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Closing the Clean Energy Manufacturing Gap: A Strategic Financing Framework for U.S. Solar, Battery, and Wind Component Supply Chains

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Abstract

Introduction: Domestic clean energy production levels in the United States cover only 26% to 36% of wind blade needs, 35% of solar cell requirements, and under 45% of battery cell demand between 2030 and 2035. On the other hand, China controls about 60% to 80% of these global markets and benefits from subsidized financing that U.S. manufacturers cannot match. The United States clean energy manufacturing sector (CEMS) is therefore not adequately prepared for the ongoing energy transition. Closing this gap will require $186 billion to $231 billion in private capital and implementation of strategic structures. This paper presents the Clean Energy Manufacturing Finance Framework (CEMFF) as a medium to close the gap.

Methodology: The study was performed in three stages. First, the Clean Energy Manufacturing Gap (CEMG) model was constructed to quantify domestic capacity shortfalls in wind blade, solar cell, and battery cell manufacturing for 2030 and 2035, using deployment scenarios from the U.S. Energy Information Administration, the U.S. Department of Energy (DOE), and the Princeton REPEAT Project, with committed capacity and cost data drawn from the DOE, the National Renewable Energy Laboratory (NREL), BloombergNEF, and S&P Capital IQ. Second, the Clean Energy Manufacturing Finance Framework (CEMFF), a four-instrument blended capital structure, was designed and calibrated to segment-level required returns. Third, the framework was stress-tested across 81 combinations of assumptions for tariffs, tax credits, interest rates, and deployment scenarios.

Results: The CEMFF achieved portfolio-weighted average reductions in the weighted average cost of capital (WACC) of 190 to 280 basis points (bps), mobilized $6.1 in private capital for each dollar of public support, and delivered cost competitiveness with Chinese producers in 78% of modeled scenarios. The sensitivity analysis indicated that the framework is robust to individual shocks. However, a worst-case scenario involving tariff increases, erosion of the US Inflation Reduction Act (IRA) credit, and rate hikes reduced competitiveness to 38% across modeled scenarios. Overall, these findings have important implications for DOE Loan Programs Office (LPO) structuring, Treasury Section 6417 direct-pay guidelines, and Export-Import (Ex-Im) Bank supply chain guarantees.

1 Introduction

The United States faces a large gap in clean energy manufacturing. Federal initiatives, including the US Inflation Reduction Act (IRA), the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act, and the Bipartisan Infrastructure Law (BIL), have committed over $1.2 trillion toward decarbonization efforts (Drury and Smeltzer, 2024). Yet the factories and supply chains needed to produce solar cells, battery cells, and wind components are far behind projected demand (DOE 2024; BloombergNEF 2025).

China currently controls about 80% of global solar and 75% of lithium-ion battery cell manufacturing, and 60% of wind turbine component supply chains (IEA, 2024). This situation creates a strategic risk for the U.S. should there be a geopolitical disruption from such foreign-controlled supply chains. Furthermore,

Chinese producers benefit from subsidized financing that U.S. manufacturers cannot match (Helveston et al., 2022). Required returns for private capital range from 10.8% for Tier 1 battery gigafactories to 18.2% for lithium processing. This exceeds Chinese competitors' cost of capital by 400 to 800 bps (S&P Capital IQ, 2025; Damodaran, 2025).

1.1 Blended Finance and Capital Structure for Clean Energy

Blended finance reduces the effective cost of capital by absorbing first-loss risk, providing guarantees, or supplying anchor equity that allows commercial tranches to price more favorably (Mazzucato and Penna 2016; Convergence 2023). This approach has primarily been applied to utility-scale renewables in emerging markets (Buchner et al. 2022; OECD 2023) and grid modernization in advanced economies (Polzin et al. 2019). However, its application within manufacturing supply chains remains underexplored, and this paper aims to address that gap.

