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Concentration Dynamics in Solar PV Supply Chains: Lessons for Clean Energy Transitions

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ديناميكيات التركيز في سلاسل توريد الخلايا الكهروضوئية الشمسية: دروسٌ في التحولات نحو الطاقة النظيفة

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Abstract:
Achieving global climate and energy targets hinges on an unprecedented acceleration in the deployment of solar photovoltaic (PV) technologies, which in turn requires a rapid and large-scale expansion of manufacturing capacity across the entire PV value chain. This study examines the structural, economic, and environmental challenges associated with scaling solar PV manufacturing under net-zero-aligned pathways, with particular emphasis on supply-chain concentration, critical mineral demand, financial sustainability, and embodied emissions. The analysis highlights the pronounced geographic concentration of upstream manufacturing, especially polysilicon, ingot, and wafer production, and the resulting exposure to geopolitical, trade, and logistics risks. It further demonstrates that demand for critical minerals, such as silver, is set to rise sharply, increasing the likelihood of supply–demand mismatches amid long mining lead times. In parallel, the sector's historically volatile profitability and expanding trade restrictions pose additional risks to investment and timely capacity expansion. The paper also evaluates the scale of investment and employment associated with PV manufacturing growth, identifying upstream segments as capital-intensive bottlenecks and downstream segments as key sources of job creation, albeit with declining labor intensity due to automation. Finally, it addresses the potential for supply-chain diversification and power-sector decarbonization to significantly reduce the embodied emissions of PV manufacturing. Overall, the findings indicate that resilient, affordable, and low-carbon solar PV supply chains are a critical prerequisite for sustaining rapid deployment and ensuring the credibility and cost-effectiveness of global net-zero transitions

Keywords: Solar photovoltaic manufacturing; Supply chain resilience; Critical minerals; Net-zero energy transition.

الملخص:
يعتمد تحقيق الأهداف العالمية للطاقة والمناخ على تسريع غير مسبوق في نشر تقنيات الطاقة الشمسية الكهروضوئية(PV) ، وهو ما يتطلب بدوره توسعًا سريعًا وعلى نطاق واسع في القدرات التصنيعية عبر سلسلة القيمة الكاملة للطاقة الشمسية.

تتناول هذه الدراسة التحديات الهيكلية والاقتصادية والبيئية المرتبطة بتوسيع تصنيع أنظمة الطاقة الشمسية الكهروضوئية ضمن مسارات متوافقة مع الحياد الكربوني، مع التركيز بشكل خاص على تركّز سلاسل التوريد، والطلب على المعادن الحرجة، والاستدامة المالية، والانبعاثات الكربونية المضمّنة في عمليات التصنيع .تُبرز الدراسة التركّز الجغرافي الواضح لمراحل التصنيع الأولية، لا سيما إنتاج البولي سيليكون والسبائك والرقائق، وما يترتب عليه من تعرّض متزايد لمخاطر جيوسياسية وتجارية ولوجستية. كما تُبيّن أن الطلب على المعادن الحرجة، مثل الفضة، مرشح للارتفاع الحاد، الأمر الذي يزيد من احتمالية حدوث اختلالات بين العرض والطلب في ظل الفترات الزمنية الطويلة اللازمة لتطوير مشاريع التعدين. وبالتوازي مع ذلك، تشكل التقلبات التاريخية في ربحية القطاع، إلى جانب التوسع في القيود التجارية، عوامل إضافية قد تعيق الاستثمارات اللازمة للتوسع السريع في القدرات التصنيعية .وتستعرض الدراسة كذلك حجم الاستثمارات وفرص العمل المرتبطة بنمو تصنيع الطاقة الشمسية الكهروضوئية، حيث تُعد المراحل الأولية من السلسلة الأكثر كثافة في رأس المال وتشكل نقاط اختناق محتملة، في حين تمثل مراحل التصنيع اللاحقة مصادر رئيسية لخلق فرص العمل، رغم تراجع كثافة العمالة نتيجة التوسع في الأتمتة. وأخيرًا، تؤكد الدراسة أن تنويع سلاسل التوريد، إلى جانب إزالة الكربون من قطاع الكهرباء، يمكن أن يسهم بشكل ملموس في خفض الانبعاثات المضمّنة في تصنيع أنظمة الطاقة الشمسية. وبصورة عامة، تخلص النتائج إلى أن بناء سلاسل توريد مرنة وميسورة التكلفة ومنخفضة الكربون للطاقة الشمسية الكهروضوئية يُعد شرطًا أساسيًا لضمان استدامة التوسع السريع في نشر هذه التقنيات وتعزيز مصداقية وكفاءة التحولات العالمية نحو الحياد الكربوني.

