

The Localisation Ladder: Which Solar Supply-Chain Stages Can Compete?

A stage-by-stage investment framework for the GCC, India, the United Kingdom and the United States

Authored by Chennakeshav Adya

Independent Researcher

October 2026

Abstract

Solar manufacturing investment requires a choice of production boundary. Importing complete modules, assembling imported cells and integrating upstream processes commit different amounts of capital and expose the investor to different input, qualification and operating risks. This paper develops a stage-specific framework for examining those choices in the GCC, India, the United Kingdom and the United States, using current primary policy and technical sources.

A hypothetical ten-year cash-flow model compares five mutually exclusive supply architectures serving the same final-module customer. It replaces purchased intermediates when stages move inside the boundary and distinguishes yield, uptime, ramp-up, electricity, capital expenditure and working capital. Separate scenarios test price compression, scale, operating setbacks and finite conditional support. All numerical inputs are author-designed assumptions; the calculations are neither observed factory results nor country-calibrated investment forecasts.

The analysis connects supply-boundary economics with customer qualification, policy evidence, industrial data and transaction sequencing. Proposed diligence gates identify the records needed before committing capital or attributing value to AI applications. The framework supports conditional stage-by-stage decisions and makes unresolved engineering, legal and commercial questions explicit.

JEL Classification: F14, F23, G31, L60, Q42, Q48

Keywords: solar manufacturing, localisation, photovoltaic supply chain, industrial policy, investment appraisal, working capital, GCC, India, United Kingdom, United States

1. Competitiveness begins with a defined product and destination

Solar manufacturing competitiveness requires a product, a qualified buyer, a destination and a period over which cash can be earned. A country label supplies none of these specifications. This paper proposes a localisation ladder that evaluates individual production stages against technical capability, delivered economics, market access, contractual demand and resilience to product change. Each rung requires its own evidence. Integration becomes a separate investment decision whenever a producer adds a process, a customer qualification or an additional regulatory obligation.

The September 2026 IEA PVPS Trends report describes persistent manufacturing overcapacity in 2025: module production exceeded annual installations and remained below available manufacturing capacity. It also reports that n-type material represented 82% of crystalline-silicon

wafers used in 2025. These observations establish a difficult competitive setting and a changing technology mix. They provide no audited cost, operating yield or contracted order book for a particular proposed factory. [2]

The research cut-off is 10 October 2026. The evidence comprises government process descriptions, official policy documents, the current IEA PVPS report and entity announcements. Company announcements establish what those companies announced. Policy eligibility retains its jurisdiction and date conditions. Announced capacity remains in that category; commissioned equipment, qualified production and invoiced sales require separate records. The analysis makes no finding that any country offers the lowest manufacturing cost.

The proposed commercial test is the amount a factory can collect for specification-compliant output after its operating, financing, replacement and compliance obligations. That test should use comparable customer bids and supplier quotations for the same bill of materials, delivery terms, warranty and currency exposure. A national deployment ambition should enter an opportunity screen as contextual information. A signed purchase commitment with a creditworthy payer should enter the contracted-sales analysis, subject to its conditions and cancellation rights.

This framework also separates strategic objectives from investment returns. A government or sponsor may explicitly value supply security, technical capability or employment. The investment committee should state the approved cost of those objectives, the payer and the measurement period. Public benefits, producer cash flows and customer savings should have separate accounts. This structure allows an industrial-policy proposition to be assessed alongside an alternatives investment without assigning an unsupported commercial premium to localisation itself.

2. Trace the physical transformation before choosing the factory boundary

The US Department of Energy describes crystalline-silicon production as a sequence that includes polysilicon purification, crystal growth, wafer slicing, cell processing and module assembly. Diamond-wire slicing creates silicon kerf. Cell processing includes surface preparation, doping, coatings and electrical contacts, with processes varying by architecture. Module manufacture connects cells and laminates them within a protective assembly. Racking, wiring and power electronics form additional parts of the photovoltaic system. [1]

For the proposed assessment, each transfer between those stages should have an incoming specification, an outgoing specification and an acceptance record. A wafer producer would therefore require evidence on qualified wafer dimensions and defects for its intended cell process. A module assembler would require cell consistency, interconnection compatibility, encapsulation performance and the approved finished-product specification. These are proposed diligence requirements; this paper has no target-specific test results.

Table 1. Proposed evidence package for each localisation rung

Manufacturing boundary	Evidence requested before investment approval	Commercial acceptance question
Metal structures and selected balance-of-system products	Approved drawings, material certificates, corrosion testing, tooling ownership and buyer qualification	Has the intended buyer accepted this exact product and delivery arrangement?
Module assembly	Qualified incoming cells and materials, line acceptance, finished-product testing and warranty allocation	Which saleable product is covered by the customer's approval?

Manufacturing boundary	Evidence requested before investment approval	Commercial acceptance question
Cell processing	Architecture-specific process rights, equipment acceptance, qualification batches and consumables specifications	Can the customer qualify repeat output from this production line?
Ingots and wafers	Feedstock qualification, crystal and slicing records, accepted dimensions and downstream conversion trials	Has downstream production accepted the proposed wafer specification?
Polysilicon	Feedstock and purification route, utilities and environmental permissions, product qualification and supply contract	Which customer has accepted the material and impurity specification?

Notes: This table is a proposed diligence framework. It ranks neither countries nor technologies and assigns no assumed yield or price. The physical stage distinctions follow DOE's manufacturing description. [1]

The proposed operating dataset should distinguish material entering the line, first-pass accepted output, reworked output, downgraded sales, scrap and customer returns. Every loss should have one location in the reconciliation. Counting nominal machine throughput as saleable output would leave the proposed investment case incomplete. The same discipline should apply to power ratings: the diligence file should state the measurement basis and the product configuration associated with each watt-denominated quotation.

An integrated plant should have an internal transfer-price schedule for evaluating each stage. The investment committee should review those stages with and without the downstream affiliate's purchase. This proposed procedure exposes the amount of value assigned to internal demand and identifies the particular conversion step that carries qualification, inventory or obsolescence risk. It does not establish an arm's-length market price for any intermediate product.

3. Use the localisation ladder as a sequence of commercial gates

This paper proposes five gates for a manufacturing investment. The first is product qualification: the exact item and production site need an identifiable acceptance route. The second is repeatable operation: the sponsor should demonstrate the required output specification through an agreed operating test. The third is delivered economics: a buyer-equivalent comparison should include transport, duties where applicable, inventory, warranty and financing. The fourth is access and payment: the contemplated transaction needs eligibility evidence and a payer with an enforceable obligation. The fifth is adaptability: the sponsor should identify the cost and authority needed to change the product or process.

The ladder is a proposed analytical framework. It creates no presumption that assembly is profitable, that upstream processing is unattractive or that deeper integration improves returns. Each producer should be assessed on the evidence for its manufacturing perimeter.

The initial comparison should hold the product and destination constant. For example, a proposed UAE frame supplier should be evaluated against quotations for the same alloy, drawing, finish, acceptance standard and delivery point. A proposed Saudi wafer line should be evaluated against qualified wafer offers of the same dimensions and electrical specification. These examples identify the comparison required; they contain no fictional quotations or conclusions about actual suppliers.

The proposed procurement file should separate an indicative quotation, a valid binding offer, a framework agreement, a call-off and a completed delivery. For each customer, it should record

minimum purchase obligations, qualification conditions, price resets, payment security, rejection rights and termination compensation. The investment committee should specify which category supports each period of its case. A customer interview or non-binding expression of interest should retain that status throughout approval.

Stage selection also needs a boundary for outsourced services. A line can depend on an external owner of tooling, process recipes, maintenance capability or certification data. The proposed review should map who can access those assets, who can modify them and what happens after a contractual default. This becomes particularly important when a joint venture relies on a technology partner for continuing production support.

Finally, the proposed gate record should identify an accountable human decision-maker and the unresolved evidence at each decision. A capital commitment may remain conditional on a signed utility contract, product approval or destination-specific opinion. Conditions should have an expiry date and a defined consequence for the next tranche of expenditure. The framework gives investors a repeatable decision structure while preserving the actual uncertainty attached to each factory proposal.

4. UAE: examine adjacent industrial capability and buyer-specific access

The UAE Ministry of Industry and Advanced Technology's 2024 supplier material describes an In-Country Value certification process involving an authorised certifying body. Its manufacturer formula includes UAE manufacturing expenditure, investment and workforce elements. These are programme measurement inputs, requiring the relevant records and certification. They establish no photovoltaic product qualification or purchase order. [3]

Emirates Global Aluminium announced an August 2025 agreement to supply Celestial-R billets to Japan's Sankyo Tateyama through ITOCHU. The announcement identifies extrusion and forging applications. It provides evidence of an announced transaction involving an adjacent industrial material; it supplies no accepted photovoltaic-frame drawing, solar-specific product approval or comparative manufacturing bid. [3]

The proposed UAE entry screen should therefore begin with a specified industrial product and a named procurement route. Frames, mounting components and other selected metal products are candidates for examination where the sponsor can produce a buyer-approved specification. Their inclusion here is a proposed search direction. The evidence reviewed establishes no profitability finding for those products.

For a metal-product case, the proposed diligence pack should reconcile billet procurement, extrusion and finishing arrangements, tooling, fabrication, scrap proceeds and delivery acceptance. It should identify which operations would occur at the proposed site and which would remain with subcontractors. A quotation for metal should be accompanied by the appropriate alloy and processing requirements. The programme score and the customer's engineering approval should occupy separate fields in the procurement record.

For a UAE module-assembly case, the proposed review should begin afresh with cell supply, finished-product qualification, warranty support and customer contracting. Semiconductor processing capability requires separate evidence. Any proposed move into cells, wafers or polysilicon should have its own technology rights, utility quotations, permits, operator plan and qualified output evidence.

The proposed investment case should also separate domestic and export sales. Each destination needs a documented customs classification, origin analysis and product-acceptance route. The review should obtain the actual power tariff, connection terms, water arrangements, premises cost and financing terms for the chosen site. Until these records and comparable bids exist, the paper assigns no UAE cost advantage. The resulting investment proposition would be a product-specific industrial case with an evidenced buyer route and a measured exposure to policy-supported procurement.