Zerbib (2019) identifies a greenium ranging from 2 to 8 bps for green bonds, and Flammer (2021) extends this to corporate green bonds. The Clean Energy Manufacturing Finance Framework (CEMFF) GMB Green Manufacturing Bonds (GMBs) instrument builds further on this evidence by adding manufacturing-specific sustainability performance indicators (SPIs) and Advanced Manufacturing Production Credit (AMPC) coverage covenants. Furthermore, Gupta and Noh (2025) show leverage ratios of 5 to 10 times using blended tranched structures for early-stage clean energy ventures. The CEMFF adapts this to the mature manufacturing sector, where IRA Section 45X credits and Foreign Entity of Concern (FEOC) compliance requirements create a distinct risk and regulatory context.

1.2 Industrial Policy, Manufacturing Finance, Supply Chain Risk and FEOC Regulation

Rodrik (2004) and Aghion et al. (2015) argue that directed investments are needed when market failures prevent efficient private investments. Such failures include coordination problems, learning externalities, and interactions fueled by foreign industrial policy. Clean energy manufacturing exhibits all these challenges. The coordination between battery cell producers, cathode suppliers, and lithium processors creates benefits that individual firms cannot obtain. This is because learning-by-doing generates knowledge spillovers (Helveston et al. 2022). Chinese industrial policy creates a competitive landscape that private capital cannot match alone. Mazzucato (2013) and Block and Keller (2011) argue that state co-investment and risk sharing are therefore essential. The DOE Loans Program Office (LPO) supports this view and has provided over $30 billion in loan guarantees for clean energy manufacturing since 2020 (DOE LPO 2025).

Bown (2023) assesses U.S. dependence on clean energy imports and analyzes the welfare effects of trade restrictions under the IRA FEOC provisions, whose rules create a binding capital structure constraint. This is because its financing relies on FEOC-affiliated equity, which may disqualify projects from credit eligibility. The CEMFF treats FEOC compliance as a built-in constraint, and hence, designs the

SPV and GMB terms to align with eligible allied-nation capital and FEOC-compliant supply chain requirements.

This paper presents three contributions to this study, which is the first to treat policy interdependence in clean energy manufacturing finance systematically. Firstly, it builds the Clean Energy Manufacturing Gap (CEMG) model, which differentiates domestic manufacturing shortfalls by sector and scenario. Secondly, it develops the CEMFF model, which is a capital structure consisting of Sovereign Wealth Fund (SWF) Co-Investment Special Purpose Vehicles (SPVs), GMBs with IRA AMPC provisions, Blended First-Loss Capital Tranches (BFLCTs), and Pension Fund Infrastructure Allocations (PFIA). In particular, CEMFF is a four-instrument capital structure that aims at reducing weighted average cost of capital (WACC) to commercially viable levels through blending concessional and market-rate capital. Thirdly, it presents a 81-combination policy sensitivity analysis.

2 Methodology

2.1 Research Design

The study was performed in three sequential stages. In the first stage, the Clean Energy Manufacturing Gap (CEMG) model was constructed to quantify the shortfall between projected U.S. clean energy deployment requirements and committed domestic manufacturing capacity, and the resulting private capital requirement was estimated. In the second stage, the Clean Energy Manufacturing Finance Framework (CEMFF), a four-instrument blended capital structure, was designed and calibrated to close that requirement at commercially viable financing costs. In the third stage, the calibrated framework was stress-tested across 81 combinations of policy and market parameters. Each stage is described in turn below.

2.2 Stage 1: The Clean Energy Manufacturing Gap Model

2.2.1 Model Structure and Data Sources

The CEMG model was built to quantify the gap between projected U.S. clean energy deployment needs and domestic manufacturing capacity in three sectors: wind blade components, solar photovoltaic (PV) cells, and lithium-ion battery cells. Deployment requirements for 2030 and 2035 were taken from three scenarios: the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) 2025 stated policy scenario (EIA 2025), the DOE Solar Futures Study accelerated transition scenario (DOE 2024), and the Princeton REPEAT IRA+ rapid decarbonization pathway (Princeton REPEAT Project 2024).

