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# Socio-energetic stamina in photovoltaics: material security and distributed manufacturing potential of Kesterite (CZTSSe)

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## ABSTRACT

Energy transitions face a materials paradox because solar resources are widely distributed, but photovoltaic systems require supply chains that operate from specific geographic locations and rely on certain thin-film technologies that use rare byproduct metals. The study investigates kesterite photovoltaics (Cu<sub>2</sub>ZnSn(S,Se)<sub>4</sub>; CZTSSe) as an energy solution for locations facing energy insecurity that require policies that go beyond cost-effective electricity to include supply security, manufacturing access, and dependable service delivery. We develop a multi-criteria assessment combining (i) indicators of mineral scarcity and refining concentration, (ii) benchmarked manufacturing capital intensity with scale adjustment, and (iii) scenario-based techno-economic analysis that incorporates grid unreliability through avoided outage costs (VoLL). Refining concentration for indium and gallium is extreme (HHI > 6,000), whereas key CZTSSe constituents exhibit substantially lower concentration. A 30 TW deployment stress test indicates that large-scale CIGS expansion faces severe indium constraints even under optimistic recycling, while for CZTSSe, the binding concern shifts toward tin reserve definitions, reserve growth, and end-of-life recovery for bulk metals. We introduce socio-energetic stamina as a development-relevant lens for comparing PV options by material security, manufacturability, and operational resilience, clarifying where efficiency-first evaluation can misrank technologies when reliability and import dependence shape real-world energy access outcomes.

## 1. Introduction

The global energy transition faces growing constraints as both device performance and the availability of materials and industrial systems for large-scale clean energy deployment pose obstacles. The dominant photovoltaic (PV) technologies, including crystalline silicon, CdTe, and CIGS, face supply chain limitations because they depend on materials that are geographically concentrated and are in limited supply. The research conducted by Sovacool et al. [1] demonstrates that decarbonization leads to systemic vulnerability, shifting from fuels to minerals and metals embedded in low-carbon infrastructure. The research conducted by Carrara et al. [2] assesses the raw material requirements of PV and wind technologies and identifies specific points in the supply chain that will restrict access to materials. The research conducted by Lin and Zhang [3] shows that energy metals and processing capacity have become key factors determining the success of renewable deployment today. The pathways to achieve net-

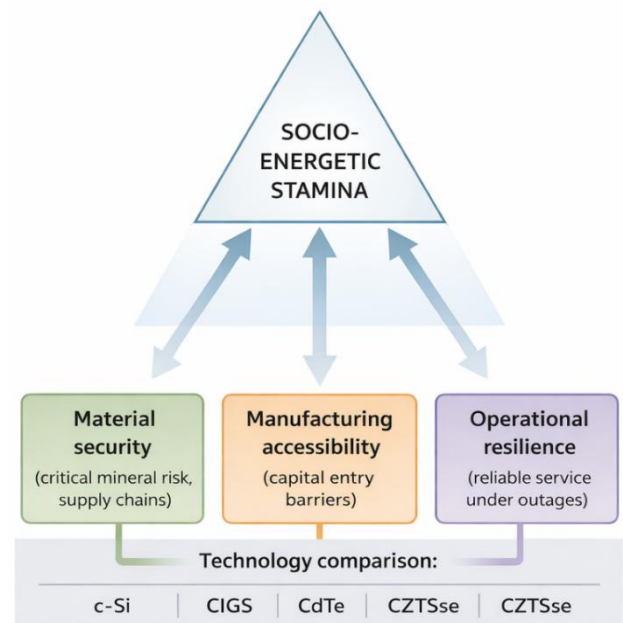
zero emissions will require critical mineral supplies that exceed current levels, thereby increasing risks associated with mining, refining, and manufacturing processes that face operational delays [4,5]. Geopolitical vulnerability now shifts from fossil-fuel chokepoints to critical-material and processing chokepoints within energy technologies [3,6]. The method of distributing these weaknesses yields two outcomes that can lead to an unequal distribution of energy access problems. The current photovoltaic (PV) development system, which produces gigawatt-scale systems through centralized manufacturing and transfers technology over long distances, has enabled cost reductions, but it creates ongoing dependency problems for regions that lack industrial development, stable institutions, and financial resources [7,8]. Global supply chains and manufacturing hubs that concentrate production capabilities create economic dependencies that increase susceptibility to supply disruptions, price fluctuations, and procurement threats,

especially in the Global South [9,10]. Current energy policy objectives prioritize resilience, independence, and equitable industrial engagement; therefore, PV technology selection is increasingly a matter of sovereignty and capacity building, alongside considerations of cost and efficiency [10,11]. Kesterite-based photovoltaics, particularly copper-zinc-tin-selenide ( $\text{Cu}_2\text{ZnSn}(\text{S,Se})_4$ ; CZTSSe), offer a potential alternative to materials limitations. CZTSSe utilizes relatively common elements, copper, zinc, tin, and sulfur/selenium, avoiding the challenges associated with incumbent thin-film absorbers (CIGS) and CdTe that stem from the use of indium, gallium, and tellurium [12,13]. Although CZTSSe currently lags incumbent PV technologies in module efficiency, laboratory progress has advanced kesterite device performance to >14% in recent reports, narrowing (but not closing) the performance gap [14-16]. Importantly, CZTSSe is compatible with non-vacuum and solution-based deposition routes (e.g., spray coating, printing, and coating-based processes), which in principle can reduce minimum efficient scale and lower entry barriers relative to vacuum-based thin films [17-19].

The current situation necessitates ongoing assessment of key evaluation points. The open-circuit voltage deficits in CZTSSe devices arise from cation disorder and defect chemistry, which prevent the achievement of phase purity across the specified compositional range [20,21]. The system is vulnerable to thermal and moisture stress due to secondary phase formation and interfacial reconversion processes, while high-temperature processing results in tin loss, creating compositional gradients that reduce system performance [22]. Consequently, the combination of technical challenges and limited sustained research funding has delayed companies' implementation of commercial solutions [23]. This study contends that assessments that focus solely on power conversion efficiency or on grid-connected levelized cost of energy (LCOE) fail to capture the strategic value of CZTSSe. Energy systems should be evaluated based on their ability to provide a sustained, autonomous electricity supply, rather than solely on the lowest-cost performance under ideal grid conditions. This is particularly relevant in areas where grids are unreliable, financial resources are limited, or institutional frameworks are weak [24,25]. We propose socio-energetic stamina as a qualitative metric for comparing photovoltaic technologies, assessing their capacity to enable autonomy under constrained conditions, and thus addressing this gap. Grounded in energy justice perspectives and capabilities approaches, we define stamina as the convergence of (i) material security (independence from critical mineral supply chains), (ii) capital accessibility (feasibility of local or smaller-scale manufacturing), and (iii) operational resilience (capacity to maintain function under institutional and resource limitations) [11,26,27]. The conceptual structure of the socio-energetic stamina framework is illustrated in Figure 1.