5. Saudi Arabia: evaluate the announced integration programme stage by stage

In July 2024, PIF announced agreements involving its Renewable Energy Localization Company. The Jinko Solar and Vision Industries venture envisaged annual cell-and-module production capacity of 10 GW. A separate venture with LUMETECH, a TCL Zhonghuan subsidiary, and Vision Industries envisaged ingot-and-wafer production associated with 20 GW annually. These are the capacities envisaged in that announcement. This source supplies no confirmation of current commissioning, accepted output, utilisation or realised selling prices. [4]

The proposed Saudi assessment should treat the two solar boundaries separately before examining the economics of their integration. An ingot-and-wafer operation would need qualified feedstock and accepted downstream specifications. A cell-and-module operation would need repeatable conversion performance, the approved product configuration and customer acceptance. The investment committee should request dated evidence for every transition from a signed agreement to commissioned equipment, qualification batches and commercial delivery.

For the proposed upstream case, site diligence should request contractual electricity terms and the applicable load profile, water supply and treatment arrangements, process-gas availability, waste-management permissions and maintenance support. These are required evidence fields, with no assumed Saudi tariff or resource-cost advantage in this paper. Equipment vendor quotations should specify performance acceptance, the permitted product range and remedies for failed commissioning.

Joint-venture governance deserves an equally concrete review. The proposed agreement analysis should identify process ownership, licence duration, rights to technical changes, access to operating data, reserved matters and the consequences of a partner's withdrawal. A parent company's experience should enter the evidence file through the particular technical support and contractual commitments supplied to the venture. The review should request proof that those rights cover the contemplated products and destinations.

The proposed customer analysis should distinguish the home-market procurement route from export channels. Local-content objectives may be relevant to an identified tender; the case needs the actual tender terms and allocation of compliance responsibility. Export proposals need destination-specific eligibility and customer approval. This paper makes no finding that the announced Saudi production will achieve a particular share of either market.

An appropriate proposed capital sequence would connect each expenditure tranche to a verified milestone and the remaining customer obligations. The sponsor should show the consequence of delayed qualification at either stage, including inventory accumulation and downstream sourcing

alternatives. That review gives the announced integration strategy an auditable investment boundary without converting its stated capacity into an assumed sales forecast.

6. India: map the project cohort before assigning a localisation benefit

India's Ministry of New and Renewable Energy (MNRE) administers the Approved List of Models and Manufacturers (ALMM). Its July 2025 amendment retained 1 June 2026 as the cell List-II framework's effective date and linked bidding-project treatment to a cut-off following initial list publication. It provided deemed cell-list compliance for qualifying integrated thin-film manufacturing units enlisted in module List-I and retained applicable scheme Domestic Content Requirement obligations. [5]

The 18 July 2026 order subsequently provided a commissioning window through 31 December 2026 for net-metering and open-access projects to obtain cell List-II relief. Its subject and operative provisions describe limited relief, leaving the broader framework in place. [5]

The 4 August 2026 clarification confirms the bidding cut-off of 31 August 2025, subject to surviving earlier tender conditions. [5]

Table 2. Selected Indian project-cohort distinctions confirmed on 4 August 2026

Project cohort	Relevant treatment
Net-metering and open-access projects	Cell List-II exemption if commissioned by 31 December 2026; module List-I obligations continue.
Residential PM Surya Ghar (PMSG) Give It Up cases using net metering	Cell exemption through 31 March 2027, conditional on mandatory PMSG portal applications; module compliance continues.
Private behind-the-meter plants solely for captive consumption	Lists I and II do not apply to consumers or groups excluding government entities and public-sector enterprises.
Government or public-sector captive behind-the-meter projects	Listed modules required; cell exemption through 31 December 2026, with listed cells required thereafter.
Scheme domestic-content obligations	Governed separately by scheme provisions; ALMM orders supply no relaxation.

Notes: Selected conditions. Government-building bidding cohorts require their specific tender-date treatment. [5]

The proposed commercial analysis should classify every prospective order before assigning an eligibility benefit to domestic cell production. The file should contain the procurement notice, bid deadline, applicable tender clause, commissioning evidence, scheme participation and relevant exemption documentation. A module manufacturer should identify the specific module-and-cell combination supplied to that cohort. The exercise requires an eligible product and the correct customer classification; a general statement about Indian localisation would leave material conditions unresolved.

Upstream requirements have a different timetable. MNRE's 17 March 2026 order sets 1 June 2028 as the wafer framework's effective date. Initial List-III issuance requires at least three independent manufacturing units with aggregate annual wafer capacity of at least 15 GW. Enlistment requires equivalent ingot capacity. The bidding cut-off is seven days after initial list issuance, with specified grandfathering. Cell-exempt projects also receive wafer exemption, and applicable scheme domestic-content provisions remain unchanged. These are prospective policy conditions, supplying no evidence that a particular wafer plant has qualified. [6]

The proposed investment case should therefore maintain separate current-cell and future-wafer eligibility schedules. Its customer commitments should state who bears a change in

commissioning date, listing status or tender interpretation. A sponsor considering upstream entry should obtain the actual qualification and offtake evidence for the planned output before treating the future rule as revenue support. This paper makes no assumption that the rule produces a price premium or an order for any named manufacturer.

7. United States: establish the manufacturer credit's actual perimeter

IRS Form 7207 instructions describe section 45X eligibility for eligible components produced by the taxpayer in the US, including territories, and sold in its trade or business, subject to sale and related-party rules. Contract manufacturing can require an agreed claimant and certifications. General specified-foreign-entity and foreign-influenced-entity exclusions, and material-assistance changes, apply to tax years beginning after 4 July 2025; the effective-control foreign-influenced-entity rule applies separately for relevant components for any applicable tax year. The solar phase-out is 75% in 2030, 50% in 2031, 25% in 2032 and zero thereafter. Revised integrated-component sales treatment applies to tax years beginning after 31 December 2026, including same-facility production and a 65% US direct-material-cost condition. [7]

The proposed factory assessment should identify the legal taxpayer, each eligible component, the production boundary, the sale and the relevant tax year. A module, cell or wafer proposal should have a separate eligibility conclusion for its own activity. The evidence pack should request contracts, title-transfer terms, the related-party structure and the allocation of production responsibilities. A label applied to a factory or joint venture should remain outside the credit calculation until the underlying conditions are established.

The proposed financial case should show the manufacturing margin before credit income and identify the period and recipient for any eligible credit. It should state the timing of cash receipt, transaction costs where applicable, assurance expenditure and the consequence of an adverse eligibility determination. A factory should have an explicit operating plan for the phase-out years relevant to its expected life. This paper provides no target-specific tax conclusion or assumed credit proceeds.

For an integrated proposal, the proposed review should map the movement of each eligible component through the facility and the transaction treated as its sale. The internal manufacturing map and the tax-claim map should be reconciled by the tax adviser. Any discrepancy should remain an unresolved approval condition. The investment committee should also request a destination-specific customer analysis, since a manufacturer's eligibility conclusion supplies only one part of the contemplated transaction.

These proposed controls give the US case a defined policy boundary. The sponsor would still need equipment, labour, utility, qualification and customer evidence to establish a commercially competitive plant. The research assigns no US manufacturing-cost position and no assumed customer willingness to share a project's tax benefit with its supplier.

8. Keep PFE material assistance and project domestic content separate

IRS Notice 2026-15 provides interim prohibited-foreign-entity guidance and safe harbours. Its eligible-component material-assistance cost ratio subtracts PFE direct material costs from total direct material costs and divides by total direct material costs. For solar components sold in calendar 2026, the notice identifies a 50% threshold. The test concerns relevant materials and

their PFE status, with separate component calculations; ownership, debt and effective-control arrangements also require attention under the PFE framework. The clean-electricity material-assistance provisions for sections 45Y and 48E concern facilities whose construction begins after 31 December 2025. The notice describes interim reliance arrangements, requiring the applicable guidance to be refreshed for a transaction. [8]

Project domestic content has its own requirements. IRS Form 3468 instructions separate steel or iron from manufactured products. Their section 48E table gives the manufactured-product percentage as 40% for construction beginning through 15 June 2025, 45% from 16 June through year-end 2025 and 50% in 2026, for the non-offshore-wind category. Notice 2025-08 provides updated elective safe-harbour tables, including photovoltaic configurations and assigned component cost percentages. These percentages are prescribed calculation inputs, supplying no observed factory-cost curve. [9]

The proposed transaction file should give these legal tests separate worksheets, document owners and adviser sign-offs. One should identify the manufacturer and the production-credit conditions. Another should identify PFE-related entity and material evidence. A third should identify the purchaser's project, construction date and domestic-content method. Any commercial promise about eligibility should identify which test it addresses, the evidence supplied and the responsibility retained by the purchaser.

For prospective exports from the UAE, Saudi Arabia, India or the UK, the proposed review should ask a US buyer to define its intended project and documentation requirements before the supplier commits to an eligibility claim. Supplier location, US manufacture and non-PFE material status answer different questions. This paper makes no eligibility finding for any foreign-produced component or actual US project.

The proposed diligence process should inspect ownership information, financing and technology agreements alongside the bill of materials. It should identify the underlying producer where a supplier is a reseller and request the evidence needed for the chosen calculation method. Changes of supplier, licence or control should trigger a dated reassessment by the responsible adviser. Unresolved documentation should retain a stated financial consequence in the proposed investment case, including the case with no assumed policy income.

9. United Kingdom: define the industrial niche and the export route

The UK's June 2025 Solar Roadmap identifies supply-chain and innovation opportunities, including balance-of-system activity and innovative technologies. It also discusses manufacturing constraints involving finance, land, planning and grid connections. Its consideration of further manufacturing support is a policy action, supplying no award to a particular factory. Deployment ambitions in the roadmap establish no contracted manufacturer order book. [10]

The proposed UK screen should examine a specific industrial niche: a buyer-approved structural or electrical product, a specialised module application, or a licensable manufacturing process with an identified customer. These are proposed candidates for investigation. Each requires evidence of customer acceptance and a delivered-price comparison. A conventional module-assembly proposal should receive the same product, site, warranty and contract review applied elsewhere in this paper.

Market access needs its own analysis. HMRC's UK-EU insufficient-production guidance describes case-specific origin assessment under the Trade and Cooperation Agreement. An operation must satisfy the relevant product rule and move beyond insufficient production; importing authorities can challenge an origin claim, and an advance ruling is an available route. The guidance supplies no photovoltaic-specific ruling for a proposed plant. [10]

The proposed export file should therefore identify the customs classification, the applicable agreement and product-specific origin rule, the manufacturing operations actually performed, and the supporting supplier records. The transaction should state who makes the origin declaration and who bears a rejected preference claim. Any quotation should include the destination's applicable duty treatment only after that treatment has been established for the specified goods and facts.

