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EDGE-SEALED MODULE (ESM) VALUE PROPOSITION REPORT

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EDGE SEALED MODULE

Executive Summary

The global PV industry is a massive and rapidly expanding market, with worldwide solar investment exceeding $480 billion in 2023[1], and an estimated 330 GW of new solar PV manufacturing capacity added globally in 2023 alone[2]. To help strengthen U.S. leadership in this critical energy sector, our group has developed a novel module architecture that radically simplifies manufacturing, reduces CAPEX and encapsulation cost by up to 80%, and enables high-value recycling.

This report outlines the key value proposition metrics and financial opportunity enabled by ESM technology. By replacing traditional polymer encapsulants with proprietary internal nanotextures, ESM fundamentally simplifies solar panel manufacturing, leading to substantial reductions in Capital Expenditure (CAPEX) and Operating Expenditure (OPEX), while enhancing long-term module reliability.

I. Technology:

1.1 What is the ESM Technology?

Encapsulant-Free Solar Module (ESM) is a disruptive module architecture that eliminates the need for Ethylene Vinyl Acetate (EVA) or Polyolefin Elastomer (POE) encapsulant films.

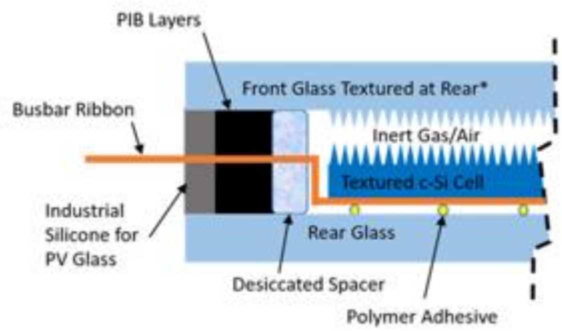

Figure 1: Cross-sectional view of ESM architecture.

- **Mechanism:** The ESM design utilizes internally applied **nanotextures—**fine surface geometries—on the top glass (interior side) and the solar cell surfaces (as shown in figure 1).
- **Function:** These nanotextures are optically engineered to mitigate the losses typically managed by the encapsulant's index of refraction, specifically by **redirecting incident light** back toward the cell and managing internal thermal dynamics through improved convection[3].
- **Proof of Concept:** Initial success has been demonstrated using over-the-counter materials in preliminary testing. The next phase, with is focused on optimizing a proprietary, scalable solution.

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[1] (2024). World Energy Investment 2024 (or similar IEA report covering 2023 data).
[2] International Energy Agency (IEA). (2023). Renewables 2023: Analysis and forecasts to 2028.
[3] D. Durney, R. Ruhle, L. Maple, S. Johnston, D. Kern and W. Sampath, "Edge Sealed Photovoltaic Modules: Matching Thermal and Optical Properties of Traditional Encapsulation," *2025 IEEE 53rd Photovoltaic Specialists Conference (PVSC)*, Montreal, QC, Canada, 2025, pp. 1208-1211, doi: 10.1109/PVSC59419.2025.11133277.

1.2 Main Advantages

The ESM approach solves critical pain points in conventional solar manufacturing, translating directly into enhanced investor value.

Advantage	Benefit	Impact
Lower Capital Expenditure (CAPEX)	Eliminate high-cost vacuum lamination process which requires substantial parallelization of lines resulting in costly equipment for high-throughput manufacturing.	**Reduction** in module assembly **CAPEX** for a new plant[4].
Lower Operating Expenditure	Eliminates the material cost of encapsulant films and significantly reduces energy consumption for the lamination step.	**Reduced material** and **energy** input compared to traditional encapsulation methods.
Superior Reliability	Removes polymer degradation pathways (UV damage, PID at the film interface, acetic acid buildup, and more). The focus shifts to a highly robust edge seal.	**Improved reliability** and **greater moisture resistance**, leading to superior long-term performance and reduced warranty risk.
Enhanced Recyclability	Eliminating polymer encapsulant films allows for simpler, cleaner module disassembly and recovery of high-value silicon cells and glass.	**Significant reduction in end-of-life disposal costs** and potential for revenue from high-value material recovery (ESM advantage).