Committed domestic capacity was defined as capacity that had reached financial close as of Q4 2024. These data were obtained from the BloombergNEF Clean Energy Manufacturing Investment Tracker (BloombergNEF 2025) and the DOE Clean Energy Manufacturing Analysis Center (CEMAC) database (DOE 2024). The gap for each sector and scenario was then computed as required capacity minus committed capacity.

2.2.2 Capital Requirement Estimation

Capital expenditure (CAPEX) benchmarks per unit of capacity were sourced from NREL Technical Report TP-7A40-87303 (NREL 2024) and applied to each sector gap to obtain gross investment requirements. IRA Section 45X Advanced Manufacturing Production Credit (AMPC) values were taken from Treasury Regulation 1.45X-1 (Treasury 2024) and discounted at 5% over the 10-year statutory credit period to compute the net present value of credit offsets. Net private capital requirements were calculated as gross CAPEX minus the AMPC offset. Tables 1 and 2 show the projected CEMG data by sector and scenario (2035), and capital requirements for the accelerated transition scenario (ATS), respectively.

Table 1
CEMG by sector and scenario (2035)

Sector	Committed 2025	Required stated 2035	Gap stated	Required ATS 2035	Gap Accel.	Gap ATS %
Wind blades (GW-eq/yr)	19	52	33	68	49	72.0
Solar cells (GW/yr)	49	140	91	200	151	75.5
Battery cells (GWh/yr)	125	480	355	620	495	79.8

Sources: DOE (2024); BloombergNEF (2025); EIA AEO (2025); Princeton REPEAT Project (2024). Committed capacity as of Q4 2024 (financial close). Gap = Required minus Committed. ATS= accelerated transition scenario. GW = gigawatt; GWh = gigawatt-hour;

Table 2
Capital investment required, ATS (2035)

Sector	Gap	CAPEX per Unit ($B)	Gross CAPEX ($B)	AMPC Offset ($B)	Net Private ($B)
Wind blades	49 GW-eq /yr	$3.20 /GW-eq	$156.8	$18.4	$138.4
Solar cells	151GW/yr	$0.28/GW	$42.3	$9.1	$33.2
Battery cells	495 GWh/yr	$0.065/ GWh	$32.2	$17.3	$14.9
Total			$231.3	$44.8	$186.5

Sources: NREL (2024) TP-7A40-87303; BloombergNEF (2025); Treasury Reg. 1.45X-1 (2024). AMPC offset = net present value (NPV) of 10-year Section 45X credits at a 5% discount rate per unit of gap closed. CAPEX = capital expenditure. ATS= accelerated transition scenario

Committed domestic capacity covered 26% to 50% of projected requirements in the stated policy scenario and falls to 23% to 34% in the Rapid Decarbonization (RD) scenario by 2035 (DOE 2024). Gross

investment totaled $231.3 billion while RA Section 45X AMPC credits offset $44.8 billion. This caused a shortfall in the private capital required of $186.5 billion, which the CEMFF seeks to address.

2.3 Stage 2: Design and Calibration of the Clean Energy Manufacturing Finance Framework (CEMFF)

2.3.1 Theoretical Foundations

The CEMFF was designed on three pillars: firstly, the blended finance catalysis principle, where concessional first-loss capital reduces the cost of commercial tranches by absorbing tail risk; secondly, the greenium hypothesis, where sustainably verified instruments trade at a yield discount; and lastly, FEOC-constrained capital structure optimization, where foreign investment eligibility is a binding constraint on instrument design. The framework seeks to reduce WACC from the standalone required returns of 10.8% to 18.2% to a threshold of 8.5% or lower for Tier 1 segments. This threshold is the level at which institutional investors can allocate capital without special approval from investment policy committees. The framework also aims to reduce the financing cost gap against Chinese producers by at least 60% across all segments.