Technology ownership and manufacturing location also need separate records. Oxford PV's September 2024 announcement reported a first shipment to a US customer and identified production of the perovskite-on-silicon cells at its pilot line in Brandenburg an der Havel, Germany. This demonstrates an announced commercial shipment associated with that production location. It establishes no UK high-volume factory or long-duration operating-fleet evidence. [11]

The proposed UK industrial case should identify where its intellectual property, equipment, qualified production and warranty obligations reside. A licence-led business and an owner-operated factory should have separate capital and revenue cases. Investors should request the actual licence terms, customer contracts, qualification route and liability allocation for the selected structure. This paper makes no finding about the value of any company's intellectual property or the competitiveness of any UK manufacturing bid.

10. Tandem readiness and technology substitution belong in the capital decision

DOE describes perovskite tandems as combining absorbers that capture different parts of sunlight. Its educational material identifies stability and durability, efficiency at scale, manufacturability, and validation and bankability as commercialisation challenges. This classification is useful for structuring diligence. An undated educational page supplies no current census of commercial tandem factories. The commercial shipment reported by Oxford PV should retain its separate company-announcement status. [12][11]

The proposed technology review should specify the architecture, substrate, deposition route, contacts, encapsulation and module configuration. For a silicon line contemplating tandem output, the sponsor should identify equipment retained, replaced or added and the required process rights. The case should include qualification batches, acceptance authority, ramp expenditure and customer-approval conditions. This paper assigns no assumed conversion cost or timetable.

Warranty diligence should request the actual performance and product warranties, exclusions, remedies, testing basis and financial support. It should map how a customer claim moves from the module supplier to the relevant cell, material and process counterparties. Field data should identify product version, climate, operating period and measurement method. Claims about suitability for GCC heat, humidity, dust or other site conditions should await product-specific

evidence. A laboratory result, shipment announcement and contractual warranty should retain their individual meanings in the investment record.

Technology substitution also deserves a proposed procurement stress test. The investment committee should ask what happens if the customer's accepted specification changes during construction or operation. The review should identify the responsible equipment vendor, licensor and buyer, the cost of requalification, the status of inventory and the available contractual remedies. A producer dependent on one licensed process should have a documented continuity and support arrangement, subject to the relevant destination rules.

The resulting localisation decision should be conditional and stage-specific. For the UAE, the proposed starting examination is buyer-qualified adjacent industrial products and separately evidenced assembly proposals. For Saudi Arabia, it is the operating and commercial proof behind each announced integrated stage. For India, it is the correct project cohort and the distinction between current cell rules and prospective wafer conditions. For the US, it is the manufacturing boundary and separate credit, PFE and purchaser-project tests. For the UK, it is a specified industrial niche with an evidenced origin and customer route. These are proposed diligence priorities, with no country ranking or profitability conclusion implied.

Capital approval should identify the stage that has passed its evidence gates, the unresolved conditions and the expenditure authorised against that finding. Competitiveness can then be tested using actual bids, qualified output and enforceable sales terms as those records become available.

11. A fictional comparison begins with a common customer boundary

Every numerical input in this worked example is a fictional author assumption. Every result is derived from those inputs. The example represents no country, company, subsidy programme, prevailing quotation or observed manufacturing project. Its purpose is to show how a proposed localisation investment changes purchased inputs, operating constraints and cash commitments. The comparisons provide no engineering validation or actual investment recommendation. Power contracts, import classifications, customer qualification and policy eligibility remain external evidence requirements.

Five mutually exclusive architectures serve the same assumed module customer. The first purchases complete modules. The second assembles modules from imported cells and an assembly kit. The third adds cell production and imports wafers. The fourth adds an ingot-and-wafer operation and imports polysilicon. The fifth adds upstream silicon conversion and buys silicon feed. Each additional stage replaces an imported intermediate at the purchasing boundary. The model assigns no transfer revenue or internal profit to intermediate movements between owned stages. Assembly kits remain purchased in every manufacturing architecture.

The reference design is 500 MW of final nominal-module output before availability and ramp limitations. The customer price is USD 0.220 per nominal W. Watts here are a commercial accounting denominator. They do not establish measured cell power, module efficiency, equipment compatibility or interchangeability between technologies. Upstream material remains in kilograms, with an explicit conversion assumption linking silicon charge to the ingot-and-wafer account. A real project would require a technology-specific bill of materials and validated process balances.

All architectures retain a common customer channel, including USD 2.500 million of reference setup expenditure and USD 1.800 million of annual fixed operating cost. Manufacturing adds the stage-specific investment and overhead shown in the assumption table. This common channel avoids treating import distribution as costless while charging local production for an entire sales organisation. The assumed service boundary excludes installation, project development and electricity generation. Customer revenue therefore contains no power-purchase-agreement receipt, electricity tariff or downstream project return.

The valuation horizon contains closing and ten operating years. The author-selected hurdle is 12% for pretax unlevered cash flows. Taxes, tax shields, financing, inflation, foreign exchange, continuing-business terminal value and plant salvage are omitted. No acquisition multiple or perpetual subsidy is added. Warranty claims, closure costs and unmodelled construction delays also remain outside the arithmetic. An investment committee would need to quantify these exposures separately before using any illustrated price or scale boundary.

Table 3. Fictional stage and power assumptions

Stage	Input unit	Yield %	Uptime %	Build capex USD m	Fixed opex USD m	kWh per input unit
Assembly	W-eq	98.000	94.000	42.000	3.200	0.040
Cell	W-eq	95.500	90.000	40.000	4.800	0.085
Ingot and wafer	W-eq	91.000	88.000	65.000	5.500	0.045
Upstream silicon	kg	90.000	86.000	110.000	6.500	35.000

Fictional 500 MW design inputs. W-eq means nominal-W accounting equivalent; upstream input is kg. Capex excludes the common channel. Ingot/wafer rejection is valued in kg; wafer-equivalent input carries 0.0022 kg per W. These assumptions provide no engineering validation.

12. Yield and uptime determine how much can actually be sold

The model sizes each installed stage backward from the same reference final output using its design yields. Assembly has 98% yield, cell conversion 95.5%, ingot-and-wafer conversion 91%, and upstream silicon conversion 90%. These are invented conversion assumptions. A downstream requirement is divided by the appropriate stage yield to calculate that stage's input. The input-capacity schedule records those different quantities explicitly; identical final design labels do not imply identical equipment throughput.

For the ingot-and-wafer step, each charge-equivalent W contains an illustrative 0.0022 kg of silicon. Silicon charge equals gross wafer-equivalent input multiplied by that factor. Product silicon equals accepted wafer-equivalent output multiplied by the same factor. Their difference is the rejected silicon stream. Upstream feed kilograms equal required polysilicon kilograms divided by upstream yield. The resulting kilogram identities reconcile the two silicon accounts. Cell and assembly conversions remain nominal-W equivalent records and supply no complete physical mass balance for an actual module.

Availability is applied separately from yield. Fictional mature uptimes are 94% for assembly, 90% for cells, 88% for ingot/wafer and 86% for upstream conversion. The import channel uses 99%. Each installed operation also has its own ten-year commissioning sequence. Assembly begins at 50% of available capacity, cell production at 40%, ingot/wafer at 30%, and upstream conversion at 25%. Full ramp arrives at different times. Fixed overhead is charged throughout those years, including periods of limited production.

Final sales equal the lowest of assumed customer demand, channel capacity and every included stage's capacity expressed in final-output equivalents. A bottleneck limits the entire owned chain. The model purchases inputs for that achievable output only. Unserved demand receives no revenue, replacement module purchase or backlog asset. No contractual non-delivery penalty is assumed. These choices need explicit review against actual minimum-delivery commitments and make-or-buy flexibility.

At the reference scale, mature annual sales are 495 MW for complete-module import, 470 MW for assembly, 450 MW for cell plus assembly, 440 MW after adding ingot/wafer, and 430 MW for the full upstream stack. First-year sales are respectively 420.750, 235, 180, 132 and 107.500 MW. Additional integration consequently changes both cost and the quantity reaching customers. A proposal that retains full module sales during a slow upstream ramp would require a separately priced external sourcing bridge; that bridge is absent here.

13. Landed inputs, power and scrap form an auditable cost stack

Each external purchase has a quotation, freight charge and assumed ad valorem import duty. Landed price equals quotation multiplied by one plus the duty rate, with freight added separately. Complete modules have a fictional USD 0.155 quotation, USD 0.009 freight and 5% duty, producing USD 0.171750 per purchased W. Imported cells have a USD 0.072 quotation, USD 0.003500 freight and 4% duty, producing USD 0.078380 per input W. These figures illustrate the formula and establish no tariff classification or market quotation.

Local assembly purchases both cells and its separate kit. Cell integration removes the cell purchase and introduces wafer purchases, cell conversion expenditure and cell rejects. Ingot-and-wafer integration removes purchased wafers and introduces polysilicon charge, conversion expenditure and kilogram rejects. Upstream integration replaces polysilicon purchases with feed kilograms and upstream conversion. Kits are counted once at assembly input. No architecture pays simultaneously for the replaced intermediate and its owned conversion route.

Power is an explicit consumption account. Assembly uses an assumed 0.040 kWh per input-equivalent W, cells 0.085, ingot/wafer 0.045, and upstream conversion 35 kWh per feed kilogram. The reference electricity price is USD 0.080 per kWh. These quantities are accounting assumptions requiring vendor guarantees, metering boundaries and engineering review. An actual power assessment also needs connection capacity, load profile, interruption arrangements, demand charges and the contract's escalation terms. A single energy-price input supplies none of that evidence.

Stage-specific reject streams receive limited fictional scrap credits. Assembly rejects receive USD 0.015 per rejected equivalent W; cell rejects receive USD 0.008. Ingot/wafer rejects receive USD 1.500 per rejected silicon kilogram and upstream rejects USD 0.200 per kilogram. Credits are deducted once from variable cost. The model contains no recycled return loop, replacement-output uplift or second sale of the same rejected stream. Actual residue composition, recovery expense and buyer acceptance could require a different treatment, including a disposal cost.

The mature operating-cost exhibit divides purchases, nonpower conversion, electricity, fixed overhead and scrap by final sold W. Derived total operating costs are approximately USD 0.175 for import, USD 0.150 for assembly, USD 0.142 for cell plus assembly, USD 0.148 for the ingot/wafer stack and USD 0.159 for the full stack. These totals exclude capital expenditure and

working-capital investment. Their relatively favourable manufacturing margins therefore need to be followed through the investment account before any ownership decision.