Empirically, we evaluate CZTSSe against current technologies using a multi-criteria analysis across three categories. First, we assess supply risk using indicators that jointly capture geological availability, byproduct coupling, and refining concentration, rather than relying on reserve-to-production ratios alone [28,29]. Second, we examine the manufacturing capital required for both vacuum and non-

vacuum processes, highlighting the importance of solution-processed materials for decentralized production [17,30]. Third, we quantify the economic value of resilience under unreliable grids using a VoLL-based avoided-outage framing, which shifts the comparison from least-cost energy to least-cost reliable service in energy-vulnerable contexts [31,32]. Furthermore, we simulate deployment to a total capacity of 30 TW as a stress test to identify material bottlenecks and strategic trade-offs under strong electrification pathways [28,29].



**Figure 1.** Conceptual framework of socio-energetic stamina in photovoltaic technologies

Our research suggests that CZTSSe is unlikely to replace c-Si or high-performance thin-film technologies in grid-stable utility-scale areas in the near future. Rather, its strategic niche develops when policy goals include supply-chain resilience, technological autonomy, and scalable energy availability under governance and financial limitations, dimensions usually regarded as secondary in regular PV comparisons. Past CZTSSe studies have primarily focused on production cost competitiveness and efficiency pathways [12-14].

In the literature, there is a growing set of kesterite-focused studies that largely emphasize device physics and performance optimization (e.g., balancing recombination pathways and diode parameters to raise PCE; Zhang et al., [33]), tandem and architecture-oriented simulations for kesterite stacks [34], and system-level integrations involving CZTSSe tandems, as well as kesterite-family thin-film processing routes (e.g., sulfide/selenide thin films) [19,35]. This paper extends that literature by reframing CZTSSe evaluation as a policy-relevant multi-criteria problem, linking critical-mineral concentration, scale-constrained manufacturing feasibility, and reliability value under weak grids, rather than treating efficiency and grid-tied LCOE as sufficient decision criteria.

## 2. Methodology

With a three-part framework, (i) critical mineral supply risk, (ii) manufacturing capital accessibility, and (iii) deployment implications under resource and reliability constraints, we compare kesterite photovoltaics ( $\text{Cu}_2\text{ZnSn}(\text{S,Se})_4$ ; CZTSSe) with existing photovoltaic technologies, including crystalline silicon (c-Si), copper indium gallium selenide (CIGS), and cadmium telluride (CdTe). In contexts where grid reliability and capital access differ [36-38], this framework provides a policy-relevant comparison of material security, industrial entry barriers, and service value, accounting for variations in grid reliability and capital access.

### 2.1 Critical mineral supply risk

We quantify supply vulnerability using complementary indicators that capture geological scarcity, geopolitical concentration, and scale-up pressure under high deployment. Reserve-to-production (R/P) ratios offer a preliminary measure of scarcity, defined as the ratio of end-of-year proved reserves to annual production. Assuming constant production and unchanged reserve classification, R/P approximates the number of years current reserves would sustain production. We compile reserves and production from the U.S. Geological Survey Mineral Commodity Summaries and the British Geological Survey, where applicable [39,40]. For each PV technology, we identify a potential bottleneck element as the element with the lowest R/P among required constituents, noting that byproduct dependence can constrain supply responsiveness beyond what R/P alone indicates [41,42]. Because R/P is a static, present-rate indicator and can be misleading for byproduct metals, we treat it as a screening metric and place greater weight on (i) byproduct coupling and supply responsiveness, (ii) refining concentration (HHI), and (iii) reserve-pressure under deployment stress tests.

Geopolitical concentration is assessed using the Herfindahl-Hirschman Index.

$$HHI = \sum_{i=1}^n s_i^2 \quad (1)$$

$s_i$  represents the market share (in percent) of country  $i$ . The index ranges from 0 (highly diversified) to 10,000 (monopoly). We interpret  $HHI > 2500$  as highly concentrated following competition guidelines. Country shares for mining and (where available) refining are drawn from the IEA Critical Minerals data and USGS statistics [43,44]. We report HHI separately for mining and refining when data permit, given that refining concentration may be the binding vulnerability in clean-energy supply chains [3,36].

To evaluate scale-up pressure, we model cumulative element demand under a 30 TW global PV deployment stress test, following prior material-demand approaches [28,29,45]. For each technology and element  $j$ :

$$M_j = \frac{P_{target} \times I_j}{\eta_{mat}} \quad (2)$$

where  $P_{target}$  is the target cumulative capacity (W),  $I_j$  is the element intensity (g/W), and  $\eta_{mat}$  is an effective material utilization factor capturing manufacturing yield and losses. Technology-specific material intensities and yields are taken from published techno-economic and material-flow studies [28,41,44]. We compare  $M_j$  to proven reserves  $R_j$  and report reserve pressure using thresholds (e.g.,  $M_j/R_j$  exceeding 25%, 50%, 75%) as a screening indicator of increasing supply risk.

To avoid overstating static scarcity, we also explored sensitivity to reserve growth using reserve-expansion concepts from the resource economics literature [29].

### 2.2 Manufacturing capital intensity and scale accessibility

We evaluate manufacturing accessibility using capital expenditure per unit of annual nameplate capacity ( $\$/W_{yr}$ ) and the implied minimum efficient scale (MES), as these factors shape entry barriers for regions with constrained capital or limited industrial base [46].

Baseline capital expenditures (CapEx) for representative manufacturing pathways are compiled from recent industry roadmaps and techno-economic studies, harmonized to a common currency year where possible [47-49]. We distinguish between non-vacuum and solution-process routes relevant to CZTSSe concepts, and vacuum-intensive thin-film routes typical of CIGS and CdTe, because vacuum infrastructure and cleanroom controls can significantly affect fixed costs [17,50,51]. Reported CapEx figures are treated as ranges and are mostly used for relative assessment across industries rather than for accurate prediction.

To compare centralized gigawatt-scale manufacturing with smaller regional-scale production, we apply a power-law scaling relationship:

$$CapEx_2 = CapEx_1 \times \left(\frac{C_2}{C_1}\right)^\alpha \quad (3)$$

where  $C$  denotes annual production capacity, and  $\alpha$  is a scaling exponent. We use  $\alpha=0.6$  as a standard engineering approximation (the six-tenths rule) for process-dominated equipment (e.g., reactors, furnaces, coating lines) and test sensitivity over plausible values (0.5-0.7). Because module assembly and other discrete steps often scale more linearly (numbering-up), Appendix A reports an alternative split-scaling sensitivity (FEOL  $\alpha \approx 0.6$ ; BEOL  $\alpha \approx 0.9$ ) to avoid overstating economies of scale at small plant sizes [52,53]. This scaling is used to estimate how entry barriers change when production is sized for municipal/regional autonomy rather than global cost minimization [46].

### 2.3 LCOE and reliability value in unreliable-grid contexts

Given that many policy-relevant contexts experience frequent outages, we complement the standard LCOE with a reliability-value adjustment based on avoided outage costs. We compute LCOE using a discounted cash-flow formulation consistent with standard PV costing practice.

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (4)$$

where  $I_t$  is investment expenditure in year  $t$ ,  $O_t$  operations and maintenance,  $F_t$  fuel (zero for PV),  $E_t$  electricity generated,  $r$  the discount rate, and  $n$  lifetime [37,54]. We varied the discount rate (e.g., 3-12%) to reflect heterogeneity in financing conditions and the cost of capital across contexts. We utilized technology parameters from recent studies examining the cost and performance of PV [38].