2.3.2 Instrument 1: SWF Co-Investment Special Purpose Vehicle

The Sovereign Wealth Fund (SWF) Co-Investment SPV was structured to pool capital from allied-nation wealth funds such as the Future Fund (Australia) into a Class A and/or B tranche structure. Class A tranches at 60% of SPV capital received a fixed spread of 250 bps over the 10-year Treasury with Development Finance Institution (DFI) equity guarantees. Class B tranches, set at 40 were assigned the equity upside and first-loss risk beyond the Blended First-Loss Capital Tranche (BFLCT). FEOC compliance was built into the structure: all SPV limited partners were required to originate from non-FEOC jurisdictions under IRA Section 30D guidance, and the operating agreement prohibited the transfer of manufacturing intellectual property (IP) to FEOC-affiliated entities, preserving full IRA credit eligibility.

2.3.3 Instrument 2: Green Manufacturing Bond

The Green Manufacturing Bond (GMB) was designed as a senior secured infrastructure bond with manufacturing-specific SPIs and IRA credit covenants. The coupon formula was calculated via Eq. (1):

$$R_{GMB} = R_f + S - \left(\Delta SPI + \varepsilon M_c\right) \quad (1)$$

$$R_{GMB} = R_f + S - \Delta SPI - \varepsilon M_c \quad (1)$$

where R_f is the risk-free rate; S is the project-level credit spread; SPI is a normalized sustainability performance score from 0 to 1; Δ (= 0.0018) is the SPI sustainability discount coefficient scaled to U.S.

manufacturing (Zerbib (2019); ε (= 0.0022) is the AMPC coverage discount coefficient credit transfer market pricing (BloombergNEF (2025) and M_c is the AMPC coverage or fraction of annual production costs covered by Section 45X credits.

2.3.4 Instrument 3: Blended First-Loss Capital Tranche

The BFLCT was designed to provide first-loss capital to reduce senior tranche returns to investment-grade levels. It is based on DOE LPO Section 1703 and DFI program funds at 3%. The required first-loss share *T** for each segment is:

$$T^* = 1 - \left\{ \frac{R_c - R_f}{R_{sta} - R_f} \right\} \qquad (2)$$

where R_c is the institutional investment-grade threshold (= 8.5%), R_f is the risk-free rate, and R_{sta} is the segment-level standalone required return. Table 3 shows *T** calibrations by segment.

Table 3
Required first-loss share (*T**) by manufacturing segment

Segment	Type	R_{sta} (%)	*T** Central	*T** Tariff + 25%	*T** IRA – 30%
Solar cells gigafactory	Tier 1	11.2	0.40	0.54	0.51
Solar wafer/ingot	Tier 2/3	13.8	0.57	0.65	0.63
Battery cell gigafactory	Tier 1	10.8	0.37	0.52	0.49
Battery cathode materials	Tier 2/3	16.4	0.66	0.71	0.70
Battery lithium processing	Tier 3/4	18.2	0.71	0.75	0.74
Wind blade facility	Tier 1/2	12.1	0.47	0.58	0.56
Wind tower/nacelle	Tier 2	13.2	0.54	0.63	0.61

Sources: S&P Capital IQ (2025); Damodaran (2025). r_commercial = 8.5% (institutional investment-grade threshold). Rf = 4.50% (10-year U.S. Treasury, February 2026). IRA = Inflation Reduction Act.

2.3.5 Instrument 4: Pension Fund Infrastructure Allocation

The fourth instrument was structured to unlock pension fund and insurance company infrastructure allocations through the credit enhancement created by the BFLCT and SPV structures. Allocations were structured as senior secured infrastructure debt with minimum ratings of BBB- or equivalent, eligible under the Employee Retirement Income Security Act (ERISA) and equivalent non-U.S. frameworks, consistent with the institutional infrastructure allocation criteria documented by OECD (2023). This

design allowed institutions such as CPP Investments and the Government Pension Investment Fund (GPIF) to classify CEMFF investments under infrastructure rather than private equity mandates, a key feature because infrastructure mandates carry much higher allocation limits.

2.3.6 Portfolio Capital Allocation

The target allocation across the four instruments was determined through a constrained optimization that minimized portfolio WACC subject to four constraints: FEOC compliance for all capital, DOE LPO first loss availability, institutional mandate compatibility, and a target leverage ratio of at least 6 times private to public capital, set above the 3 to 5 times historically achieved by single instrument LPO guarantees (DOE LPO 2025). The resulting allocation was: SWF Co-Investment SPV at 28%, Pension Infrastructure and GMB senior tranche at 32%, GMB institutional tranche at 22%, and BFLCT at 18%.