Table 4. Fictional landed purchases and price pass-through

Purchased input	Price unit	Quote	Freight	Duty %	Landed price	Lagged quote pass-through %
Complete module	USD/W-eq	0.155000	0.009000	5.000	0.171750	85.000
Cell	USD/W-eq	0.072000	0.003500	4.000	0.078380	65.000
Wafer	USD/W-eq	0.036000	0.001800	4.000	0.039240	50.000
Polysilicon	USD/kg	9.000000	0.450000	2.000	9.630000	30.000
Silicon feed	USD/kg	2.500000	0.250000	3.000	2.825000	10.000
Assembly kit	USD/W-eq	0.042000	0.004000	3.000	0.047260	25.000

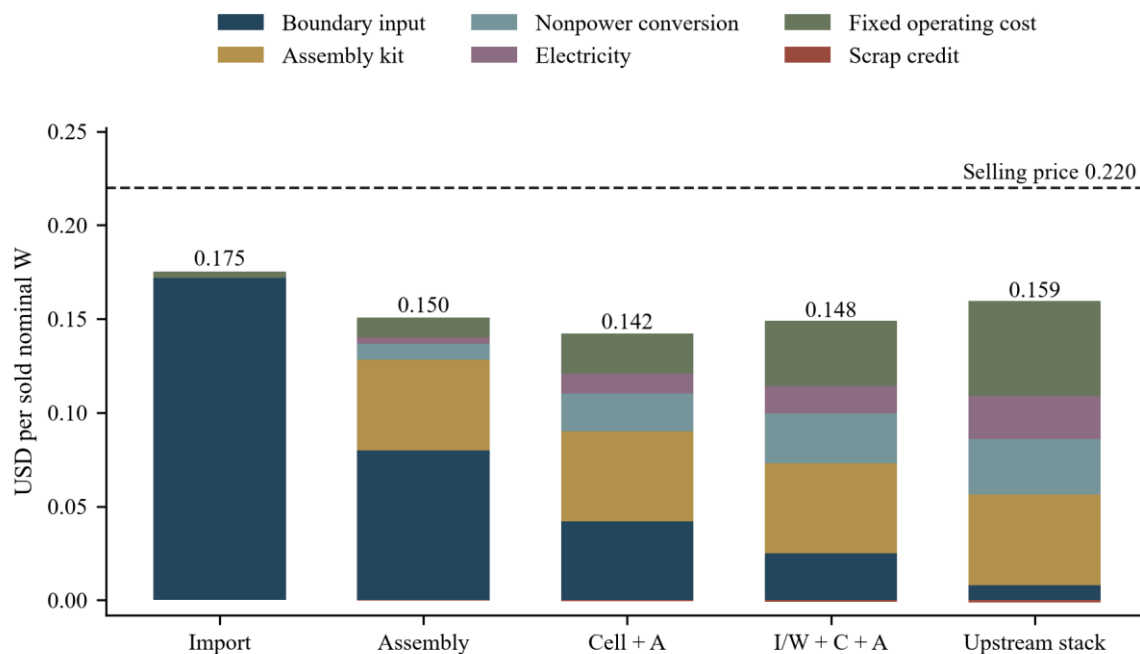
Fictional input prices, freight and ad valorem duty assumptions. Pass-through applies only to the prior year's market shock and only to the quotation; freight remains fixed. No country or actual tariff is represented.

Table 5. Fictional mature output and cost replacement

Architecture	Sold MW year five	Outer purchase boundary	Purchased cost USD m	Conversion USD m	Scrap credit USD m
Import	495.000	module	85.016	0.000	0.000
Assembly	470.000	cell	60.256	5.611	0.144
Cell + A	450.000	wafer	40.568	13.691	0.311
I/W + C + A	440.000	polysilicon	32.164	18.088	0.457
Upstream stack	430.000	silicon feed	24.223	22.613	0.472

All values derive from fictional no-policy assumptions at 500 MW design. Purchased cost includes the outer intermediate and, for local assembly, its separate assembly kit. Intermediate transfers are unpriced internal flows.

Figure 1. Fictional purchasing boundary and mature operating cost



Fictional year-five costs at 500 MW design divide boundary purchases, assembly kits, conversion, electricity, overhead and scrap by sold nominal W. Totals exclude capital expenditure and working-capital funding. A means assembly; C means cell; I/W means ingot and wafer. The upstream stack includes all manufacturing stages.

14. Construction and working capital are funded before a steady margin emerges

The reference stage-build assumptions are USD 42 million for assembly, USD 40 million for cells, USD 65 million for ingot/wafer and USD 110 million for upstream conversion. The architectures accumulate only their included stages and the common channel. Seventy per cent of build expenditure is paid at closing and 30% in year one. Additional manufacturing ramp expenditure equals 5% of stage-build cost in year one and 2% in year two. Annual maintenance expenditure is 2% of manufacturing build cost and 1.5% of channel setup cost.

Initial working capital is a purchased-input inventory advance equal to twenty days of first-year purchases. Subsequent normal inventories equal sixty days of external purchased cost plus fifteen days of conversion cost. Customer receivables equal sixty days of sales, while supplier payables equal thirty days of variable cost after scrap credits. These stylised annual conventions replace no monthly production, shipment or funding schedule. They assume that customers and suppliers perform on those terms and contain no separate deposit-financing arrangement.

Operating cash flow equals EBITDA less the change in ordinary net working capital, with received hypothetical support added separately where applicable. Free cash flow then deducts build, ramp and maintenance capital expenditure. Initial inventory is funded at closing and enters the opening working-capital balance; later changes are measured against that balance. It is never counted as a second initial investment. The model contains no debt proceeds, interest expense or financing benefit.

At the end of year ten, the model collects operating receivables, realises inventory at its carrying value and settles supplier payables. Closing ordinary working capital becomes zero. The resulting cash release is the balance-sheet unwinding of the finite operation. There is no additional inventory-sale margin, plant disposal receipt or continuing-business terminal value. Continuing production would require a different terminal convention and ongoing working-capital funding. Actual inventory realisability remains an evidence requirement; write-downs would reduce the illustrated final receipt.

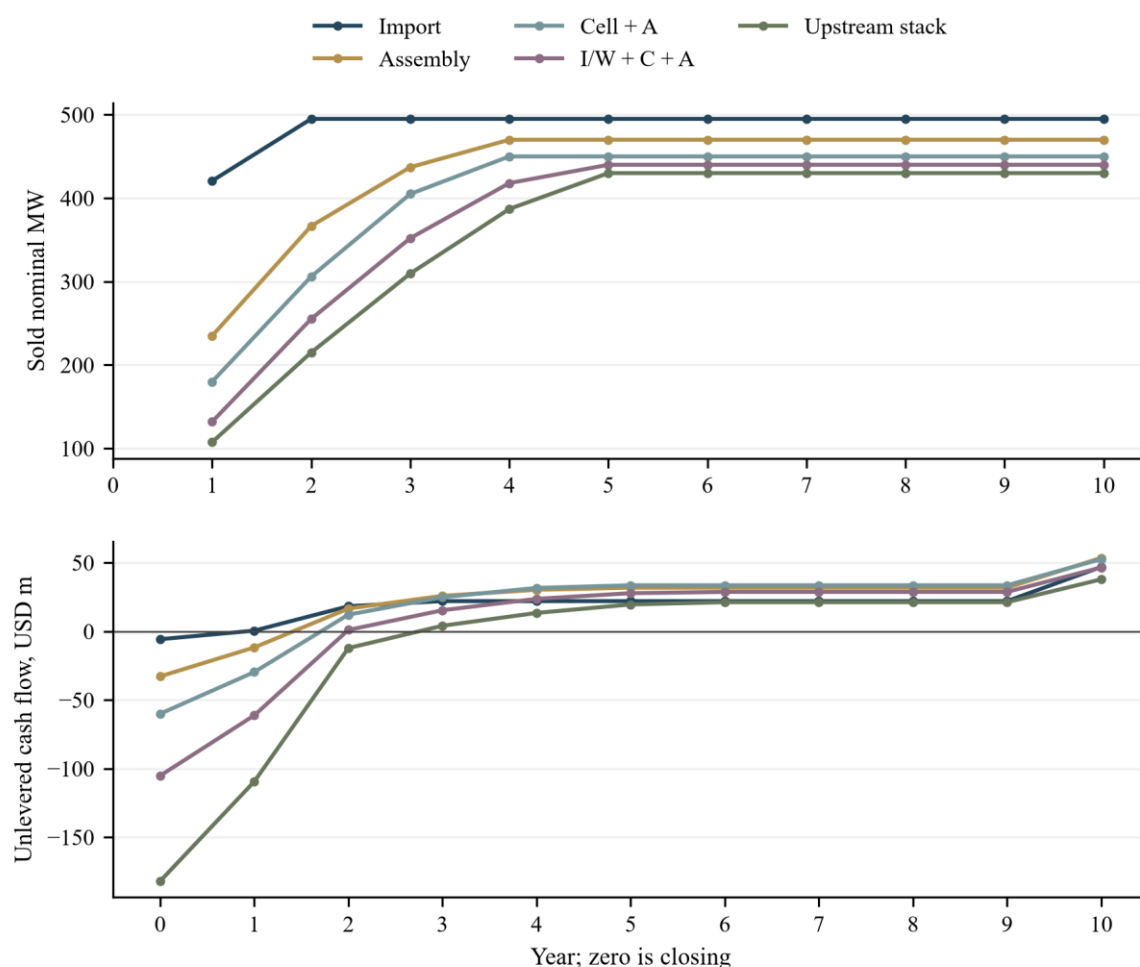
Reference closing uses rise from USD 5.710 million for import to USD 32.801 million for assembly, USD 60.039 million for cell plus assembly, USD 105.179 million for the ingot/wafer stack and USD 181.982 million for the upstream stack. First-year free cash flow is positive USD 0.518 million for import and negative USD 11.704 million for assembly. The full stack requires a further USD 109.450 million in year one. These annual values describe unlevered project funding requirements, with no claim that an investor or lender has committed capital.