الكلمات المفتاحية: تصنيع الخلايا الكهروضوئية الشمسية؛ مرونة سلسلة التوريد؛ المعادن الحيوية؛ التحول إلى صافي طاقة صفري.

1. Introduction

At present, the electricity-intensive manufacture of solar photovoltaic (PV) technologies is still largely supplied by fossil-fuel-based power systems; nevertheless, PV modules typically require only about 4–8 months of operation to offset the emissions embodied in their production [1,2]. This carbon payback interval is vanishingly small when benchmarked against the average service lifetime of PV panels, which is commonly estimated at approximately 25–30 years. Electricity constitutes roughly 80% of total energy inputs across the PV manufacturing value chain, with the dominant share consumed during the production of polysilicon and the subsequent fabrication of ingots and wafers, processes that depend on sustained heat at very high and tightly controlled temperatures [3,4]. Reflecting the geographic concentration of PV manufacturing, coal currently supplies more than 60% of the electricity used in global PV production, substantially exceeding coal's share in worldwide power generation (around 36%). This discrepancy is largely attributable to the clustering of PV manufacturing capacity in China, particularly in Xinjiang and Jiangsu, where coal provides more than 75% of annual electricity supply and is further reinforced by favourable industrial tariff structures [5,6].

Attaining international energy and climate objectives necessitates an unprecedented expansion in the global deployment of solar photovoltaic (PV) technologies. This acceleration, however, is inseparable from a substantial increase in manufacturing capacity, thereby intensifying concerns about the global system's ability to scale resilient supply chains within a compressed timeframe. To remain aligned with the International Energy Agency's Roadmap to Net Zero Emissions by 2050, annual solar PV additions must more than quadruple to approximately 630 gigawatts (GW) by 2030 [7,8]. Delivering such a deployment trajectory would require worldwide production capacity across the PV value chain, including polysilicon, ingots, wafers, cells, and modules, to more than double by 2030 relative to current levels. As governments and industries intensify decarbonization efforts, it is essential that the transition to a sustainable energy system rests on secure and credible industrial foundations. Accordingly, PV supply chains must be expanded in a manner that simultaneously enhances resilience to disruptions, maintains affordability at scale, and advances sustainability across production, sourcing, and end-of-life management to meet the operational demands of a net-zero pathway [9,10].

In a net-zero-aligned transition, solar PV will exert rapidly rising demand for a range of critical minerals and refined materials. Supply conditions for several of these inputs remain structurally tight because production is geographically concentrated, with China occupying a particularly influential position across multiple stages of extraction, processing, and manufacturing. While ongoing gains in material efficiency and process optimization are reducing mineral intensity per unit of PV capacity, these improvements are unlikely to fully offset the scale effects associated with accelerated deployment; consequently, the sector's aggregate mineral requirements are projected to increase markedly [11,12]. Within the IEA's Roadmap to Net Zero Emissions by 2050, for example, demand for silver in PV manufacturing by 2030 could surpass 30% of total global silver production recorded in 2020, rising from roughly 10% at present. Such a steep demand trajectory, when coupled with the long development lead times and capital intensity of new mining and refining projects, elevates the likelihood of supply–demand imbalances [11-13]. A growing body of scholarly literature has examined the concentration dynamics characterizing solar photovoltaic (PV) supply chains, with particular attention to their structural, economic, and strategic implications, as outlined below.