1.3 Competing Technologies and Differentiation

The primary competitors are incremental efficiency gains in existing cell architectures (e.g., TOPCon, HJT) and cost reduction via thin-glass or polymer backsheets.

- **Differentiation:** ESM is **cell-agnostic**. It applies to all high-efficiency crystalline silicon cells (PERC, TOPCon, HJT).

[4] Industry Price Data (2024). *Pricing for high-volume, fully automatic PV Module Vacuum Laminators*. (Single units range from $170,000 to $450,000 USD).

- **Strategic Position:** While competitors focus on increasing efficiency within the cell, ESM focuses on **radically reducing the cost and complexity of the package**, offering an immediate and scalable structural cost advantage not available through incremental cell improvements.
- **Forward-Looking:** Due to the improved moisture barrier and reduced process conditions, ESM may also prove to be extremely beneficial for next-generation PV devices such as perovskites.

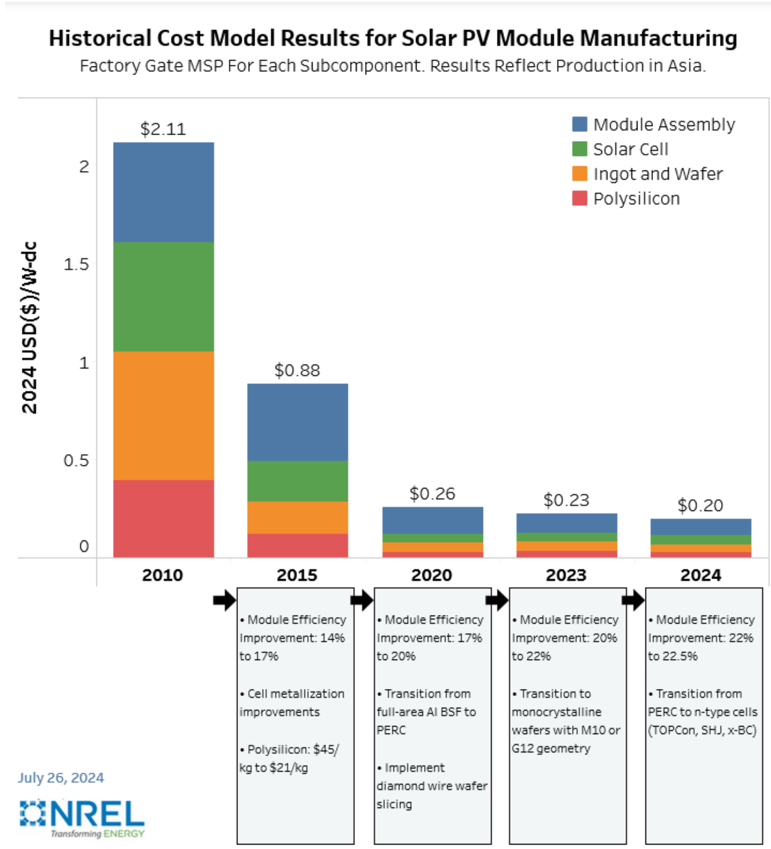

Figure 2: Cost breakdown by year of PV manufacturing. Despite massive improvements, note that Module Assembly remains a dominant part of PV manufacturing costs.

2. Manufacturing Strategy and Cost Analysis:

SCOPE CLARIFICATION: The following analysis focuses exclusively on the **PV Module Assembly** segment of the PV supply chain, assuming finished solar cells and glass components are supplied externally to the factory gates. For this report, data is primarily source from NREL provided solar market research which is publicly available[5]. Capitol cost savings are approximated by narrowing the scope of this report to focus on the elimination of vacuum lamination and its subsequent replacement, including process steps developed at CSU which would be involved in the replacement of traditional encapsulation techniques. Figure 2 shows a cost breakdown of PV module manufacturing by year provided by NREL. Despite cost being reduced to $0.20/Wp, module assembly remains a majore cost center for PV manufacturing[6].