Table 6. Fictional no-policy investment and cash results

Architecture	NPV USD m	Closing uses USD m	Year-one FCFF USD m	Year-five FCFF USD m	Peak normal NWC USD m	Zero-NPV price USD/W
Import	104.672	5.710	0.518	22.046	24.889	0.181020
Assembly	97.734	32.801	-11.704	31.799	21.731	0.177532
Cell + A	54.894	60.039	-29.646	33.574	19.071	0.194098
I/W + C + A	-52.662	105.179	-61.202	27.835	17.850	0.246942
Upstream stack	-217.991	181.982	-109.450	19.593	16.651	0.339319

Fictional ten-year pretax unlevered NPV at a 12% author-selected hurdle; no debt, tax shield, terminal business value or salvage. Closing uses include 70% of build capex and initial inventory funding. Zero-NPV prices hold all other 500 MW inputs fixed.

Figure 2. Fictional ramp, output bottlenecks and unlevered cash



Fictional no-policy output and cash flows retain every included stage's yield, availability and ramp. Closing includes initial investment and inventory funding. Year ten realises operating working capital at carrying value, without plant salvage or a continuing-business terminal value.

15. The no-policy result separates operating contribution from investment value

The no-policy baseline assigns zero support to every architecture. At 500 MW design, derived pretax unlevered NPVs are USD 104.672 million for import, USD 97.734 million for assembly and USD 54.894 million for cell plus assembly. The ingot/wafer stack produces negative USD 52.662 million, while the full upstream stack produces negative USD 217.991 million. Those rankings apply solely to the assumed prices, ramp schedules, cost functions and ten-year horizon. They establish no country's competitive position.

Assembly's mature cash contribution exceeds import's, while its illustrated NPV is USD 6.938 million lower. The initial investment and slower early output account for the difference within these assumptions. Cell integration lowers mature operating cost further and introduces another capital commitment with a slower bottleneck. The ingot/wafer and upstream stacks retain positive mature operating cash flow while failing the illustrated investment hurdle. A positive mature margin therefore cannot substitute for the full discounted cash schedule.

The downward-market scenario reduces final selling price by 10% in year two, 20% in year three and 30% from year four. Imported quotations respond only one year later and by different

assumed fractions: 85% for complete modules, 65% for cells, 50% for wafers, 30% for polysilicon, 10% for silicon feed and 25% for kits. Freight remains fixed. This represents a specified hypothetical purchasing response. It supplies no evidence of indexation, negotiation power or actual supplier conduct.

Under that scenario, import NPV becomes USD 44.261 million and assembly USD 6.903 million. Cell plus assembly falls to negative USD 44.059 million. The ingot/wafer stack falls to negative USD 152.079 million, and the upstream stack to negative USD 315.330 million. The owned conversion costs and fixed investment receive no automatic market-price relief. These results show the cash consequences of the selected mismatch between selling-price adjustment and input-price pass-through.

A joint large-plant and downward-market case uses 1,800 MW design with the same declining-price sequence and additional scale-price pressure. Its year-four selling price is USD 0.143753 per W. Import NPV is USD 80.617 million, assembly USD 46.620 million and cell plus assembly negative USD 32.287 million. The full stack falls to negative USD 650.247 million. This case retains the unverified assumption of accessible demand at the larger scale; it supplies no evidence that expanding production can sell that volume.

Two further no-policy stresses address operational and external-input exposure. The yield-and-uptime case multiplies every manufacturing yield by 97% and every availability assumption by 90%, including channel availability. The power-and-duty case increases electricity to USD 0.120 per kWh and adds five percentage points to every assumed external-input duty. The paired duty shock is a parameter test, with no suggestion that the inputs share an actual customs treatment. Scenario NPVs remain separate results, with no probabilities, weighted aggregate or composite competitiveness score.

Table 7. Fictional scenario NPVs

Scenario	Import	Assembly	Cell + A	I/W + C + A	Upstream stack
No-policy baseline	104.672	97.734	54.894	-52.662	-217.991
Downward market price	44.261	6.903	-44.059	-152.079	-315.330
Large plant with market decline	80.617	46.620	-32.287	-276.599	-650.247
Yield and uptime stress	92.925	67.348	14.260	-98.188	-267.256
Power and landed-duty stress	83.316	80.200	34.758	-73.890	-243.758
Hypothetical finite credit	104.672	107.581	74.731	-25.483	-183.074
Credit eligibility denied	104.672	97.734	54.894	-52.662	-217.991
Credit receipt delayed	104.672	105.584	70.708	-30.995	-190.155
Credit ends after year two	104.672	101.321	61.398	-44.629	-208.442

USD million, fictional pretax unlevered NPVs. The downward case reaches a 30% final-price decline with one-year-lagged partial quotation relief. Hypothetical credit is unattached to any country; denied eligibility equals the no-policy baseline.

16. Scale thresholds need a demand and price mechanism

The scale test changes reference design from 50 to 2,500 MW. Installed input capacities move proportionally. Manufacturing build expenditure follows a fictional function with 25% of reference cost fixed and 75% multiplied by scale to the power 0.82. Stage overhead follows scale to the power 0.55. Channel expenditure and overhead use powers of 0.70 and 0.50. These transparent functions create a specified economy of scale; they are unsupported as empirical manufacturing cost curves and require replacement with actual quotations.

The test also changes the assumed selling environment. Above 500 MW, final selling price is reduced by USD 0.008 multiplied by the natural logarithm of scale divided by 500 MW. At 1,800 MW, that reduction is approximately USD 0.010247 per W. Accessible annual demand is assumed to rise with the selected design scale. There is no evidence of customers for that volume. An actual expansion case would need qualified orders, delivery capacity and price terms at each step. The scalable demand assumed here requires its own market validation.

For each local architecture, the executable calculation compares its NPV with complete-module import at the same design scale and selling environment. A grid locates sign changes, followed by scalar bisection within each bracket. Assembly crosses at approximately 642.328 MW and cell plus assembly at 1,457.192 MW. Neither deeper stack has a crossing in the scanned interval. The absence of a crossing reports the tested range; it supplies no claim about every possible scale or technology configuration.

The separate zero-NPV selling-price calculation holds reference scale and all other no-policy inputs fixed. Derived prices are USD 0.181020 per W for import, USD 0.177532 for assembly, USD 0.194098 for cell plus assembly, USD 0.246942 for the ingot/wafer stack and USD 0.339319 for the upstream stack. These are each architecture's own hurdle boundaries. They differ from the scale at which one architecture matches another and from a selling price that a customer has accepted.

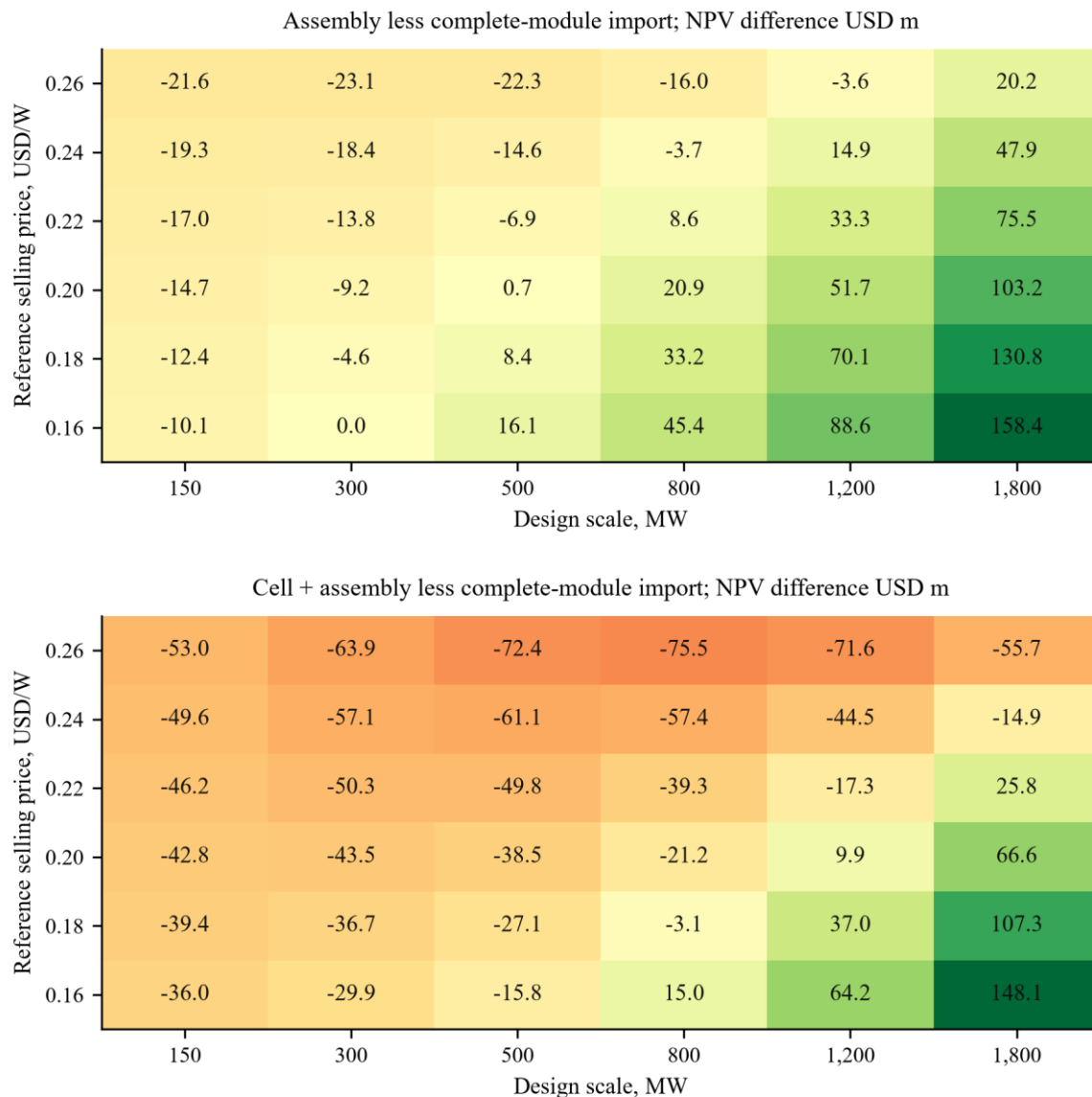
The price-scale maps display incremental NPV relative to import, with absolute values retained in the reproducible results. A positive relative cell can coexist with negative NPVs for both choices. Lower final prices can make assembly's relative result improve because the import route sells more units and therefore loses more contribution when only the selling-price axis changes. Input quotations remain fixed in that particular map. The separate downward-market scenario supplies lagged purchasing relief and produces a different comparison. Both views require their stated assumptions.