In [14, 15], Geographic concentration in solar PV supply chains has emerged as a critical vulnerability for the global energy transition. The clustering of manufacturing capacity within a small number of regions, often reliant on carbon-intensive power systems, has amplified risks related to geopolitics, trade policy, and logistics. Events such as the COVID-19 pandemic and recent trade disputes have highlighted how disruptions in a single country or province can propagate globally, delaying project timelines and increasing costs.

According to [16,17], the global solar photovoltaic (PV) industry is characterized by a high degree of structural concentration, particularly in upstream manufacturing segments such as polysilicon, ingot, and wafer production. Over the past decade, economies of scale, aggressive industrial policy, and access to low-cost energy have enabled a limited number of producers, predominantly located in China, to capture a dominant share of global capacity. This concentration has delivered significant cost reductions and accelerated global PV deployment; however, it has simultaneously increased systemic exposure to localized disruptions, regulatory shifts, and energy supply constraints.

The dominance of a few producers across key solar PV manufacturing stages has reshaped market dynamics by consolidating market power while driving down production costs. Vertical integration and scale economies have enabled leading firms to exert pricing influence across the PV value chain, often setting global benchmarks for module costs [18,19]. Although this has benefited consumers and accelerated deployment, it has also created strategic dependencies for importing countries, raising concerns about long-term supply security and bargaining asymmetries.

This work contributes a structured synthesis showing that meeting net-zero-aligned solar PV deployment targets depends on transforming PV manufacturing supply chains as much as expanding installation rates. It clarifies how concentration-driven vulnerabilities, upstream capacity bottlenecks, and investment volatility can constrain scale-up, while highlighting the dual opportunity of supply-chain diversification and grid decarbonization to strengthen resilience, sustain affordability, and reduce embodied emissions. Overall, it positions a secure, diversified, and low-carbon PV manufacturing base as a core enabling condition for a credible and cost-effective clean energy transition.

2. The concentration of photovoltaic supply chains raises vulnerabilities, presenting prospective challenges for the energy transition.

Achieving international energy and climate targets implies an unprecedented acceleration in global solar photovoltaic (PV) deployment. This scale-up necessarily entails a commensurate expansion of manufacturing capacity, thereby heightening concerns about whether resilient supply chains can be developed rapidly enough to support sustained growth. Consistent with the IEA's Roadmap to Net Zero Emissions by 2050, annual PV capacity additions would need to more than quadruple to around 630 gigawatts (GW) by 2030 [20-22]. Meeting this installation trajectory would require global production capacity across the PV value chain, polysilicon, ingots, wafers, cells, and modules, to more than double by 2030 relative to current levels. As countries intensify decarbonization efforts, it is therefore essential that the transition to a sustainable energy system is anchored in secure industrial foundations. Accordingly, PV supply chains must be expanded in a manner that simultaneously strengthens resilience to disruptions, preserves affordability at scale, and advances sustainability across sourcing, manufacturing, and end-of-life management to meet the demands of a net-zero pathway [23-25].

Through 2025, global supply of the principal upstream inputs for solar PV module production is projected to remain overwhelmingly dependent on China. On the basis of manufacturing capacity currently under construction, China's share of worldwide polysilicon, ingot, and wafer output is expected to approach roughly 95%, implying a highly concentrated supply structure at precisely the stages that determine the pace and cost of downstream module assembly [26,27]. Within China, this concentration is further amplified geographically: Xinjiang alone accounts for around 40% of global polysilicon manufacturing capacity, underscoring the extent to which a single region can influence global availability and pricing dynamics. Industrial concentration is also evident at the firm and facility level, with approximately one in seven PV panels produced globally originating from a single manufacturing site [28-30].

