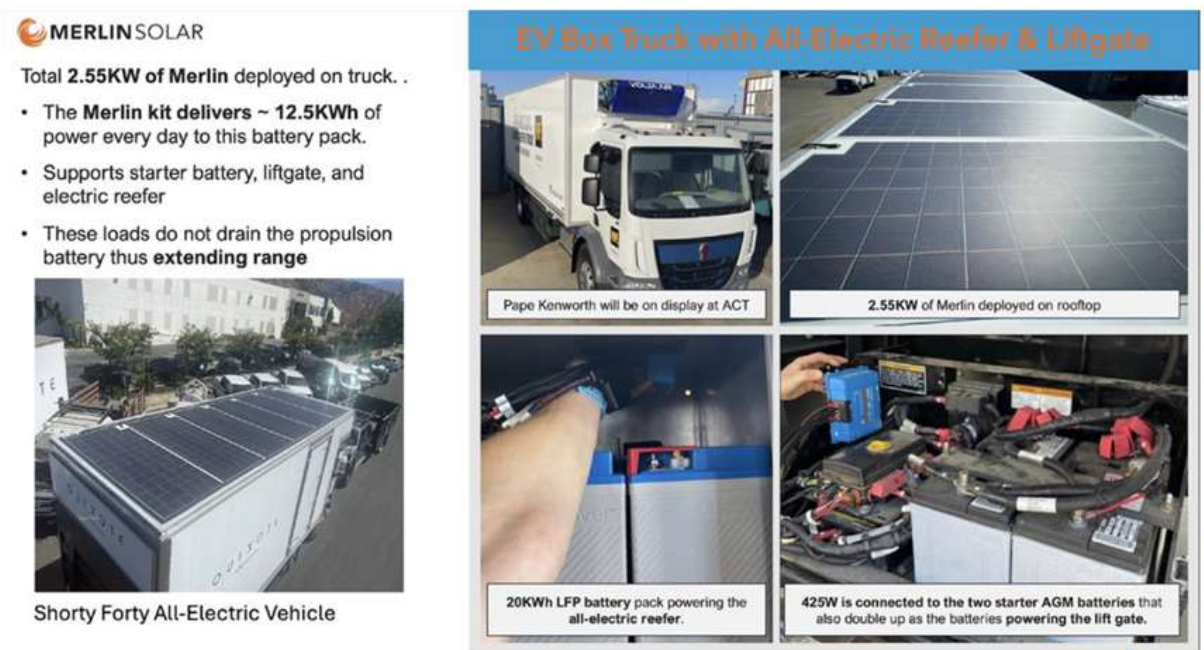

Figure 6.5. *2.55 kW Merlin Solar array integrated on the box truck roof, delivering daily solar energy to a 20 kWh LFP battery pack and AGM starter batteries to support refrigeration and liftgate loads independent of propulsion energy.*

Application

Class 4–6 electric box trucks (e.g., "Shorty Forty" platforms)

Challenge

In electric vehicle fleets, auxiliary loads, including refrigeration units, cabin HVAC, and liftgates, draw energy from the primary traction battery, reducing vehicle range and limiting route flexibility.

Merlin Solar Solution

Installation of a 2.55 kW Merlin Solar array on the vehicle roof to provide dedicated energy generation for auxiliary systems. The solar array generates approximately 12.5 kWh per day, supplying power directly to electric reefers, liftgates, and 12 V starter systems.

Results

By offloading auxiliary electrical loads to solar generation, the main battery is reserved primarily for propulsion, resulting in a measurable extension of vehicle operating range.

6.5 Off-Grid Energy Systems & Disaster Relief

Merlin Solar's lightweight, peel-and-stick form factor enables rapid deployment in disaster zones. From relocatable containers to deployable tents, Merlin Solar provides critical power where the grid is nonexistent.

Figure 6.6. *Multiple Merlin Solar energy systems, ranging from containers to deployable tents.*

6.6 Frontier and Tactical Applications

Merlin Solar's unique durability allows for highly specialized applications:

Maritime: Utilized on uncrewed ocean drones, Merlin panels withstand constant saltwater spray and hurricane-force winds while powering critical navigation and sensor arrays.

Stratospheric: Deployed on high-altitude balloons, Merlin Solar's technology endures extreme UV radiation and thermal shock in the upper atmosphere.

Figure 6.7. *Several autonomous ocean drones equipped with Merlin Solar panels.*

Figure 6.8. *High-altitude balloon powered by Merlin Solar.*

6.8 Forward Deployment

Merlin Solar powers "pop-up" energy systems on deployable tents and relocatable containers, providing immediate, fuel-free electricity for operation in contested environments.

Figure 6.9. Containerized solar power system. *Merlin Solar panels integrated onto a relocatable container provide immediate, fuel-free electricity for a pop-up energy system.*

Figure 6.10. Deployable solar-powered shelter system enabled by lightweight, flexible PV arrays. *Merlin Solar modules are integrated into rapidly deployable ground-mounted structures and temporary shelters, enabling scalable, fuel-free power generation for forward operations, emergency response, and expeditionary infrastructure. The modular architecture supports rapid setup, relocation, and operation in environments where permanent power infrastructure is unavailable or impractical.*

7. Conclusion

Figure 7.1. *Representative Merlin Solar deployments across diverse mobile and fixed applications, including (from top left to right): refrigerated trailers, Class 8 trucks, last-mile delivery vehicles, containers, deployable solar shelters, industrial drums, tensioned fabric roof structures, autonomous ocean platforms, and mobile utility carts.*

Renewable energy deployment in commercial transportation and mobile operations requires a fundamental rethinking of PV system architecture. Solar technologies optimized for static rooftop installations are structurally incompatible with the mechanical, thermal, and environmental conditions encountered by mobile assets. Field experience has repeatedly shown that conventional glass-framed modules and solder-dependent interconnect architectures are unable to sustain durable, continuous energy generation under vibration, thermal cycling, and dynamic loading.

Since 2016, Merlin Solar has addressed this limitation through a purpose-engineered interconnection architecture developed specifically for mobile energy generation. This approach has been validated through extended laboratory fatigue, thermal, and environmental testing, as well as more than **10 billion cumulative fleet road miles** of commercial field deployment.

Together, these results demonstrate that electrical performance can be preserved under sustained mechanical stress when the silicon cell is mechanically decoupled from rigid, solder-dependent interconnects. By separating electrical continuity from structural loading, Merlin Solar's architecture enables high-efficiency crystalline silicon to operate reliably in mechanically dynamic environments traditionally considered incompatible with photovoltaic systems.

This architectural approach delivers measurable operational advantages:

- **Durability:** Orders-of-magnitude improvement in fatigue resistance under vibration and thermal cycling.
- **Energy Yield:** Increased real-world energy production under diffuse light, partial shading, and non-ideal orientation.
- **Battery Health:** Continuous charge maintenance that reduces deep discharge events, eliminates jump starts, and extends battery service life.

Collectively, these results establish Merlin Solar as a technical benchmark for photovoltaic deployment in mechanically dynamic and infrastructure-limited environments. More broadly, the architecture expands the viable operating envelope of solar energy itself, enabling reliable, scalable, and sustainable power generation wherever mobile and remote assets operate.