Table 8. Fictional scale crossings against complete-module import

Local architecture	First crossing MW	All scanned crossings MW	Delta NPV at 2,500 MW USD m
Assembly	642.328	642.3	129.769
Cell + A	1,457.192	1,457.2	85.891
I/W + C + A	No crossing in scanned interval	None in scanned interval	-217.050
Upstream stack	No crossing in scanned interval	None in scanned interval	-696.864

Fictional no-policy scale tests scan 50 to 2,500 MW. Each comparison uses equal design scale, the same assumed accessible demand, and a selling-price reduction of USD 0.008 times $\ln(\text{scale}/500 \text{ MW})$ above 500 MW. A crossing is a conditional arithmetic boundary, not proof of feasible demand or a universal minimum.

Figure 3. Fictional scale and selling-price comparison against import



Fictional cell values are incremental ten-year NPV against complete-module import at equal design scale, with the stated scale-price pressure and fixed input quotations. Positive relative NPV can coexist with negative absolute NPV. Scalable accessible demand is an author assumption; the map supplies no engineering or market validation.

17. A finite hypothetical credit requires its own cash reconciliation

The policy illustration is unattached to any jurisdiction. It assumes eligibility only for the stated scenario and grants no actual legal entitlement. A single architecture-specific payment is assigned to final sold output: USD 0.008 per W for assembly, USD 0.018 for cell plus assembly, USD 0.028 for the ingot/wafer stack and USD 0.040 for the upstream stack. These invented rates are alternatives. The full-stack case receives its stated rate once; it does not add assembly, cell and wafer credits to that amount.

Eligible output earns support in operating years one through five only. Cash arrives one year after earning, producing receipts in years two through six. The separate support-receivable account records earned amounts less cash received. Support is excluded from ordinary working capital, and operating EBITDA excludes the support accrual. Free cash flow can be reproduced either by adding support cash or by adding earned support and deducting the support-receivable increase. Using both treatments together would duplicate the benefit.

The derived present value of cash support is USD 9.847 million for assembly, USD 19.836 million for cell plus assembly, USD 27.179 million for the ingot/wafer stack and USD 34.917 million for the upstream stack. Each amount equals that architecture's NPV increase over its unchanged no-policy case. Assembly NPV becomes USD 107.581 million, exceeding import's USD 104.672 million under this conditional payment design. The two deepest stacks remain negative. The support illustration consequently leaves substantial investment conditions unresolved.

Eligibility denial returns the entire case to the no-policy baseline. Extending the receipt lag to three years reduces assembly NPV to USD 105.584 million. Ending earning after year two reduces it to USD 101.321 million. Neither scenario assumes a replacement grant, an extension after expiry or a continuing-business support value. All modelled support receivables settle within the ten-year horizon. Administrative expenses, tax interactions, clawback and disputed claims are omitted and require separate terms in an actual eligibility assessment.

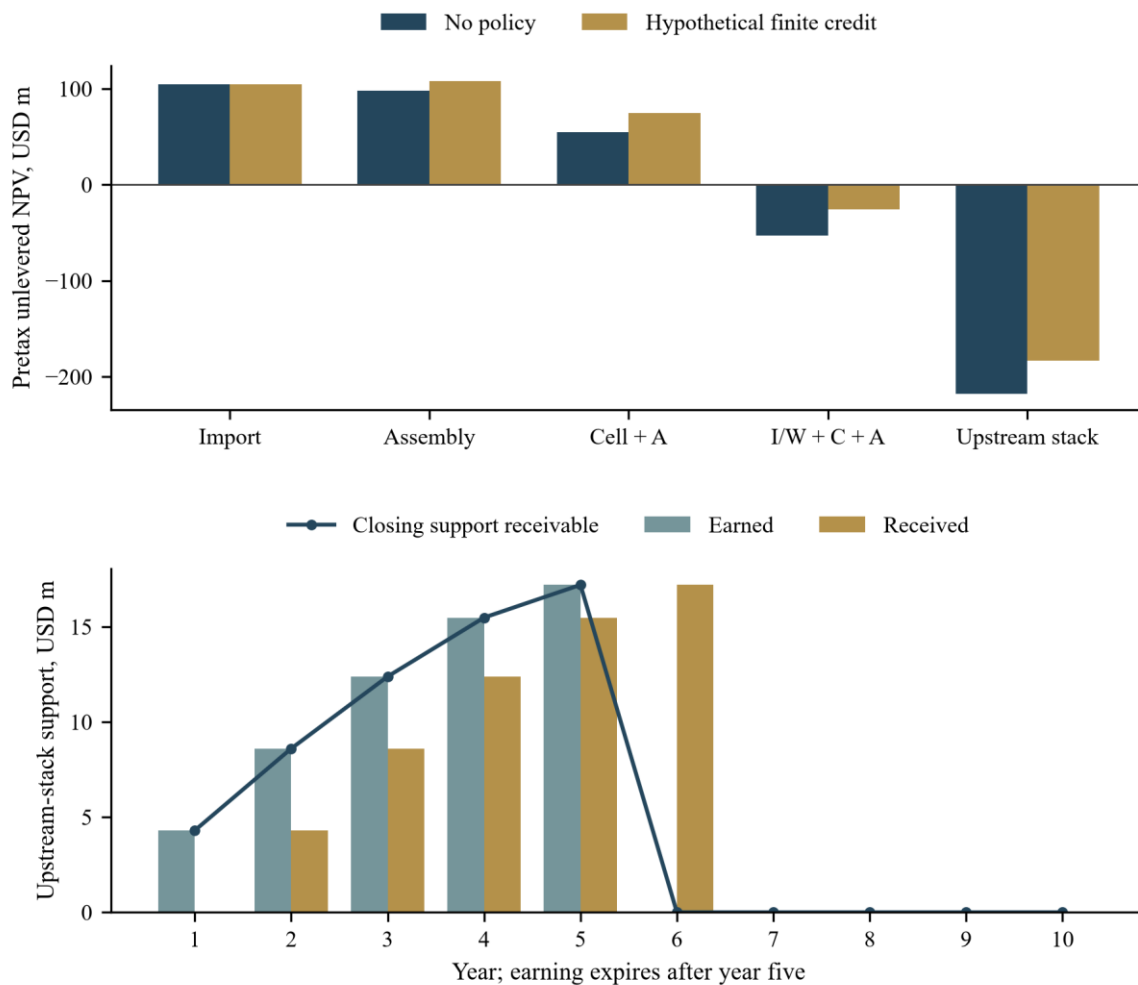
The investment file should therefore identify the legal claimant, qualifying stage, output denominator, origin documentation, payment schedule, expiry and recourse before assigning support value. A construction funding plan also needs to establish whether a receivable can finance expenditure before cash arrives. The model assumes no borrowing against expected support. Policy analysis elsewhere in this paper supplies jurisdiction-specific context; the invented credit remains a separate arithmetic experiment and should retain that label when the exhibits are reused.

Table 9. Fictional finite-credit cash and value bridge

Architecture	Credit USD/W	Earned support USD m	PV cash support USD m	Credit-scenario NPV USD m	Peak support AR USD m
Import	0.000	0.000	0.000	104.672	0.000
Assembly	0.008	15.830	9.847	107.581	3.760
Cell + A	0.018	32.238	19.836	74.731	8.100
I/W + C + A	0.028	44.722	27.179	-25.483	12.320
Upstream stack	0.040	57.964	34.917	-183.074	17.200

Fictional eligibility is assumed only in this scenario. One architecture-specific rate applies to final sold output, without stacking credits for internal stages. Credits are earned in years one to five and received one year later. The support receivable is excluded from ordinary NWC and reconciled separately to cash.

Figure 4. Fictional finite support and the timing of cash receipts



Fictional conditional credits apply once to final sold output at the selected architecture's rate. Earning ends after year five; one-year-lagged receipts end in year six. The lower panel shows the full upstream stack's separate support receivable. No actual country eligibility, indefinite renewal or financing against support is assumed.

18. The ownership route remains a conditional transaction decision

The worked comparison can support a structured sourcing discussion by making the required evidence explicit. A complete-module supply contract needs product qualification, delivery commitments, warranty recourse, landed pricing and import classification. Local assembly adds equipment performance, kit availability, customer acceptance and production-management requirements. Cell and ingot/wafer integration add their own process controls, material specifications and input reservations. Upstream conversion adds a kilogram-based material account and a larger energy and construction commitment.

A staged build could use documented assembly performance as a gate before further integration. The model's simultaneous architectures do not value that option or assume that later stages can be added without disruption. A joint venture would require a separate schedule of capital contributions, control, transfer prices, operating responsibilities and distributions. Those terms could change the cash boundary materially. The present integrated cases contain no minority interest, partner contribution or shared-liability allocation.

Acquisition offers a different starting asset and evidence set. Historical output, maintenance, customer qualification and power contracts could replace parts of the fictional ramp account.

Purchase consideration, debt-like liabilities, refurbishment and integration expenditure would then replace the corresponding build assumptions. The model assigns no acquisition discount or superiority to buying an existing facility. Contract manufacturing or an intermediate-supply agreement also requires an independently specified price, capacity reservation and remedy structure before comparison with owned operations.

Before an ownership decision, the sponsor should replace each external input with evidence at its stated unit and boundary. The principal requests are stage equipment quotations, accepted-yield trials, availability commitments, qualification schedules, power supply, land and permits, logistics quotations, customs advice, customer orders and working-capital terms. Any proposed credit belongs in a separate eligibility and cash-settlement schedule. Where those records remain unavailable, the no-policy case and unresolved conditions should stay visible in the decision materials.

Executable identities reconcile stage inputs, rejects, silicon kilograms, available capacity, outer purchases, landed values, sales and working-capital movements. They also reconcile finite support earnings to receipts and reproduce discounted cash flows. These are internal consistency checks by the model author and provide no independent assurance of the assumptions. The supported conclusion is conditional: each additional owned stage needs a demonstrated cost replacement, achievable output, financed ramp and acceptable incremental value. The example supplies no universal localisation ladder, country ranking or recommended purchase without transaction evidence.