We incorporate a Value of Lost Load (VoLL) correction to reflect the financial value of electricity during disruptions. Let stand for the part of PV production that in year  $t$  matches grid outages. We estimate this as the annual PV output multiplied by the proportion of time the grid is unavailable during periods when PV may generate, utilizing documented outage

lengths and a given daylight overlap factor (Table A5). The avoided outage cost (resilience value) is then:

$$B_t = E_t^{out} \cdot VoLL \quad (5)$$

According to reliability economics literature, VoLL is included as an additional revenue source (or alternatively deducted from the effective net cost stream) when calculating reliability-adjusted results [55,56]. VoLL is considered sector- and scenario-specific, with ranges derived from available data and pertinent research [57,58]. Utilizing established outage-cost concepts, this approach measures the resilience value of dispersed generation without assigning financial values to broader institutional or political contexts.

#### 2.4 Geographic screening

Through open screening, the CZTSSe proposal has to be evaluated across four different dimensions: (i) availability of solar resources; (ii) grid reliability; (iii) reliance on PV import; and (iv) closeness to big-scale PV production. Through Global Horizontal Irradiance (GHI) values given by Solargis [59], Global Solar Atlas products illustrate solar resources. The World Bank [60] uses data from utility reports and business surveys on how long and how often power outages occur to assess grid reliability. Estimating import dependence relies on UN Comtrade figures on PV module imports [61].

Manufacturing proximity is defined as the shortest great-circle distance from the capital city of each country, which serves as a stand-in for the main administrative and demand center, to the closest photovoltaic (PV) manufacturing facility with at least 1 GW per year module or cell capacity. To lessen sensitivity to hub-list incompleteness and prevent over-precision, this variable is presented as distance bands: Near (<1,000 km), Mid (1,000-3,000 km), and Far (>3,000 km). The screening process identifies specific, high-leverage situations that require evaluation through actual testing to obtain thorough findings. The outcomes of this study show the scientists' appraisal of present priorities in future policy development needs.

#### 2.5 Limitations and uncertainty handling

This research presents a strategic comparative study that addresses some questions. (i) A conservative range illustrates the performance of the CZTSSe module to show current laboratory developments and little commercial validation [62, 63]. (ii) Reserves are represented as financial values that change a lot; Appendix A shows the numbers we have now. To make sure our calculations aren't biased by how we define things, we use USGS proven reserves consistently across all resource types and in probability-of-occurrence (R/P) calculations. (iii) Given that indium is mostly a byproduct of zinc processing, theoretically, a notable rise in zinc output might improve indium recovery. Therefore, our stress test primarily focuses on indium risk as a refining/processing constraint and examines sensitivities to recycling and reserve growth [43]. (iv) Learning-by-doing and cost decreases for linked photovoltaic (PV) technologies are projected using experience-curve statistics. However, specific learning rates for CZTSSe remain unknown [46]. (v) Material intensities show how things are now, but better designs or thinner absorbers could change how good things can be. (vi) Rather than directly modeling institutional and governance components, quantifiable reliability criteria serve to approximate them. These assumptions suggest that the results should be seen as directional signals for strategy and policy rather than as exact forecasts of market results.

Appendix A lists parameter values and data sources; Appendix B shows calculated reserve-pressure outputs.

### 3. Results

We report results in three aspects: (i) the vulnerability of vital mineral supplies, (ii) manufacturing capital intensity and possible output levels, and (iii) techno-economic performance depending on grid dependability. Unless specified differently, production and reserves statistics match USGS and IEA datasets as detailed in Section 2 and Appendix A [39,43].

#### 3.1 Material supply vulnerability and deployment constraints

R/P measures offer a preliminary view of potential scarcity; nonetheless, careful interpretation is needed, as reserves, especially for bulk metals, represent economic values that may rise with prices, exploration, and investment. With R/P values in the decades range, around 19 and 14 years, respectively, zinc and tin using USGS proved reserves are similar to indium (about 18 years). Therefore, the strategic difference is not that indium, gallium, and tellurium are tiny or byproduct metals whose availability depends on host-metal markets and is limited by concentrated refining capability [39,41,43], whereas zinc and tin are produced as large-volume base metals with a broad producer base and vast known resources. Therefore, R/P ought to be seen as a screening indicator; reserve-pressure and concentration findings should be relied upon to more strongly evaluate scaling risk (Table 1).

Concentration analysis reinforces these distinctions. Refining and, where available, production of several PV-critical materials exhibits high Herfindahl-Hirschman Index (HHI) values that exceed commonly used thresholds for *high concentration*, indicating susceptibility to geopolitical disruption and market power. This is most pronounced in the refining of indium and gallium, and is also evident in silicon refining, despite silicon's geological abundance, reflecting the capital- and energy-intensive nature of high-purity processing and the concentration of industrial capacity [6,43]. Consequently, the R/P and HHI indicators imply that CZTSSe's constituent materials are structurally less exposed to concentrated bottlenecks than those dependent on indium, gallium, or tellurium pathways. Together, the R/P and HHI indicators imply that CZTSSe's constituent materials are structurally less exposed to concentrated bottlenecks than indium-, gallium-, and tellurium-dependent pathways.

We next evaluate cumulative material requirements under a 30 TW PV deployment stress test. Under baseline assumptions about absorber thickness, module efficiency, and material utilization, CIGS and CdTe exhibit reserve-pressure ratios that far exceed the current proven reserves of their most constrained elements, even under optimistic recycling assumptions. This reserve pressure remains substantial under sensitivity tests that reduce absorber thickness, indicating that terawatt-scale deployment of these technology-specific material portfolios would require either major reserve expansion, material substitution, or architectural shifts that materially reduce reliance on the constrained elements. Conversely, CZTSSe demonstrates significantly less reserve pressure for zinc and copper and moderate, though not complete, pressure for tin under the same deployment scale, thereby supporting earlier arguments for earth-abundant absorbers.

**Table 1.** Reserve-to-production ratios and crustal abundance of photovoltaic precursor materials

Element	R/P (years)	Abundance (ppm)	Production Type	Key Technology	2023 Production (tons)	Reserves (tons)	Supply type	Scalability risk (qual.)
Indium	18	0.05	Byproduct (Zn)	CIGS	760	13700	Byproduct	High
Gallium	29	17.0	Byproduct (Al)	CIGS	320	9280	Byproduct	High
Tellurium	42	0.001	Byproduct (Cu)	CdTe	450	19000	Byproduct	High
Selenium	67	0.05	Byproduct (Cu)	CIGS; CZTSSe	2800	—	Byproduct	Medium
Tin	14	2.2	Primary + byproduct	CZTS	305000	4200000	Mixed	Medium
Zinc	19	75.0	Primary	CZTS; CIGS	12000000	230000000	Primary	Low-Medium
Copper	43	68.0	Primary	All thin-film	23000000	980000000	Primary	Low-Medium
Silicon	500	277200.0	Primary	c-Si	8500000	4250000000	Primary	Industrial bottleneck

**Table 2.** Manufacturing capital intensity comparison at baseline scales

Technology	Min Scale (MW/year)	Baseline CapEx (\$M)	CapEx per MW (\$/kW)
c-Si	1000	350.0	350
CIGS (vacuum)	200	127.0	635
CdTe	100	100.0	1000
CZTSSe (solution)	5	7.5	1500

The stress test highlights that, at multi-terawatt levels, the material feasibility envelope varies drastically across PV technology families; it does not forecast market shares. Full reserve-pressure ratios and computed  $M_j$  values are provided in [Appendix B](#).