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[5] National Renewable Energy Laboratory. (n.d.). *Solar market research & analysis*. Retrieved December 4, 2025, from https://www.nrel.gov/solar/market-research-analysis

[6] Zuboy, J. (n.d.). *Module Manufacturing Costs* [Data visualization]. Tableau Public. https://public.tableau.com/app/profile/jarett.zuboy/viz/ModuleManufacturingCosts/ModuleManufacturingCosts

2.1 Value Approximation of Benefits Breakdown

To illustrate the financial impact and the scale advantage of ESM, we benchmark savings across two distinct module assembly facility sizes: a modular 200 MW plant and a large-scale 5 GW assembly facility.

This report approximates the savings for two separate plants (200 MW and 5 GW) to represent the difference between larger plants which may have economies of scale to benefit from, while also representing the smaller end of projections where the cap ex savings may be more significant to the plant operator.

2.1.1 CAPEX Breakdown

Traditional lines are limited by the cycle time of vacuum lamination, which typically takes **8–15 minutes** per cycle to ensure proper cross-linking of the polymer. Because of this "slow" step, factories must use multiple parallel laminators to match the high-speed output of tabbing and stringing machines. We estimate the cost of the vacuum laminator, supporting hardware such as cooling, automation, vacuum hardware, and utility infrastructure. While machines can cost as little as **$350K**, we estimate an average of **$750K** for a large-scale factory taking advantage of economies of scale, and about **$1.0M** fully burdened for these additional elements[7].

While roll-to-roll (R-2-R) processing first-of-a-kind estimates come as high as **$1.2 million**, we utilize this number for a small factory which would also be representative of an initial pilot. Approximating based on **8-minute cycle times** (traditional) versus **50 meters/minute** production speed (ESM)[8]. Estimating a modern panel to produce **700 watts** (large-scale manufacturing) and about **450 watts** for smaller scale manufacturing, we also reduce the **50 meters/minute** by a factor of two since both rear glass and cell must be manufactured. However, estimating that the roll can be the width of the panel itself, we can actually arrive at this producing up to **600 MW**, which is significantly higher than the 200 MW benchmark.

Comparing this directly to traditional vacuum laminators, we see that even if a first-of-a-kind machine at higher cost will significantly drive the unit price up, **the capital efficiency per watt is vastly superior.** A single ESM machine replaces the equivalent of **12 to 15 traditional lamination stations** required to reach the same 600 MW throughput. Consequently, the ESM architecture achieves a **60-80% reduction in module assembly CAPEX** by consolidating a massive, energy-intensive parallel fleet into a single high-speed processing line.

200 MW Facility: Modular/Small Scale

At this scale, the traditional plant suffers from the high cost of burdening individual lamination stations.

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[7] Qinhuangdao Zenithsolar Technological Co., Ltd. (2024). *Double stack laminator: ZST-AYZ-24-46DS*. https://www.zenithsolarmachinery.com/Double-Stack-Laminator-pd523220858.html

[8] Internal correspondence and technical validation call with nanotexture application equipment manufacturer (2025), confirming a baseline throughput of **50 m/min** for proprietary R2R imprinting/coating processes.

- **Traditional CAPEX (Lamination):** To produce **200 MW** annually with an **8-minute** cycle time, a facility requires approximately **5 stations**. At a fully burdened cost of **$1 million** per station, the total lamination CAPEX is **$5 million**.
- **ESM CAPEX (Nanotexture):** A single R2R machine with a first-of-a-kind estimate of **$1.2 million** replaces the entire fleet.
- **Direct Equipment Savings: $3.8 million** (a **76% reduction** in lamination-specific capital).
- **Total Facility Impact:** This contributes to the overall projected module assembly CAPEX of **$4–$8 million** for an ESM plant, compared to **~$20 million** for a traditional plant.