19. Turn qualification into an investment gate

A manufacturing line can produce a module that passes the factory's own inspection while leaving the buyer unable to establish its suitability for a particular project. An investment committee should therefore define customer acceptance before choosing equipment. The proposed gate is a documented sequence: product design and bill of materials; applicable testing and certification; purchaser-specific qualification; reproducible production-lot performance; and the warranty obligations attached to the delivered product. Each step answers a different question. A certificate for one design does not establish the commercial acceptance of every subsequent materials substitution.

The public description of IEC 61215-1:2021 identifies design qualification for terrestrial modules and expressly separates qualification results from a quantitative lifetime prediction. This paper relies on that public description; it does not reproduce the full standard or conduct a compliance assessment. The distinction matters when an investment memorandum translates a test certificate into a long-dated warranty assumption. Site conditions, operating exposure and the particular product design remain relevant. [13]

The following proposed diligence framework connects those questions to the supply architecture. For an importer, the evidence starts with the supplier and the particular goods acquired. Assembly introduces responsibility for local materials handling, lamination and finished-product consistency. Bringing cell production inside the perimeter adds process recipes, cell performance distributions and interface control. Upstream integration extends the chain of technical evidence further. Each additional stage needs a defined owner of deviations and a route to customer approval. Vertical integration alone does not demonstrate that these responsibilities are being performed.

Table 10. Qualification evidence at the investment boundary

Gate	Evidence to obtain	Capital decision affected
Product identity	Versioned bill of materials, design and relevant test documents	Freeze eligible product before committing dedicated tooling
Repeatable manufacture	Lot-level yield, acceptance and traceable process changes	Release commissioning funds against agreed evidence
Customer acceptance	Written qualification scope and accepted substitutions	Include only qualified demand in the financing case
Claims responsibility	Contractual warranty, supplier recourse and claims process	Price residual liability and liquidity needs

Notes: Proposed diligence gates, not a certification checklist or a statement that any factory has satisfied them. An independent technical adviser should define the applicable tests and acceptance criteria.

For an acquisition, the diligence team should sample shipped serial numbers back to raw-material lots and forward to customer orders. The proposed exercise tests whether the records actually join. A spreadsheet listing serial numbers without matching process changes cannot establish which production cohorts share a defect risk. The team should also distinguish claims paid, claims rejected, open claims and claims that have not yet emerged. A low recorded claims rate may reflect a short operating history or an incomplete reporting process; these possibilities require investigation and a documented evidential basis for any numerical adjustment.

Contract design follows the identified boundary. Equipment acceptance can be linked to demonstrated throughput and quality under specified conditions. Supplier warranties can address a defined input or machine; a purchaser's product warranty may remain broader. Proposed holdbacks and indemnities require legal negotiation, counterparty-credit analysis and a practical enforcement route. The financial model should recognise the expected cash costs only when evidence supports their amount and timing. An unresolved warranty exposure belongs in the decision memorandum even when a reliable valuation is unavailable.

20. Use data and AI against a measured production loss

An AI proposal becomes investable when the factory can identify the loss being addressed, measure a credible baseline and connect a change to cash. Potential applications include inspection triage, process-drift detection, maintenance scheduling and reconciliation of supplier, lot and customer records. These are proposed applications in this paper. No improvement in yield, production uptime or valuation is asserted for a particular plant.

The June 2026 IEA PVPS Task 13 public summary links quality management, monitoring and economic decisions in utility-scale photovoltaic projects. Its setting is principally the project lifecycle. It provides a useful reason to examine the quality-to-value connection, while leaving the manufacturing application's effectiveness to be tested separately. The report summary cannot supply an assumed factory yield improvement or software return. [14]

A proposed inspection pilot should retain the distinction between false acceptance and false rejection. A model that reduces manual review by allowing defective products through may improve a dashboard while increasing claims. A conservative classifier may reject too many acceptable products and destroy contribution. The relevant experiment measures both errors against an independently adjudicated sample, records the cost of each error and identifies the production decisions that the software is allowed to influence. Human escalation should remain explicit for uncertain or safety-relevant results.

Validation should be separated from the observations used to develop the model. A proposed test would hold out later production periods, supplier lots or lines, according to the intended deployment. Training and evaluation on near-identical images from the same lot risks overstating the system's ability to generalise. Equipment changes, new cell designs and lighting changes can also alter performance. The deployment plan should specify monitoring, retraining triggers, a rollback method and the rights to retain and use supplier and customer data. These are design requirements for a prospective pilot, not claims that one validation approach suits every factory.

Table 11. Proposed AI-to-cash validation register

Application	Test evidence	Cash link to validate
Visual inspection	Adjudicated held-out defects and both error rates	Net scrap, rework and claims after review costs
Process-drift alerts	Time-stamped alarm and intervention history	Accepted production recovered without double counting
Maintenance planning	Comparable downtime and maintenance records	Additional saleable output within demand and stage limits
Lot traceability	Reconciled supplier-to-shipment record sample	Faster containment and demonstrable claims recourse

Notes: Author-proposed experiments. No AI benefit is included in the worked valuation. The table identifies evidence required before an incremental benefit could be added.

Cash attribution should also respect the bottleneck. More good cells cannot create additional module sales when assembly or contracted demand is already the constraint. The analyst should rerun the physical architecture with the proposed change and recompute purchased materials, output, working capital and incremental software costs. Benefits from avoided defects and higher accepted output may overlap; recording each on separate revenue lines would overstate value. A smaller pilot that resolves these measurement questions can be useful even when the software itself appears inexpensive relative to the factory.

In an acquisition, assess whether the relevant data, code, licences and skilled staff transfer with the business. A demonstration operated by a vendor's specialist may not represent the buyer's deployable capability. Proposed transition-service terms should specify data access, model-operation responsibility, cybersecurity dependencies and exit arrangements. The purchase price should reflect demonstrated transferable capability and remaining implementation expenditure. A generic AI label supplies neither of those inputs.

21. Keep carbon, origin and operating economics in separate ledgers

Industrial policy, customer procurement and environmental assessment may all ask where a product was made. They can use different definitions and evidence. A country-of-origin determination, a component eligibility test, a lifecycle inventory and a marketing claim should each retain their own basis. A low-carbon electricity assumption does not establish customs origin; a domestic-content conclusion does not measure lifecycle emissions. Combining these claims in one localisation score would conceal the decision being made.

The July 2026 IEA PVPS Task 12 public summary describes an updated photovoltaic lifecycle inventory with measured and simulation-based datasets. Its monocrystalline-silicon inputs include 83 screened factory-level assessments from French tenders, with different coverage across manufacturing stages. That evidence supports attention to stage-specific material and energy flows. It is not a census of every factory or a direct ranking of national production costs.

Prospective simulated inventory data also needs to remain distinguishable from measured operations. [15]

For the proposed investment framework, establish a material-flow and evidence register alongside the cash model. Record the input supplier, location, quantity, energy evidence, processing stage and applicable reporting boundary. Link records to product and lot identifiers. Purchased electricity, on-site generation and contractual instruments should be documented under the relevant assessment rules; an analyst should not select whichever representation produces the most favourable result. Where information is missing, disclose the gap and test how dependent the customer or policy claim is on it.

The commercial implication depends on a demonstrable mechanism. A purchaser may require a specified disclosure or qualification before accepting supply. A contract may attach a premium or liability to a particular verified attribute. In the absence of that evidence, the model should not invent a carbon premium, a credit receipt or a higher exit multiple. It can still evaluate the operating consequences of electricity consumption, sourcing alternatives and traceability expenditure. Those cash items have their own evidence requirements.

Acquisition diligence should compare environmental statements with the underlying boundary and period. A corporate average can conceal the electricity mix or process performance of the factory being bought. A planned renewable-energy arrangement may differ from the electricity actually consumed during ramp-up. Missing wastewater, hazardous-material or permitting information can affect execution independently of a carbon calculation. The decision record should separate verified current operation, contracted changes and prospective improvements so the buyer understands what transfers at closing.

For financing, document who maintains the register and who may audit it. A representation unsupported by accessible records can create a dispute without producing a usable remedy. Proposed conditions precedent should focus on evidence material to eligibility, customer acceptance and legal operation. Each additional document request should identify the defined risk it resolves. The result is a chain from physical process to documented claim to contractual consequence, with a separate cash treatment for each consequence that can be substantiated.

22. Sequence transactions around irreversible commitments

The localisation ladder can be entered through supplier contracts, a joint venture, an acquisition or a greenfield build. The worked model compares operating architectures, not the negotiated economics of those transaction routes. A route decision requires additional evidence on purchase consideration, intellectual property, change-of-control permissions, construction risk, equipment condition, liabilities and available customer contracts. An operating architecture with a favourable illustrative NPV does not establish that an acquisition at any price creates value.

A proposed sequence begins with the customer and product boundary, proceeds to site and input feasibility, and then reaches the irreversible plant commitment. Conditional contracts may help establish whether the required demand, inputs and partner capability can be assembled. Their usefulness depends on enforceable terms, creditworthy counterparties and consistency between conditions. An offtake agreement that permits broad termination while the equipment order is non-cancellable leaves the sponsor holding the mismatch.

Table 12. Proposed staged commitment map

Commitment stage	Evidence before release	Unresolved exposure to record
Customer and product	Qualified product scope and demand terms	Volume, price and specification changes
Site and inputs	Utilities, permits and supplier feasibility	Connection dates, input origin and shortages
Equipment or acquisition	Technical diligence and agreed perimeter	Ramp-up, refurbishment and legacy liabilities
Commercial operation	Accepted output and collection evidence	Working capital, warranty and payment delays
Further integration	Incremental economics and capability test	Additional fixed cost and technology change

Notes: Proposed transaction sequencing, not legal advice or a commitment by a lender, purchaser or public authority. Actual milestones require project-specific technical and contractual assessment.

For a joint venture, map each partner's contribution to a verifiable deliverable. Cash, a brand, a recipe, equipment access and purported offtake are different assets. The agreement should specify which rights are exclusive, how technology updates are provided, who approves changes and how deadlock or underperformance is handled. Where a partner supplies intermediates and receives a share of manufacturing profits, transfer pricing and procurement rights need particular scrutiny. The model's external-input price should reflect the proposed contract's pricing basis, duration and reset provisions.

For debt, distinguish assets that can support enforceable security from specialised equipment whose recovery value has not been established. Construction and ramp-up can consume cash before qualified sales begin; borrowing against a mature operating case does not finance that interval by itself. A proposed financing plan would show equity committed before drawdown, contingency funding, working-capital availability and the treatment of delayed support receipts. The unlevered model in this paper supplies no debt-capacity estimate, covenant headroom or lender approval.