### 3.2 Manufacturing capital intensity and entry barriers

Manufacturing benchmarks reveal significant differences in the minimum efficient scale and absolute capital requirements across photovoltaic pathways ([Table 2](#)). Reflecting the infrastructure for polysilicon refining, wafering, and cell manufacturing, fully integrated c-Si supply chains often require gigawatt-level production and significant financial investment. While they can work at smaller sizes than c-Si, vacuum-deposited thin films (CIGS, CdTe) yet call for specialized vacuum equipment and rigorous process control, hence raising both technical complexity and fixed expenses. In theory, solution-processed CZTSSe pathways could shift the capital structure toward less expensive coating and thermal processing tools, enabling smaller production runs; however, there is little commercial evidence. The main result is not that CZTSSe is currently less costly per watt; rather, it may reduce barriers to entry for regional or local manufacturing initiatives.

Under scale adjustment, the distance between pathways increases as facility size decreases toward the tens-of-megawatts range, suitable for municipal or regional autonomy scenarios. Using the same scaling rule, solution-based concepts have lower fixed-capital thresholds; however, vacuum-intensive pathways and c-Si show large rises in capital intensity per unit of capacity across these distributed ranges. This discovery reinforces the policy contention that, notwithstanding performance and bankability restrictions, manufacturing decentralization is essentially more likely for non-vacuum routes.

### 3.3 Techno-economic performance under variable grid reliability

Usually, when connected to the grid, the LCOE ranking meets expectations. Higher-efficiency, mature technologies yield lower LCOE values; lower-efficiency CZTSSe designs incur a cost penalty primarily driven by conversion efficiency and balance-of-system issues. Since LCOE depends on financing conditions, the magnitude of this penalty varies with different discount rates, but the trend remains constant. These results imply that, given current module efficiencies, CZTSSe is unlikely to be competitive on a grid-tied LCOE basis alone without compensating advantages such as increased supply security or reduced reliance on imported modules.

The relevant comparison changes from least-cost energy to least-cost reliable service when the grid supply is erratic. Using a VoLL-based avoided-outage framework, the financial worth of PV production rises with (i) the percentage of PV output matching with outage periods and (ii) the sectoral value of disturbed service. Practically speaking, we estimate the coincidence term using a daylight-overlap factor and recorded outage hours. Under high-outage conditions, the avoided-outage value can have a significant impact on the cost of generating electricity from different types of solar panels. This shows that reliability advantages may be more important than small cost differences, especially for businesses and critical services where the cost of a power outage is high. This realization clarifies the decision-making guideline from reducing energy cost to minimizing the cost of a trustworthy energy supply; it does not lessen the significance of performance and durability.

Three main components define the break-even criteria for locally produced CZTSSe and imported c-Si goods: (i) scale-adjusted manufacturing economics, (ii) import cost premia including foreign-exchange exposure, logistics, and

tariffs, and (iii) reliability value resulting from avoided outage expenses. Three factors make local CZTSSe production more appealing: significant import expenses, high outage risks, and the product satisfies its minimum projected performance level, as shown by pilot manufacturing and lab testing. The break-even threshold appears as a sensitivity band, as VoLL estimates and outage timing vary with the situation (Table A5). Two main needs define CZTSSe's strategic niche: a high dependability value for dispersed supply and major difficulties importing or funding current technology.

### 3.4 Geographic contexts where the CZTSSe proposition is most relevant

Regions with the requisite conditions to test CZTSSe's purported benefits in material security and capital-accessible manufacturing were found using screening criteria from Section 2.4 (solar resource, outage prevalence, manufacturing distance, and import dependency), therefore meeting the urgent need for dependable electricity services. Table 3 records these circumstances; Appendix B includes thorough screening thresholds, scores, and information on country coverage. The screening process does not predict future adoption; rather, it provides a policy-based framework that identifies high-leverage contexts where non-standard PV value propositions will be most impactful.

## 4. Discussion

Modern photovoltaic (PV) technologies vary not only in efficiency but also in the materials and industrial infrastructures needed for their scale-up. Current options offer strong performance; however, many rely on geologically scarce or geopolitically concentrated inputs and require capital-intensive refining and manufacturing processes. These structural conditions determine who can finance, produce, and procure PV hardware, and consequently, who captures value from the energy transition [1,3,9]. This section interprets our results through the frameworks of energy access and technology autonomy, while highlighting the technical constraints that condition the policy relevance of CZTSSe in real-world applications.

### 4.1 Critical minerals and the geopolitics of PV scale-up

The stress-test results provide evidence supporting existing research indicating that clean-energy transitions generate new geopolitical dependencies, stemming from shifts from fuel requirements to mineral and refining/manufacturing needs [3,36]. The production of CIGS and CdTe relies on both byproduct supply and centralized refining operations, creating distinct risks of demand and policy disruption compared to bulk metals. The price of minor metals is sensitive to small fluctuations in demand and constrained by supply-response limitations imposed by host-metal economic factors. Deployment of CIGS and CdTe technologies is anticipated in the near future, as they will remain crucial to the industry; however, the multi-terawatt development of these technologies will necessitate substantial material replacements, system design changes, and the development of new reserve materials exceeding current limits.

The distinctiveness of CZTSSe stems primarily from its operational flexibility, owing to the abundance of its constituent elements, copper, zinc, tin, and sulfur/selenium, which are readily available in quantities comparable to those of common industrial metals. The use of this technology offers advantages by reducing the risk of single-point bottlenecks, which occur in indium-, gallium-, and tellurium-based systems. The widespread use of both technologies would require additional mining activities and strong environmental protection systems. The analysis shows that CZTSSe technology has fewer essential limitations than efficiency-frontier technologies.

### 4.2 Technology sovereignty and the industrial distribution of the transition

Ongoing energy policy debates underscore technology sovereignty as a key concern, enabling nations and regions to develop vital technologies free from external assistance. According to research, a country's attainable sovereignty largely depends on its material portfolio and degree of capital intensity.