2.4 Stage 3: Sensitivity Analysis

In the final stage, the calibrated framework was stress tested across a full factorial space of 81 combinations of four policy parameters: (1) tariff escalation on clean energy imports at 0%, 25%, and 45%; (2) IRA credit value changes at 0%, -15%, and – 30%; (3) interest rate shifts at 0, 150, and 300 bps; and (4) deployment scenario at Stated Policy, Accelerated, and Rapid Decarbonization (EIA 2025; DOE 2024; Princeton REPEAT Project 2024). The tariff and credit erosion ranges were chosen to bracket the trade policy scenarios analyzed by Bown (2023). For each combination, segment-level WACC reductions, cost competitiveness against Chinese landed cost plus applicable tariff, and capital adequacy against the $186.4 billion requirement were recomputed. This stress test was designed to capture the main policy interactions facing U.S. clean energy manufacturing finance from 2025 to 2035.

3 Empirical Results

3.1 WACC Reduction by Segment

Table 4 shows CEMFF WACC reductions and cost competitiveness by segment. The framework achieves a portfolio-weighted average WACC reduction of 190 bps to 280 bps. Tier 1 segments reach or approach the commercial investment-grade threshold. Higher-risk Tier 2/3 segments achieve WACC reductions of 200 bps to 350 bps, but remain above 8.5% and need continued public capital support.

Table 4
CEMFF WACC reduction and cost competitiveness by segment

Segment	Baseline WACC (%)	CEMFF WACC (%)	Reduction (bps)	Competitiveness vs. China
Solar cell gigafactory	11.2	8.6	260	Competitive (net of AMPC)
Solar wafer /ingot	13.8	9.8	400	Marginal
Battery cell gigafactory	10.8	8.4	240	Competitive (net of AMPC)
Battery cathode materials	16.4	11.0	540	Gap remains ($4 to $6/kWh)
Battery lithium processing	18.2	11.9	630	Not competitive
Wind blade facility	12.1	9.0	310	Competitive
Wind tower/ nacelle	13.2	9.5	370	Marginal

Sources: S&P Capital IQ (2025); BloombergNEF (2025); IEA (2024). CEMFF WACC reflects portfolio-weighted average across four instruments. Competitiveness assessed against Chinese landed cost plus applicable tariff. bps = basis points.

3.2 Capital Mobilization Leverage

Table 5 shows capital mobilization outcomes by instrument. Total CEMFF capital is $193.3 billion, with $27.4 billion in public concessional capital and $165.9 billion in private capital. This is a 6.1 times private-to-public leverage ratio, which compares favorably with the 3 to 5 times leverage that DOE LPO loan guarantees typically achieve for utility-scale renewable projects (DOE LPO 2025).

Table 5
Capital mobilization leverage by CEMFF instrument

Instrument	Public ($B)	Private ($B)	Leverage	Catalysis Mechanism
SWF Co-Investment SPV	12.4	56.8	4.6x	DFI equity anchor + Class A guarantee
GMB	8.2	38.1	4.6x	LPO credit enhancement + AMPC covenant
BFLCTs	6.8	22.4	3.3x	T^*= 0.15 first-loss absorption
Pension Fund Infrastructure	0.0	48.6	N/A	Investment-grade via SPV/BFLCT
Total CEMFF	$27.4	$165.9	6.1x	Portfolio-level blended catalysis

Sources: Authors' calculations based on DOE LPO (2025); ICC (2024); BloombergNEF (2025). Public capital = concessional DOE LPO and DFI contributions. Leverage = Private divided by Public. LPO = Loan Programs Office; DFI = Development Finance Institution.

3.3 Sensitivity Results

Table 6 shows selected scenarios. WACC reductions are positive in all 81 cases. Cost competitiveness holds in 78% of scenarios under individual shocks. The combined worst case, which is tariff at + 45%, IRA at − 30%, and interest rates at + 300 bps, reduces cost competitiveness to 38% of segments. This underscores how the framework depends on maintaining all three policy levers at once.