5 GW Facility: Large Scale/Dedicated

At the 5 GW scale, economies of scale reduce individual unit costs, but the massive number of units required for a traditional fleet creates a staggering capital burden.

- **Traditional CAPEX (Lamination):** Assuming a high-capacity laminator station handles approximately **40–50 MW** per year, a **5 GW** facility requires roughly **100 to 125 units**. Even at a reduced bulk price of **$750,000** per station, the lamination fleet alone costs between **$75 million and $93.75 million**.

- **ESM CAPEX (Nanotexture):** Based on the logic that one R2R machine can produce up to **600 MW**, a 5 GW facility would require approximately **9 machines** to handle the load with some redundancy. At a reduced cost of **$600,000** per unit, the total CAPEX for texturing is **$5.4 million**.

- **Direct Equipment Savings: $69.6 million to $88.35 million**.

- **Total Facility Impact:** This massive reduction in hardware, floorspace, and utility infrastructure drives the absolute dollar savings of **$270–$360 million** projected for a 5 GW facility.

2.1.2 OPEX Breakdown

To break down the Operational Expenditure savings, we begin by evaluating the displacement of traditional polymer encapsulants with proprietary internal nanotexturing. Conventional modules rely on Ethylene Vinyl Acetate (EVA) or Polyolefin Elastomer (POE) films, which currently carry a material cost of approximately **$1.00 per square meter**. At an assumed module efficiency of 20%, a standard panel produces **200 Watts per square meter**, resulting in an encapsulant material cost of roughly **0.5 cents per watt**. This material cost is eliminated in ESM architecture.

The ESM process replaces these films with a nanotexture application estimated at **2 cents per square foot** per treated surface[9]. Because the ESM design requires texturing both the rear glass and the silicon cell to manage light redirection and thermal dynamics, this cost is adjusted to **4 cents per square foot**. When converted, this equates to roughly **43 cents per square meter**, or **0.215 cents per watt** at 20% efficiency. This shift creates a direct material cost advantage of approximately **0.285 cents per watt** before accounting for the significant reduction in energy consumption typically required for high-heat (150°C+) lamination steps.

[9] Technical validation and cost analysis correspondence with R2R equipment manufacturer (2026), confirming a nanotexture application cost of **per square foot** per treated surface. This figure accounts for proprietary material chemistry and high-volume imprinting/coating throughput.

200 MW Facility: Modular/Small Scale At this scale, the OPEX advantage is driven by both material savings and the elimination of the energy-intensive lamination bottleneck.

- **Traditional OPEX (Encapsulant & Energy):** Operational costs are estimated between **$0.05 and $0.06/W**.
- **ESM OPEX (Nanotexture):** Streamlined manufacturing and lower energy requirements reduce costs to **$0.04 - $0.045/W**.
- **Direct Savings: $0.01 – $0.02/Wp**, representing a cost reduction of **16.7% to 40%**.

5 GW Facility: Large Scale/Dedicated While large-scale facilities already benefit from high optimization, the ESM architecture provides a structural margin improvement through material displacement.

- **Traditional OPEX (Encapsulant & Energy):** Baseline operating costs range from **$0.045 to $0.05/W**.
- **ESM OPEX (Nanotexture):** Large-scale material procurement and high-speed R2R processing lower costs to **$0.04 - $0.045/W**.
- **Direct Savings: $0.005 – $0.01/Wp**, providing a **10% to 22.2%** reduction in operating expenses.

2.1.3 Material Recovery Breakdown

Conventional PV recycling is often cost-prohibitive because the ethylene vinyl acetate (EVA) or polyolefin elastomer (POE) must be thermally or chemically stripped, frequently damaging the silicon cells and contaminating the glass. By eliminating these films, ESM modules allow for clean, mechanical disassembly at end-of-life. This transforms the module from a waste burden into a recoverable asset, specifically targeting the high-purity silicon and "solar grade" glass that represent the bulk of the module's original material value.