**Table 3.** Illustrative contexts for the geographic screening (indicative ranges; not a ranking)

Country/region (illustrative)	GHI (kWh/m <sup>2</sup> /yr)	Annual outage hours	PV import dependence (%)	Distance to nearest GW-scale PV manufacturing hub	Notes
East Africa (e.g., Kenya/Tanzania)	1,800-2,000	150-300	90-100	Far	High solar; import reliant; reliability deficits
West Africa (e.g., Nigeria/Ghana)	1,600-1,900	200-500	85-100	Far	High VoLL relevance for SMEs/health systems
Horn of Africa (e.g., Ethiopia/Somalia)	1,900-2,200	200-600	90-100	Far	High resilience value; fragile-grid contexts
Central Asia (e.g., Uzbekistan)	1,700-2,100	100-250	80-95	Mid	Good solar; import exposure; intermediate proximity
Andean region (e.g., Peru/Bolivia)	2,000-2,400	150-300	85-95	Far	Excellent solar; long supply chains
Mainland SE Asia (e.g., Myanmar/Cambodia/Laos)	1,600-1,900	200-400	85-100	Mid	Reliability deficits; mixed proximity
South Asia, interior states (e.g., Bihar/UP)	1,700-2,000	150-350	70-90	Near	Reliability issues; closer to manufacturing

Countries seeking essential inputs available only at a small number of refining sites face supply chain access issues that increase procurement risks and exposure to price fluctuations, and limit their ability to choose standards and technologies. Moreover, the focus on photovoltaic (PV) production capacity fosters greater reliance, preventing businesses from diversifying their supply sources and building permanent equipment supply lines. Material sovereignty requires more advanced knowledge than a basic understanding of material requirements. The geographic distribution patterns of photovoltaic (PV) systems depend on the specific combination of materials used in their production and on supply networks that rely on centralized facilities producing essential components such as glass, encapsulants, and inverters. The CZTSSe technology offers only limited advantages since its design depends on one main functional element, which serves as the absorber while enabling users to produce locally without achieving total supply chain control.

#### 4.3 Distributed manufacturing and the resilience premium

Manufacturing results indicate that, if validated, non-vacuum, solution-process-compatible methods might reduce the minimum effective size and total capital expenditures (CapEx) required to set up a production line compared with c-Si and vacuum thin films. This is important because barriers to industrial entry significantly affect a region's ability to realize value beyond installation and maintenance. If PV generation is limited to gigawatt-scale plants, the shift toward global growth might still concentrate wealth in a small number of manufacturing hubs. The economic value of distributed manufacturing depends on particular conditions. Markets tend to favor established modules that demonstrate superior efficiency because their performance exceeds current industry standards under stable grid operation, unrestricted trade, and minimal loan expenses. Consequently, decision-making processes prioritize grid failure management, with service providers focusing on operational reliability rather than cost-effective kilowatt-hour delivery. These conditions allow established outage costs to exceed existing differences in PV LCOE, particularly due to the high value placed on continuous service delivery by commercial operations and essential services. Evidence suggests that CZTSSe attains its greatest strategic value within a niche market when resilience premiums are maximized and reliance on imported goods is minimized. The results of our research support the development of a socio-energetic stamina framework that assesses the ability to deliver energy services during periods of restriction. Stamina originates from energy justice research, which defines material security, manufacturability, and operational resilience as fundamental policy elements that should be evaluated alongside efficiency and cost. We define stamina as a qualitative metric that complements, rather than replaces, techno-economic measurements. The fairness of distributed manufacturing systems hinges on ownership rights, labor conditions, and environmental impacts, as well as on procurement decision-making processes.

A stamina-oriented approach requires procedural and recognition-justice protections, achieved through transparent procurement, community participation, worker protections, and sitting standards, to prevent the emergence of extractive patterns that new technologies may introduce.

#### 4.4 Technical feasibility as the binding condition

The technical problems that affect CZTSSe materials need to be solved before they can be used in policy applications. System costs increase due to efficiency shortfalls that drive up space requirements, while evidence on the longevity of commercial photovoltaic systems is still developing. Product development faces its major challenge in heat and humidity resistance, which impedes market entry, while system performance suffers from voltage deficits due to cation disorder, defect states, and interface recombination. The demonstration of champion devices shows progress, but banks require specific solution-processed routes, which exist as the foundation of distributed manufacturing, to create bankable module production from laboratory performance. The technology readiness assessment reveals that CZTSSe is still in its pre-commercial stage; emphasis should be on risk-based technology demonstration and controlled learning development rather than quick nationwide-scale technology substitution. Early deployment situations will probably include systems providing significant autonomous value while users accept reduced efficiency performance criteria, such as off-grid systems replacing costly diesel, remote-location services, or resilience-oriented procurement. These niches help people learn by doing real-life activities. This makes CZTSSe better than c-Si technology in terms of being used in real-world applications.

#### 4.5 Policy implications and research priorities

The central policy issue concerns whether governments and development agencies should incorporate earth-abundant, lower-capital expenditure photovoltaic (PV) production methods into resilience and sovereignty plans, rather than focusing on replacing current PV technologies with materials such as CZTSSe. While technology-neutral deployment policies, including feed-in tariffs and general auctions, can effectively lower prices, they may undervalue industrial inclusion and supply-chain robustness. Resilience and independence are clear goals, so procurement systems can add additional criteria such as reliability, reliance on imports, and supply chain concentration. This keeps things clear and reduces the chance of people making money off of things.

The research priorities for CZTSSe material testing begin with efficiency improvements that decrease system balance costs, while the second priority requires testing material stability through actual stress testing systems, and the third priority needs to confirm through pilot factory testing that high-yield processes can be scaled up successfully. The study requires additional research to determine how institutional and financial factors affect local production by shaping access and the ability to create new module assembly locations.

#### 5. Conclusion

The research determined if kesterite photovoltaics ( $\text{Cu}_2\text{ZnSn}(\text{S},\text{Se})_4$ ; CZTSSe) could help society achieve a more secure material supply and wider industrial participation in solar energy development. The inspiration is a tangible contradiction: While solar energy is widely dispersed, several leading PV technology routes rely on geographically concentrated mineral supply chains and refining capacity, which, for some absorber materials, could be scale-limited. We assessed CZTSSe in comparison to crystalline silicon (c-Si), CIGS, and CdTe using a multi-criteria approach that combined (i) indicators for critical mineral shortages and concentration, (ii) manufacturing capital intensity and scale accessibility, and (iii) techno-economic effects under