Table 6
CEMFF sensitivity analysis, selected scenarios (Accelerated Transition)

Scenario	Avg. WACC Red. (bps)	Min. WACC Red. (bps)	Competitive Segs. (%)	Capital ($B)	Adequacy
Central (baseline)	391	239	100	193.3	Adequate
Tariff at + 25%	402	250	100	263.7	Adequate
Tariff at + 45%	410	258	100	269.0	Adequate
IRA Credits at -30%	398	246	100	260.8	Adequate
IRA at -30%, Tariff at + 25%	408	256	100	267.7	Adequate
Interest rate at + 150 bps	350	198	100	229.6	Adequate
Interest rate + 300 bps	309	156	71	202.4	Adequate
Combined worst case	334	182	38	219.1	Marginal

Note: Competitiveness threshold: CEMFF WACC reduction of at least 180 bps. Capital adequacy: mobilized capital of at least $186.5B (net private requirement). Combined Worst Case = Tariff + 45%, IRA − 30%, Interest Rate + 300 bps.

4 Discussions

4.1 Capital Mobilization and Blended Finance Literature

The portfolio-level leverage ratio of 6.1 times private to public capital falls within the 5 to 10 times range that Gupta and Noh (2025) report for blended tranched structures in early-stage clean energy ventures. This agreement is expected because both structures rely on the same catalytic mechanism, in which concessional first-loss capital compresses the risk premium demanded by senior tranches. The CEMFF result sits toward the lower end of that range because mature manufacturing assets carry larger ticket

sizes and offer less equity upside than early-stage ventures, so each concessional dollar catalyzes private capital less aggressively, although at a far greater absolute scale.

At the same time, the 6.1 times ratio exceeds the 3 to 5 times leverage that DOE LPO loan guarantees have historically achieved for utility-scale renewable projects (DOE LPO 2025). The reason for this deviation is structural. The LPO figure reflects a single instrument guarantee, whereas the CEMFF blends four instruments at the portfolio level, and in particular admits pension fund infrastructure capital at zero incremental public cost once the BFLCT and SPV structures have established investment-grade credit quality. The results therefore support the broader blended finance evidence from Convergence (2023) and Buchner et al. (2022) and extend it in geographic and sectoral scope. That literature documents first loss catalysis primarily in emerging market utility-scale renewables, while the present results indicate that the same mechanics operate in advanced economy manufacturing, which is consistent with the fact that first loss absorption acts on tail risk rather than on jurisdiction-specific characteristics. The FEOC compliance constraint, however, has no counterpart in the emerging market literature and materially narrowed the eligible investor base in the optimization.

4.2 Green Bond Pricing and Greenium

The GMB pricing results deviate upward from the pure greenium estimates in the literature. Zerbib (2019) identifies a greenium of 2 to 8 bps for euro area green bonds, and Flammer (2021) finds comparably modest pricing effects for corporate green bonds. The combined SPI and AMPC coverage discounts embedded in the GMB coupon formula exceed this range. The reason for the deviation is that the GMB discount is not pure greenium. It bundles the investor preference effect measured by Zerbib (2019) with a credit quality effect arising from the AMPC coverage covenant, because statutory Section 45X cash flows lower the default probability of the issuer. The larger discount therefore reflects collateral quality in addition to sustainability preference. The design choice itself is supported by Flammer (2021), who shows that green bond pricing effects concentrate where certification and verification are credible, since manufacturing-specific SPIs are directly measurable at the facility level.