That being said, our approximation compares throwing the material away versus being able to recover high-purity silicon, glass, and other elements within the solar panel. This becomes slightly complicated since while we anticipate a longer life span, approximating this we can start with the baseline of about $5.00 per panel to dispose of[10]. Instead of also assuming a longer lifespan, we simply will assume that all panels last approximately 30 years and use an average Internal Rate of Return (IRR) of 12.5%[11].

Removing the polymer "cement" (EVA/POE) allows for the extraction of silicon and metals without the chemical contamination or mechanical breakage that plagues traditional thermal recycling. Based on 2025 commodity benchmarks and module composition, the recoverable value of the laminate core is approximately **to per panel**:

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[10] Taylor, R., Enbar, N., & Moore, S. (2021). *Solar photovoltaic module recycling: A review of the current landscape*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/79450.pdf
[11] Solar Energy Industries Association. (2025). *Solar market insight report: Q4 2025*. https://seia.org/research-resources/solar-market-insight-report-q4-2025/

Recoverable Material Breakdown (Laminate Only)[12]:

- **Silver & Copper: $1.50 – 3.50**. These represent the highest value-to-weight ratio. ESM allows for the clean separation of silver-paste busbars and copper ribbons.
- **Silicon (Solar Grade): $1.00 – $2.00**. Traditionally, silicon is recovered as low-grade "fines." ESM preserves the wafer's integrity or high-purity shards, which can be re-melted into new solar-grade ingots.
- **Glass (Solar Grade): $0.50 – $1.50**. Because there is no polymer residue, the glass retains its "low-iron" high-transparency rating, allowing it to be sold back into the flat-glass or solar-glass market rather than being downcycled into road aggregate.

Utilizing a "middle of the road" estimate of **$5.00 per panel** in material recovery , combined with the avoided **$5.00 per panel** disposal liability , the total terminal gain is **$10.00 per panel**. At a panel output of 500 Watts, this represents a net gain of **$0.02 per watt**[13]. When calculating back 30 years using the 12.5% IRR, this yields an NPV savings of **$0.00058 per watt**.

2.1.4 Value Added Summary:

Cost Metric	Capacity Benchmark	Traditional PV Module Assembly CAPEX (Estimate)	ESM PV Module Assembly CAPEX (Estimate)	CAPEX Savings	Percent Savings
CAPEX	**200 MW Facility** (Modular/Small Scale)	~$20 Million	~$4-$8 Million	~$12-16 Million	**60% to 80%**
	5 GW Facility (Large Scale/Dedicated)	~$450 Million	~$90–$180 Million	$270–$360 Million	**60% to 80%**
OPEX[14]	**200 mw Facility** (Modular/Small Scale)	$0.05 - $0.06/W (Traditional)	$0.04 - $0.045/W (ESM)	**$0.01 – $0.02/Wp Savings**	**10% to 20%**
	5 GW Facility (Large Scale/Dedicated)	$0.045 - $0.05/W (Traditional)	$0.04 - $0.045/W (ESM)	**$0.005 – $0.01/Wp Savings**	**10% to 22.2%**

[12] Global Market Insights (2025) identifies silver and copper as the primary economic drivers of PV recycling, with silver recovery alone projected to exceed a **billion** market value by 2034. ESM's polymer-free architecture is the critical enabler for capturing this value, moving the end-of-life stage from a disposal liability (NREL, 2021) to a net-positive asset recovery.

[13] Sinha, P., Raju, S., Drozdiak, K., & Wade, A. (2020). Life cycle management and recycling of PV systems. *Photovoltaics International, 38*, 72–78. https://www.pv-tech.org/wp-content/uploads/legacy-publication-pdfs/3d7e3f2260-photovoltaics-international-volume-38.pdf

[14] PV Magazine (2023). *Solar giants bet big on US manufacturing*. (Provides CAPEX context for multi-GW scale PV module assembly plants and industry cost trends).