conditions of less-than-perfect grid reliability. The research demonstrates that photovoltaic (PV) technology families display distinct differences in their ability to resist minor-metal limitations throughout the entire material spectrum. The CIGS and CdTe materials exhibit high reserve pressure for indium and tellurium under multi-terawatt testing conditions because their recycling rates exceed the established limits, which match their byproduct-based material acquisition and specialized material processing systems. The bulk metals used by CZTSSe include copper, zinc, and tin, which have higher availability because they exist in multiple locations throughout the Earth's crust. The data shows different risk factors than those associated with indium, gallium, and tellurium; however, it indicates that CZTSSe requires mining and processing development and environmental protection activities for all production expansion efforts. Further examination of manufacturing shows that the industrial geography of photovoltaics (PV) is defined more by capital thresholds and minimum efficient scale than by wages and trade policies alone. Vacuum thin-film techniques require specialized equipment and process controls that impose fixed-cost barriers, whereas fully integrated c-Si supply chains are often tailored to gigawatt-class facilities and high-capital-cost refining and wafering infrastructure. Theoretically, non-vacuum and solution-process-compatible CZTSSe routes could operate at smaller scales, thereby lowering the entry barriers for areas aiming to build regional or local manufacturing capacity. The major point is not that, if its performance is verified, its manufacturing technique would enable the production of suitable-sized models that current technologies would find structurally difficult to produce, but rather that CZTSSe is currently the least expensive PV technology. The current module efficiencies of solar power systems make CZTSSe uncompetitive, as its levelized cost of energy (LCOE) for grid-connected systems is higher than that of present module efficiencies. The research establishes that when grid reliability declines, the focus should shift from least-cost energy to least-cost reliable service. The total avoided outage costs (VoLL-based) during high-outage periods will exceed the LCOE differences among photovoltaic (PV) technologies because specific performance requirements determine which small efficiency losses take priority. The economic worth of the supply chain creates substantial value for the economy. The need to treat locally producible, earth-abundant PV options as suitable for resource-limited areas becomes evident when overseas material dependence, foreign currency fluctuations, and procurement risks increase total expenses associated with international supply chains. There exist two main restrictions that affect these conclusions. The strategic potential of CZTSSe depends on upcoming stability, efficiency, and reproducible production yield developments because it remains in pre-commercial status. Technological sovereignty involves both absorbed chemistry and the entire system of balance-of-system components, plus all manufacturing facilities that exist in the market. We consider CZTSSe as a potential supplementary solution that delivers its highest benefits in specific situations where organizations need to balance resilience and industrial availability requirements instead of serving as a substitute for existing photovoltaic solutions. The energy policy framework indicates that technology-neutral deployment frameworks, which prioritize immediate LCOE optimization, may underestimate long-term risks stemming from mineral concentration, manufacturing centralization, and the need for reliable grid service. A comprehensive policy package supports the continued

deployment of existing PV systems while simultaneously enabling dedicated research into material-secure alternatives through R&D studies, pilot database studies, and procurement processes that publicly evaluate both reliability and supply chain stability. Scientific studies need to prove the capabilities of CZTSSe through pilot testing before its potential can be understood.

#### **Ethical issue**

The authors are aware of and comply with best practices in publication ethics, specifically concerning authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere in any language.

#### **Data availability statement**

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

#### **Conflict of interest**

The authors declare no potential conflict of interest.

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### Appendix A

#### Data sources and parameter assumptions (inputs)

This appendix reports the primary data sources and parameter assumptions used in the critical minerals, manufacturing scale, and reliability-value analyses.

**Table A1.** Material intensity and process assumptions (by technology and element)

Technology	Binding element(s)	Absorber thickness ( $\mu\text{m}$ )	Module efficiency (%)	Material intensity $I_j$ (g/W)	Material utilization $\eta_{\text{mat}}$	Recycling rate (%)	Primary/byproduct note	Source
CIGS	Indium (In)	1.0–1.5	20.8 (low-intensity case) / 12 (high-intensity case)	0.0154–0.0231 (= 15.4–23.1 t/GW)	0.7 (assumed; sensitivity in Appendix)	0 / 60 (scenario)	Byproduct of Zn; refining concentrated	DOE CMS / NREL assumption set
CIGS	Gallium (Ga)	1.0–1.5	20.8 / 12	0.0124–0.0185 (= 12.4–18.5 t/GW)	0.7 (assumed)	0 / 60 (scenario)	Byproduct of Al (and Zn); refining concentrated	DOE CMS / NREL assumption set
CdTe	Tellurium (Te)	1.0–2.5	18 (low-intensity case) / 11.7 (high-intensity case)	0.017–0.074 (= 17–74 t/GW)	0.8 (assumed; mature manufacturing)	0 / 60 (scenario)	Byproduct of Cu; supply inelastic	DOE CMS / NREL assumption set
c-Si	Silicon (Si) (refining bottleneck)	— (wafer-based)	20–22	$\approx 2.2$ (polysilicon consumption, 2023)	0.6–0.8 (implicit in reported consumption)	0 / 60 (scenario)	Primary, abundant; refining concentrated/energy-intensive	IEA PVPS Trends 2024 (data for 2023)
CZTSSe (solution/non-vacuum)	Tin (Sn) (binder/constant candidate)	2.0 (baseline)	12 (baseline)	$\approx 0.020$ (computed from compound mass $\times$ Sn fraction)	0.6 (assumed; solution losses can be higher)	0 / 60 (scenario)	Mixed (primary + byproduct depending on deposit); market smaller than Zn/Cu	Density/stoichiometry basis
CZTSSe	Zinc (Zn)	2.0	12	$\approx 0.011$ (computed)	0.6 (assumed)	0 / 60	Primary (large market)	Density/stoichiometry basis
CZTSSe	Copper (Cu)	2.0	12	$\approx 0.022$ (computed)	0.6 (assumed)	0 / 60	Primary; multi-sector demand	Density/stoichiometry basis
CZTSSe	Sulfur/Selenium (S/Se)	2.0	12	$\approx 0.022$ (S-equivalent; composition dependent)	0.6 (assumed)	0 / 60	Se is often Cu-byproduct; sulfur abundant	Density/stoichiometry basis

For CZTSSe we estimate absorber material intensity from absorber thickness, absorber density, and module efficiency, and convert compound mass-per-watt to element mass-per-watt using stoichiometric mass fractions.  $\eta_{mat}$  and recycling are scenario parameters; conclusions are robust to reasonable ranges.

**Table A2.** Reserves and production statistics (year and source)

Element	Production (t/yr)	Reserves (t)	R/P (yr)	World resources (USGS, if stated)	Primary/byproduct (host metal)	Data year	Source
Indium (In)	1,080 (world refinery production, est. 2024e)	NA (USGS does not report global reserves in MCS)	NA	Not quantified in MCS; described as trace in sphalerite (ZnS) and other base-metal sulfides	Byproduct (primarily Zn-sphalerite)	2024e	USGS MCS (Jan 2025) - Indium
Gallium (Ga)	760 (world total low-purity primary production, 2024e; 760,000 kg)	NA (USGS does not report global reserves in MCS)	NA	“World resources of bauxite estimated to exceed 1 million tons (Ga content); <10% potentially recoverable”	Byproduct (bauxite; also Zn-processing residues)	2024e	USGS MCS (Jan 2025) - Gallium
Tin (Sn)	305,000 (world mine production, 2023)	4,200,000 (world reserves)	~14	—	Primary + byproduct (mixed; varies by deposit)	2023	USGS MCS (Jan 2025) - Tin
Zinc (Zn)	12,100,000 (world mine production, 2023)	230,000,000 (world reserves)	~19	—	Primary	2023	USGS MCS (Jan 2025) - Zinc
Copper (Cu)	22,600,000 (world mine production, 2023)	980,000,000 (world reserves)	~43	—	Primary	2023	USGS MCS (Jan 2025) - Copper

R/P is computed only where USGS reports global reserves.

For In and Ga, the supplied USGS MCS entries report production/capacity and discuss resources rather than providing a consistent global reserves figure; therefore R/P is not reported. For these elements, supply risk is assessed primarily through byproduct coupling and refining concentration (HHI) plus deployment-scale demand (stress test).

Stage labels differ: In is reported as world refinery production, whereas Ga includes low-purity primary production and separate high-purity refined output; these are retained verbatim from USGS to avoid false comparability.