4.3 Financing Costs and Competitiveness with Chinese Producers

The baseline financing cost gap of 400 to 800 bps against Chinese producers, derived from S&P Capital IQ (2025) and Damodaran (2025), was reduced substantially but not eliminated by the framework. Tier 1 gigafactory segments reached or approached the 8.5% institutional threshold, while battery cathode materials and lithium processing remained uncompetitive in most scenarios despite the largest absolute WACC reductions of 540 to 630 bps. This pattern agrees with Helveston et al. (2022), who show that the Chinese cost advantage in clean energy supply chains rests on scale economies, learning by doing, and supply chain integration rather than on financing costs alone. The residual upstream gap in the present results arises for precisely this reason: capital structure innovation can neutralize the financing component of the cost differential, but it cannot offset process knowledge and vertical integration advantages accumulated over two decades. The finding is also consistent with IEA (2024), which

documents the deepest Chinese concentration in upstream materials processing, the same segments where the CEMFF proved least sufficient.

4.4 Industrial Policy and Policy Interdependence

The sensitivity results support the industrial policy literature on which the framework was built. Rodrik (2004) and Aghion et al. (2015) argue that directed investment is justified where coordination failures and learning externalities prevent efficient private investment, and Mazzucato (2013) and Mazzucato and Penna (2016) argue that state co-investment and risk sharing are essential where foreign industrial policy distorts the competitive landscape. The combined worst-case result, in which competitiveness fell to 38% of segments when tariff erosion, IRA credit cuts, and rate increases occurred together, supports these arguments quantitatively: no private capital structure, however well designed, sustained competitiveness once the public policy levers were withdrawn simultaneously. The present study deviates from this literature only in method, since prior work treats policy complementarity qualitatively, whereas the 81-combination design measures the interaction effects directly. Finally, the binding role of FEOC eligibility in the SPV and GMB design agrees with Bown (2023), who shows that trade and investment restrictions under the IRA propagate into firm-level financing decisions, and the present results extend that finding by demonstrating the propagation into capital structure design itself.

4.5 Strengths and Limitations

The strengths of these results lie in the multi-source calibration, which draws required returns, CAPEX benchmarks, and credit market pricing from independent datasets, in the conservative 5% discounting of AMPC cash flows, and in the full factorial stress design, which avoids selective scenario reporting. Two limitations qualify for the comparisons above. First, the greenium coefficients were transferred from euro area sovereign settings (Zerbib 2019) and U.S. corporate settings (Flammer 2021) rather than estimated from manufacturing bond transactions, which do not yet exist at scale. Second, the leverage and WACC results are model-based rather than observed, so agreement with Gupta and Noh (2025) and DOE LPO (2025) indicates consistency of mechanism rather than replication of realized outcomes.

4.6 Policy Implications

4.6.1 DOE Loan Programs Office

This study proposes three needed changes to the LPO rules. Firstly, LPO Section 1703 eligibility should explicitly include manufacturing SPV structures. Secondly, for purposes of lowering transaction costs, it is needful for the LPO to set up a manufacturing finance facility (MFF) with standard BFLCT terms and T* calibration methods. Thirdly, LPO credit subsidy cost calculations should include AMPC net present value (NPV) in the risk-adjusted return model. This reflects the credit risk reduction that stable AMPC cash flows provide.

4.6.2 Treasury and Internal Revenue Service Section 6417 Direct Pay

The GMB instrument relies on AMPC direct pay under IRA Section 6417. This allows tax-exempt entities to receive direct payments instead of credits. Current Internal Revenue Service (IRS) guidance does not address whether direct-pay AMPC rights can be pledged to bond indenture trustees as collateral. A Treasury guidance notice clarifying that these rights may be pledged as collateral would expand GMB market depth. Institutional investors could then underwrite AMPC collateral coverage ratios in bond prospectuses.

4.6.3 Ex-Im Bank Supply Chain Finance Guarantee

The SPV structure requires Ex-Im Bank guarantees covering allied-nation capital repatriation risk. Current Ex-Im authority under the Export-Import Bank Reauthorization Act of 2019 covers supply chain finance for U.S. exporters. It does not explicitly authorize guarantees for inbound manufacturing investment from allied-nation sovereign funds. Expanding Ex-Im authority to cover FEOC-compliant allied sovereign manufacturing investment would remove a key barrier to SPV deployment.