Material Recovery Value	**Estimates are the same** (Modular/Small Scale)	$0.00029/W **cost** for disposal	$0.00029/W **Value Added** for material recovery	**$0.00057/Wp Value Added**	

The benefit of ESM varies by scale, supporting a dual market strategy:

- **CAPEX Advantage (5 GW Scale):** The large facility realizes the maximum **absolute** dollar savings (up to $360M), driven entirely by eliminating the massive vacuum lamination fleet and its associated infrastructure. This makes ESM technology critical for major manufacturers like Maxeon pursuing large-scale expansion.
- **OPEX Advantage (200 MW Scale):** The smaller, modular facility realizes the maximum **per-watt OPEX savings** (up to $0.02/Wp or 40% cost reduction for smaller plants). This is due to the smaller traditional lines being inherently less energy and labor efficiency. By removing the energy-intensive lamination bottleneck, ESM drastically optimizes the entire small-scale production cost structure, providing a stronger competitive edge for regional or specialized manufacturers.

2.2 Process Flow Transformation

ESM fundamentally alters the high-heat lamination sequence, substituting it with a high-throughput nanotexturing process and edge sealing.

Traditional Factory Layout:	**Encapsulant-Free (ESM) Factory Layout:**
1. Tabbing & Stringing	**1. Tabbing & Stringing**
2. Layup: Glass, EVA/POE, Cells, EVA/POE, Backsheet	**2. Nanotexture Application:** Imprint/Coat Glass & Cells (**Specialized Tooling Partner**)
3. Lamination: High heat (150°C+), High-pressure pressing (Slow, high energy) and high-cost parallelization	**3. Modified Layup:** Treated Glass, Cells, Treated Back Layer
4. Framing & Sealing	**4. Edge Seal & Press:** Focus on rapid, hermetic sealing (Low heat, minimal press)
5. Testing (QA/QC)	**5. Testing (QA/QC)**

Key Process Advantage: The vacuum lamination step (Traditional Step 3), historically one of the **largest capital and cycle-time bottlenecks** in the entire **PV module assembly** line requiring multiple and costly parallel machines to achieve line speed[15], is replaced by an integrated, high-

[15] K. L. Barth, et al., "Abound Solar's CdTe module manufacturing and product introduction," in *2009 34th IEEE Photovoltaic Specialists Conference (PVSC)*, Philadelphia, PA, USA, 2009, pp. 228-232. doi: 10.1109/PVSC.2009.5411358.

speed nanotexture application and edge seal machine. This elimination is the core driver of the 60-80% CAPEX savings.

Conclusion

The **Edge-Sealed Module (ESM)** architecture represents a paradigm shift in solar manufacturing by moving away from traditional polymer-based encapsulation toward a streamlined, **encapsulant-free design**. By replacing high-cost vacuum lamination with proprietary nanotextures and advanced edge sealing, this technology addresses the most significant bottlenecks in the current PV supply chain.

The financial and operational benefits are clear across all production scales:

- **Capital Efficiency**: Achieving a **60–80% reduction in module assembly CAPEX** by eliminating the need for massive, energy-intensive parallel lamination fleets.
- **Operational Savings**: Realizing up to a **40% reduction in OPEX** for modular facilities through material displacement and reduced energy consumption.
- **Sustainability & Circularity**: Transforming end-of-life modules from a $5.00 disposal liability into a **recoverable asset** with approximately $5.00 in high-value material value per panel.

Ultimately, ESM technology provides a scalable, cell-agnostic solution that radically simplifies the packaging of solar modules. Whether applied to massive 5 GW installations to maximize absolute dollar savings or modular 200 MW plants to capture superior per-watt margins, ESM offers a structural cost advantage that positions it as a cornerstone for the next generation of high-efficiency and sustainable solar energy.