**Table A3.** HHI inputs and concentration results

Element	Stage (mining/refining)	Data year	Top 3 country shares (from USGS table)	HHI (calc.)	Source
Indium	Refining (refinery production)	2023	China 67.6%; Korea 17.6%; Japan 6.4%	4,951	USGS MCS 2025 - Indium (refinery production table).
Gallium	Primary production (low-purity)	2023	China 98.1%; Russia 0.9%; Japan 0.5%	9,626	USGS MCS 2025 - Gallium (primary production table).
Zinc	Mining (mine production)	2023	China 33.6%; Peru 12.1%; Other countries 14.0%	1,699	USGS MCS 2025 - Zinc (mine production table).
Tin	Mining (mine production)	2023	China 23.0%; Indonesia 22.6%; Burma 11.1%	1,436	USGS MCS 2025 - Tin (mine production table).
Copper	Mining (mine production)	2023	Chile 23.2%; Congo (Kinshasa) 13.0%; Peru 12.2%	1,207	USGS MCS 2025 - Copper (mine production table).

HHI values are computed from USGS country production tables for the specified stage/year; where USGS aggregates ‘Other countries,’ the resulting HHI should be interpreted as an approximate (typically conservative) concentration indicator.

**Table A4.** Utility-scale PV cost and performance benchmark inputs (used in LCOE modeling) (from Intal & Ebong (2026) cost/performance summary; 2024–2025 benchmark)

Technology (utility-scale)	Module price (\$/W)	Plant CAPEX (\$/kW-AC)	FOM (\$/kW-yr)	WACC (%)	Lifetime (yr)	Degradation (%/yr)	CF (%)	LCOE (\$/MWh)
CdTe	0.18	1150	22	8	30	0.6	28	43–65
c-Si (PERC/TOPCon)	0.15	1200	22	7	30	0.5	26	38–78
CIGS	0.28	1300	22	10	30	0.7	25	52–65
CZTS (kesterite)	0.40	2000	24	12	25	1.0	24	75–120

These CAPEX values are installed power-plant costs (\$/kW-AC) for LCOE benchmarking. They are not manufacturing-factory CapEx.

**Table A5.** Reliability-value (VoLL) and outage assumptions

Scenario	Sector	VoLL (\$/kWh)	Outage hours (hr/yr)	Daylight overlap (%)	Outage overlap assumption	Source
A. Moderate unreliability (typical SSA firm conditions)	Residential / households	2–5	150–300	40	Assume 40% of outage hours occur during daylight/active-use windows (daylight proxy), applied uniformly for comparability	Outage magnitudes consistent with World Bank Enterprise Survey summaries (firms in SSA often face ~200–700 hr/yr in many countries); VoLL ranges consistent with VoLL literature showing strong sectoral variation
A. Moderate unreliability (typical SSA firm conditions)	SMEs / commercial	5–15	150–300	40	Same as above; for commercial loads, interpret VoLL as “interruption cost per kWh not served” during business operation	Outage magnitudes; VoLL ranges consistent with published VoLL ranges for I&C customers (few €/kWh to very high outliers depending on method/country)
B. High unreliability / fragile-grid contexts	Critical services (healthcare, telecoms, cold chain)	15–50	300–900	40	Same overlap assumption; remember this is a <i>screening</i> scenario intended to represent high consequence loads (not an average economy-wide VoLL)	Outage magnitudes consistent with WBES discussion that many countries experience hundreds of outage-hours annually; high-end VoLL values justified by literature documenting extremely high interruption costs for some customer classes and contexts
C. Grid absence (off-grid)	All users (baseline comparator)	N/A (use avoided cost)	8760 (no grid)	40	Replace VoLL term with avoided diesel generation cost (e.g., \$0.25–0.65/kWh), not “damage cost”	Approach aligns with microgrid/resilience valuation practice where avoided fuel cost is the comparator (VoLL is mainly for grid-outage valuation)

**Daylight overlap:** we use 40% as a transparent proxy for daytime coincidence (approximate daylight share of hours). This is a conservative simplification for cross-context comparison; country-specific hourly outage timing is rarely available.

**VoLL values:** VoLL is highly method- and context-dependent; published studies report ranges from a few €/kWh to very high values for certain customer classes and outage conditions.

**Outage hours:** the WBES-based summaries indicate that in many Sub-Saharan African contexts, outage totals commonly fall in the hundreds of hours per year for firms.

**Appendix B**

Computed outputs (reserve pressure, scale-adjusted CapEx, and context screening)

Constants / conventions used

- $P_{target}=30 \text{ TW}=30,000 \text{ GW}$
- Demand uses Eq. (2):  $M_j = \frac{P_{target} \times I_j}{\eta_{mat}}$
- Recycling sensitivity:  $\rho = 60\% \rightarrow M_j^* = 0.4M_j$
- Reserve pressure reported as  $100 \times M_j/R_j$

**Note:** For tellurium, USGS reports reserves in MCS with a specific caveat (**Te** reserves reflect estimated **Te** content of copper reserves except for some countries).

**Table B1.** 30 TW deployment stress test: cumulative demand and reserve pressure

Technology	Binding element	$P_{target}$ (TW)	Demand $M_j(t)$	Reserves $R_j(t)$	Reserve pressure $M_j/R_j$ (%)	Recycling assumption	Reserve pressure w/ recycling (%)	Notes
CIGS	Indium (In)	30	660,000 – 990,000	13,700	4,818– 7,226	0% / 60%	1,927–2,890	Uses A1: 15.4–23.1 t/GW; $\eta_{mat}=0.7$ . Strong byproduct coupling (Zn) + concentrated refining.
CIGS	Gallium (Ga)	30	531,429 – 792,857	9,280	5,726– 8,543	0% / 60%	2,290–3,417	Uses A1: 12.4–18.5 t/GW; $\eta_{mat}=0.7$ . Byproduct coupling (Al and partly Zn) + concentrated refining.
CdTe	Tellurium (Te)	30	637,500 – 2,775,000	35,000	1,821– 7,929	0% / 60%	728–3,172	Uses A1: 17–74 t/GW; $\eta_{mat}=0.8$ . Byproduct-coupled to Cu; reserve concept has embedded assumptions.
c-Si	Silicon (Si)	30	82,500,000 – 110,000,000	4,250,000,000	1.94–2.59	0% / 60%	0.78–1.04	A1 notes $\eta_{mat}$ is implicit in reported polysilicon consumption; here shown as range using $\eta_{mat}=0.8$ to 0.6. Main constraint is processing concentration/energy, not geology.
CZTSSe (solution)	Tin (Sn)	30	1,000,000	4,200,000	23.81	0% / 60%	9.52	Uses A1: $I_j=0.020 \text{ g/W}$ ; $\eta_{mat}=0.6$ . Mixed primary/byproduct; smaller market → “medium” scalability risk rather than “low.”
CZTSSe (solution)	Zinc (Zn)	30	550,000	230,000,000	0.24	0% / 60%	0.10	Uses A1: $I_j=0.011 \text{ g/W}$ ; $\eta_{mat}=0.6$ . Large primary market; low–medium risk (multi-sector demand).
CZTSSe (solution)	Copper (Cu)	30	1,100,000	980,000,000	0.11	0% / 60%	0.04	Uses A1: $I_j=0.022 \text{ g/W}$ ; $\eta_{mat}=0.6$ . Large market, but multi-sector demand and refining dynamics matter.