Technology change should enter the transaction terms as well as the sensitivity model. Equipment compatibility, supplier support, access to recipes and the cost of a product transition can determine whether additional integration remains useful. Proposed acquisition diligence should identify machinery that needs replacement and the production interruption that replacement may cause. A capital budget that treats the whole facility as continuously productive during refurbishment can overstate both revenue and operating cash available to service financing.

The final approval memorandum should contain explicit stop conditions. Examples include failure to qualify a product, unsupported policy eligibility, unavailable grid capacity, or a customer contract that cannot sustain the downside price and collection case. The thresholds should come from the actual project and negotiated risk allocation. They should be revisited when evidence changes; retaining a sunk development cost is not an economic reason to make a much larger irreversible investment.

23. Interpret the ladder within its evidence limits

This paper combines current primary-source policy and technical evidence with a deliberately hypothetical financial comparison. The source evidence describes market structure, technology or applicable rules within its stated scope. The numerical comparison is an author-designed illustration of supply-boundary accounting. Its prices, engineering conversions, costs, operating parameters and discount rate do not represent a quoted plant, measured factory or investable

offer. The calculations cannot establish a preferred country or an expected return for a real investor.

Several omitted elements could change an actual decision. Product-specific engineering would replace the illustrative watt-equivalent conversions and yield relationships. Local wages, site tariffs, logistics, duties and customer contracts would replace assumed inputs. Tax, financing, construction delay, exchange rates, warranty claims, refurbishment and residual value would require their own evidence. Policy qualification would need analysis of the legal entity, product, supply chain, transaction and effective dates; a country heading is insufficient.

The framework's practical contribution is the order of the questions. Define the customer and the saleable product; select one consistent operating boundary; establish which purchased intermediate is displaced; balance production and demand; and calculate the incremental cash required. Evaluate each deeper stage against the alternative available to the investor. Then test policy expiry, price compression, commissioning performance and cash timing. Each step should retain a record of the evidence and the assumptions on which it depends.

Further empirical research could compare actual factories using consistently defined accepted output, energy consumption, input specifications and capital boundaries. It could test how customer qualification and supply-chain evidence affect contract terms, or measure the cash contribution of validated industrial AI applications. Such work would need permission to use plant-level records and careful treatment of confidentiality, selection and period effects. Public capacity announcements alone cannot supply the required observations.

The resulting investment discipline is conditional and stage-specific. A location may support one manufacturing stage while lacking the scale, capability, customer access or economics for another. Policy can change the opportunity, while its conditions and timing determine whether support becomes cash. A credible localisation plan therefore explains the next commitment, the evidence needed to make it and the circumstances under which the investor should stop.

Frequently Asked Questions

Does localisation require the entire solar manufacturing chain?

A project can define a narrower boundary, such as module assembly using imported cells. The investment case should identify the purchased inputs displaced by each additional stage and the capability, capital and customer evidence required. Full integration should be assessed incrementally against available alternatives.

Can the worked model rank the GCC, India, the UK and the US?

The model is a hypothetical comparison of supply architectures. It has no country-calibrated prices, taxes or plant engineering. A real location decision requires project-specific utilities, logistics, suppliers, qualification, policies and financing terms.

Why can a lower operating unit cost produce a weaker investment value?

The additional operating margin can be outweighed by capital expenditure, ramp-up losses, fixed costs or working-capital commitments. The illustration therefore combines the mature unit-cost comparison with annual cash flows and incremental investment value.

How should policy support enter a financing case?

Establish the applicable entity, product, supply chain, effective dates and payment conditions. Recognise cash timing separately from eligibility or earning. The hypothetical support case in this paper demonstrates that distinction; it does not establish entitlement under any country's programme.

Where can AI contribute to a manufacturing investment?

Proposed uses include inspection, process-drift detection, maintenance and lot traceability. Each application needs a measured baseline, independent validation and a reconciled link to accepted output or costs. The worked valuation includes no assumed AI uplift.

What should be checked before acquiring a solar manufacturer?

Define the acquired assets and rights; assess equipment condition, production records, customer acceptance, intellectual property, supplier terms and legacy claims. Transferable capability and future expenditure require evidence. The operating architecture comparison does not value a particular acquisition or approve a purchase price.

References

- [1] US Department of Energy. Solar Photovoltaic Manufacturing Basics. Undated. <https://www.energy.gov/cmei/systems/solar-photovoltaic-manufacturing-basics> Accessed 10 October 2026.
- [2] IEA PVPS. Trends in Photovoltaic Applications 2026. September 2026. https://iea-pvps.org/trends_reports/trends-2026/ Accessed 10 October 2026.
- [3] UAE Ministry of Industry and Advanced Technology; Emirates Global Aluminium. (a) National In-Country Value Program supplier awareness material. 2024. <https://moiat.gov.ae/-/media/site/moiat/programs/icv-formula/icv-supplier-awareness-2024.ashx> (b) EGA to deliver first-ever Celestial-R billets to leading Japanese manufacturer Sankyo Tateyama. 14 August 2025. <https://media.ega.ae/ega-to-deliver-first-ever-celestial-r-billets-to-leading-japanese-manufacturer-sankyo-tateyama/> Accessed 10 October 2026.
- [4] Public Investment Fund. PIF strengthens renewable energy localization in Saudi Arabia with three new joint ventures. 16 July 2024. <https://www.pif.gov.sa/en/news-and-insights/press-releases/2024/pif-strengthens-renewable-energy-localization-in-saudi-arabia-with-three-new-joint-ventures/> Accessed 10 October 2026.
- [5] Ministry of New and Renewable Energy, Government of India. (a) ALMM for Solar PV Cells: Amendment dated 28 July 2025. 28 July 2025. <https://static.pib.gov.in/WriteReadData/specificdocs/documents/2025/jul/doc2025728593401.pdf> (b) ALMM List-II: limited commissioning window for net-metering and open-access projects. 18 July 2026. <https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2026/07/202607181895863474.pdf> (c) ALMM List-II for solar PV cells: Clarification. 4 August 2026. <https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2026/08/20260804911824842.pdf> (d) ALMM official current document index. Index accessed 10 October 2026. <https://mnre.gov.in/en/approved-list-of-models-and-manufacturers-alm> Accessed 10 October 2026.
- [6] Ministry of New and Renewable Energy, Government of India. Amendment to ALMM Order for Implementation of ALMM for Wafers. 17 March 2026. <https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2026/03/20260317182261117.pdf> Accessed 10 October 2026.
- [7] Internal Revenue Service. Instructions for Form 7207, Advanced Manufacturing Production Credit. December 2025. <https://www.irs.gov/instructions/i7207> Accessed 10 October 2026.
- [8] Internal Revenue Service and US Department of the Treasury. Notice 2026-15: Interim PFE and material-assistance guidance. 12 February 2026. <https://www.irs.gov/pub/irs-drop/n-26-15.pdf> Accessed 10 October 2026.
- [9] Internal Revenue Service. (a) Instructions for Form 3468, 2025. 2025. <https://www.irs.gov/instructions/i3468> (b) Notice 2025-08: First Updated Elective Safe Harbor. 16 January 2025. <https://www.irs.gov/pub/irs-drop/n-25-08.pdf> Accessed 10 October 2026.
- [10] Department for Energy Security and Net Zero; HM Revenue and Customs. (a) Solar Roadmap: United Kingdom Powered by Solar. 30 June 2025. <https://www.gov.uk/government/publications/solar-roadmap/solar-roadmap-united-kingdom-powered-by-solar-accessible-webpage> (b) Case studies for insufficient production when trading between the UK and EU. 6 October 2021. <https://www.gov.uk/guidance/case-studies-for-insufficient-production-when-trading-between-the-uk-and-the-eu> Accessed 10 October 2026.
- [11] Oxford PV. 20% more powerful tandem solar panels enter commercial use for the first time in the US. 5 September 2024. <https://www.oxfordpv.com/press-releases/oxford-pv-solar-technology-patent> Accessed 10 October 2026.
- [12] US Department of Energy. Perovskite Solar Cells. Undated. <https://www.energy.gov/cmei/systems/perovskite-solar-cells> Accessed 10 October 2026.
- [13] International Electrotechnical Commission. IEC 61215-1:2021: Terrestrial photovoltaic modules; design qualification and type approval; public description. 23 February 2021. <https://webstore.iec.ch/en/publication/61345> Accessed 10 October 2026.

[14] IEA Photovoltaic Power Systems Programme, Task 13. Photovoltaic Project Decisions: Quality, Performance, and Economic Value; public summary. June 2026. <https://iea-pvps.org/key-topics/t13-pv-project-decisions-2026/> Accessed 10 October 2026.

[15] IEA Photovoltaic Power Systems Programme, Task 12. Life Cycle Inventories of Photovoltaic Systems; public summary. July 2026. <https://iea-pvps.org/key-topics/t12-lci-pv-systems-2026/> Accessed 10 October 2026.

About the Author

Chennakeshav (CK) is a corporate finance and investment banking executive with 25+ years of global experience in deal origination, structuring and execution across M&A, growth capital and corporate strategy. He has led value-creation mandates for founders, corporates and funds — bridging the boardroom view to hands-on execution and close.

His career spans Morgan Stanley, HSBC, Lloyds Banking Group, EWEC, ADQ portfolio companies and Emirates Growth Fund, across TMT, real estate, fintech, deeptech, cleantech, infrastructure and energy. He has partnered with C-suite leaders, private equity and venture funds, sovereign wealth funds and family offices to finance complex fund raises and scale-up ventures, and has led M&A due diligence, post-merger integration and business-transformation initiatives to create value.

At Matchpoint Partners he is Managing Partner, leading the firm's corporate finance, M&A and capital-raising practice. He holds an MBA from London Business School, an engineering degree from VTU and a Master of Laws (LLM, in progress) from UCL London.

An active start-up mentor, CK mentors at Techstars, DIFC FinTech Hive, Startup Grind, Founder Institute and IN5, serves as Entrepreneur Mentor in Residence (EMiR) at London Business School, and judges the Entrepreneurship World Cup.

<https://www.linkedin.com/in/ckadya/>

<https://www.matchpoint-partners.com/team/ck-adya.html>

Disclaimer

This paper is part of a continuing series on the structure of private and alternative markets. The views expressed are the author's own. The paper is for information only, describes market structure in general terms, and does not constitute investment, legal, tax or regulatory advice or a recommendation in respect of any security, vehicle or counterparty.