4.6.4 Battery Materials Gap

The sensitivity analysis shows a persistent competitiveness gap for battery cathode materials and lithium processing in all but the most favorable scenarios. The CEMFF works well for Tier 1 gigafactory segments. But it is not enough to close the cost gap in upstream materials processing. Additional tools are needed. These could include critical minerals off-take agreements, royalty financing structures, or direct production subsidies beyond Section 45X. Policymakers should treat the materials processing gap as a separate policy challenge.

5 Conclusion

This paper develops the CEMFF, a four-instrument capital mobilization structure designed to close the U.S. clean energy manufacturing gap while remaining cost-competitive with Chinese producers. The CEMG model quantifies the gap at 49 GW-eq/yr for wind blades, 151 GW/yr for solar cells, and 495 GWh/yr for battery cells under the accelerated decarbonization scenario by 2035. Closing these gaps requires $186.5 billion in net private capital after IRA Section 45X offsets.

The CEMFF achieves portfolio-weighted average WACC reductions of 190 bps to 280 bps. It mobilizes $6.1 of private capital per dollar of concessional public support. It delivers manufacturing cost competitiveness with Chinese producers in 78% of modeled scenarios under central assumptions. Sensitivity analysis across 81 policy-stress combinations confirms robustness to individual shocks, and also reveals a combined worst-case vulnerability that shows the importance of maintaining tariff policy, IRA credit integrity, and monetary stability at the same time.

Three policy priorities follow: DOE LPO Section 1703 eligibility should cover manufacturing SPV structures. IRS guidance under Section 6417 should clarify that AMPC direct-pay rights can be pledged as bond collateral. Ex-Im Bank authority should be expanded to cover FEOC-compliant allied sovereign manufacturing investment. Battery cathode materials and lithium processing need tools beyond the

current CEMFF, such as critical minerals offtake agreements or additional direct subsidies. Future studies could extend the CEMFF to electrolyzer components, heat pump manufacturing, and EV motor rare earth supply chains.

Abbreviations

AEO Annual Energy Outlook

AMPC Advanced Manufacturing Production Credit

BFLCT Blended First-Loss Capital Tranche

BIL Bipartisan Infrastructure Law

Bps Basis points

CAPEX Capital expenditure

CEMAC Clean Energy Manufacturing Analysis Center

CEMFF Clean Energy Manufacturing Finance Framework

CEMG Clean Energy Manufacturing Gap

DFI Development Finance Institution

DOE U.S. Department of Energy

EIA U.S. Energy Information Administration

ERISA Employee Retirement Income Security Act

EV Electric vehicle

Ex-Im Export-Import Bank

FEOC Foreign Entity of Concern

GIC Government of Singapore Investment Corporation

GMB Green Manufacturing Bond

GPIF Government Pension Investment Fund (Japan)

GW Gigawatt

GWh Gigawatt-hour

IEA International Energy Agency

IP Intellectual property

IRA Inflation Reduction Act

IRS Internal Revenue Service

LPO Loan Programs Office

NPV Net present value

NREL National Renewable Energy Laboratory

OECD Organisation for Economic Co-operation and Development

PV Photovoltaic

SPI Sustainability performance indicator

SPV Special-purpose vehicle

SWF Sovereign Wealth Fund

WACC Weighted average cost of capital

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S.D.A-S conceived and designed the study, developed the CEMG model and CEMFF framework, conducted the primary analysis, and wrote the main manuscript text. K.S.M-B contributed to the literature review, assisted with data collection and interpretation, and provided critical revisions to the manuscript. P.A. contributed to the sensitivity analysis and prepared the tables and figures. All authors reviewed and approved the final manuscript. All authors reviewed the manuscript

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None

Data Availability

This study used publicly available data from the U.S. Department of Energy (DOE), the U.S. Energy Information Administration (EIA), the National Renewable Energy Laboratory (NREL), and the Princeton REPEAT Project, accessible via their respective institutional websites. Proprietary data from BloombergNEF and S&P Capital IQ were used under licence and are not publicly available due to subscription restrictions. Model outputs generated for this study are available from the corresponding author on reasonable request.

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Supplementary Files

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- DataClosingtheCleanEnergyManufacturingGap.xlsx