- 1- Reserve pressure is reported as a stress indicator; binding-element risk is interpreted jointly with (i) byproduct coupling and (ii) refining concentration (HHI), because minor-metal supply can be constrained by processing capacity and co-production dynamics even when ‘reserves’ exist.
- 2- We report ranges where  $I_j$  varies (low-/high-intensity cases in Table A1) and propagate those ranges through Eq. (2).

Using the scaling rule:

$$CapEx_2 = CapEx_1 \times \left(\frac{C_2}{C_1}\right)^\alpha, \alpha = 0.6$$

**Assumptions (central cases used for scaling):**

- **c-Si:**  $C_1=1000 \text{ MW/yr}$ ,  $CapEx_1=\$350M$
- **CIGS (vacuum):**  $C_1=200 \text{ MW/yr}$ ,  $CapEx_1=\$127M$
- **CdTe:**  $C_1=100 \text{ MW/yr}$ ,  $CapEx_1=\$100M$
- **CZTSSe (solution):**  $C_1=10 \text{ MW/yr}$ ,  $CapEx_1=\$11.4M$

CapEx intensity is computed as:

$$Intensity = \frac{CapEx(\$)}{C(kW/yr)}$$

**Table B2.** Scale-adjusted manufacturing CapEx results (selected scales)

Technology	CapEx @ 10 MW/yr (\$M)	CapEx @ 100 MW/yr (\$M)	CapEx @ 1,000 MW/yr (\$M)	CapEx intensity @ 10 MW (\$/kW.yr)	CapEx intensity @ 100 MW (\$/kW.yr)	CapEx intensity @ 1,000 MW (\$/kW.yr)
c-Si	22.1	87.9	350.0	2,208	879	350
CIGS (vacuum)	21.0	83.8	333.6	2,105	838	334
CdTe	25.1	100.0	398.1	2,512	1,000	398
CZTSSe (solution/non-vacuum)	11.4	45.4	180.7	1,140	454	181

Values are scale-adjusted using a central scaling exponent  $\alpha=0.6$ ; sensitivity to  $\alpha$  is reported separately (Appendix A/Table A4–A5), and results should be interpreted as comparative scaling signals rather than precise project quotes.

**Table B3.** Break-even sensitivity summary (local CZTS vs imported c-Si)

Scenario	Outage hours threshold band (hr/yr)	Import premium band (%)	VoLL (sector)	CZTS module efficiency (%)	Key assumptions	Result/notes
A. Grid-present, moderate unreliability	300–900	25–40	5–15 \$/kWh (SMEs/commercial)	$\geq 12$	Daylight overlap $\approx 40\%$ (Table A6); $\alpha=0.6$ scaling; local plant 10 MW/yr class; c-Si imported modules face tariff/logistics/FX premium	Break-even is possible but not robust; depends strongly on VoLL and import premia. Use as <i>pilot candidate</i> band rather than general competitiveness claim.
B. Fragile-grid / high unreliability	600–1,200	20–35	15–50 \$/kWh (critical services: health, telecom, cold chain)	$\geq 11-12$	Same overlap assumption; priority loads have high outage costs; reliability value dominates modest LCOE differences	Break-even becomes likely/robust for critical loads; CZTS competitiveness is driven mainly by reliability value + supply/finance constraints rather than pure LCOE.
C. Off-grid / grid-absent comparator	N/A (no grid)	10–30 (import/logistics/FX still relevant)	Use avoided cost (diesel) rather than VoLL	$\geq 10-12$	Compare against diesel generation cost bands; assume local maintenance advantage and reduced FX exposure	Break-even framed as diesel displacement rather than VoLL; CZTS can be attractive if it reduces reliance on imported fuel and parts, even if module efficiency is lower.
D. Grid-stable context (control case)	<150	<15	2–5 \$/kWh (residential)	$\geq 13-15$	Low outage overlap; import premia small; cost competition dominated by efficiency + BOS	CZTS is unlikely to break even unless performance improves substantially (efficiency, yield, durability) and/or policy assigns explicit value to supply security.

- Threshold bands are screening indicators, not precise cutoffs; results are sensitive to outage timing (daylight overlap), VoLL method, and the magnitude of import premia.
- VoLL ranges and outage-overlap assumptions follow Table A6; manufacturing scaling follows Table B2 ( $\alpha$  sensitivity in Appendix A).

**Table B4.** Context screening results

Country/Region	GHI (kWh/m <sup>2</sup> /yr)	Outage hours (hr/yr)	Distance to GW-scale PV manufacturing (km)	Module import dependence (%)	Criteria met / score	Notes	Source(s)
East Africa (e.g., Kenya/Tanzania)	1,800–2,000	150–300	Far (>3,000; ~5,000–7,000)	90–100	4/4	High solar; high import exposure; reliability deficits make resilience value salient for SMEs and public services	Solargis / Global Solar Atlas (GHI); World Bank Enterprise Surveys (outages); UN Comtrade (imports)
West Africa (e.g., Nigeria/Ghana)	1,600–1,900	200–500	Far (>3,000; ~5,000–7,000)	85–100	4/4	High outage exposure; VoLL relevance for commerce/health systems; strong FX/logistics sensitivity	Solargis; World Bank Enterprise Surveys; UN Comtrade
Horn of Africa (e.g., Ethiopia/Somalia)	1,900–2,200	200–600	Far (>3,000; ~4,500–7,000)	90–100	4/4	Fragile-grid contexts; resilience value dominates; imports often constrained by logistics/security	Solargis; World Bank Enterprise Surveys; UN Comtrade
Central Asia (e.g., Uzbekistan)	1,700–2,100	100–250	Mid (1,000–3,000; ~2,500–4,000)	80–95	3–4/4	Good solar; import exposure; intermediate proximity suggests partial access to regional supply chains but still nontrivial logistics	Solargis; World Bank Enterprise Surveys; UN Comtrade
Andean region (e.g., Peru/Bolivia)	2,000–2,400	150–300	Far (>3,000; ~9,000–12,000)	85–95	4/4	Excellent solar; long supply chains; import + logistics costs material; strong case for “appropriate-scale” local production pilots	Solargis; World Bank Enterprise Surveys; UN Comtrade
Mainland SE Asia (e.g., Myanmar/Cambodia/Laos)	1,600–1,900	200–400	Mid (1,000–3,000; ~1,500–3,000)	85–100	3–4/4	Reliability deficits; mixed proximity to manufacturing; policy relevance depends on trade/industrial policy setting	Solargis; World Bank Enterprise Surveys; UN Comtrade
South Asia—interior states (e.g., Bihar/UP)	1,700–2,000	150–350	Near (<1,000; ~500–1,500)	70–90	2–3/4	Reliability issues exist, but proximity to manufacturing may reduce import/logistics barriers; resilience argument remains relevant for critical loads	Solargis; World Bank Enterprise Surveys; UN Comtrade