In a net-zero-aligned pathway, solar PV will drive a rapid escalation in demand for critical minerals and refined materials. Supply for many of these inputs remains highly concentrated geographically, with China occupying a dominant position across several segments of mineral processing and manufacturing [31-34]. Although continued advances in material efficiency are reducing mineral intensity per unit of PV capacity, these gains are unlikely to offset the magnitude of deployment-driven growth; consequently, aggregate mineral requirements for the PV industry are expected to rise substantially. Under the IEA's Roadmap to Net Zero Emissions by 2050, for example, silver demand associated with PV manufacturing in 2030 could exceed 30% of total global silver production recorded in 2020, up from roughly 10% at present [35-40].

Beyond material constraints, the long-term financial viability of solar PV manufacturing is a critical precondition for sustaining rapid and cost-effective clean energy transitions. Net profitability across PV supply-chain segments has historically been volatile, and the sector has experienced multiple bankruptcies despite policy support. Persistently thin margins and elevated bankruptcy risk can undermine investment appetite and reduce the sector's capacity to absorb sudden shifts in demand, prices, or policy, dynamics that could slow expansion precisely when manufacturing scale-up is most needed [41-45]. In parallel, the growing use of trade restrictions introduces an additional layer of deployment risk. Because solar PV supply chains depend on cross-border flows of diverse materials, components, and finished products, they are inherently exposed to trade-policy uncertainty. Since 2011, the number of antidumping, countervailing, and import duties applied to parts of the PV supply chain has expanded markedly, from a single import tax to 16 duties and import taxes, with a further eight measures under consideration [46-49].

3. Resilience, Investment, and Decarbonization Pathways in the Global Solar PV Manufacturing Supply Chain

Recent shocks have renewed scrutiny of supply-chain fragility and import dependence. The COVID-19 pandemic, the surge in commodity prices, and Russia's invasion of Ukraine collectively underscored how strongly many economies rely on cross-border supplies of energy, raw materials, and manufactured inputs that are central to energy security and industrial continuity. In response, resilience can be strengthened through strategic investment that diversifies both domestic manufacturing capacity and the geographic composition of import sources, thereby reducing exposure to concentrated production nodes and disruptive geopolitical or logistical events [50-53].

Against this backdrop, the expansion of solar PV manufacturing capacity implies substantial capital requirements. New facilities across the PV value chain could mobilize on the order of USD 120 billion in investment by 2030, with annual investment flows needing to approximately double across upstream and downstream segments to keep pace with expected demand growth. Given their high energy intensity, technical complexity, and pivotal role as bottlenecks, upstream stages, particularly polysilicon production and ingot and wafer manufacturing, are expected to capture a large share of this investment as the system scales [54-56].

The employment implications of such industrial expansion are also material. The PV manufacturing ecosystem is estimated to support roughly 1,300 manufacturing jobs per gigawatt of production capacity, implying that direct manufacturing employment could rise to about one million jobs globally by 2030, approximately doubling current levels under ambitious deployment pathways. Job creation is concentrated in module and cell production, which involve a larger number of process steps and operational roles. However, the sector has simultaneously experienced rapid increases in labour productivity over the past decade due to automation, robotics, and the use of automated guided vehicles, which tend to reduce labour intensity per unit of output even as total employment grows with scale [57-60].

In this direction, supply-chain diversification, together with power-sector decarbonization, offers a near-term lever to reduce embodied emissions associated with PV manufacturing. Relocating or expanding production in jurisdictions with lower-carbon electricity systems can reduce manufacturing-related CO_2 emissions, particularly because electricity dominates energy inputs in PV production. Domestic or regional manufacturing can therefore deliver climate benefits when the local grid mix is cleaner than that of the exporting country. Europe exhibits especially high mitigation potential due to the relatively large contribution of renewables and nuclear in its power mix, followed by parts of Latin America and sub-Saharan Africa where hydropower provides a substantial share of generation.

4. Key Lessons for Clean Energy Transitions from Solar PV Supply Chain Concentration

The rapid expansion of solar photovoltaic (PV) technologies is central to global decarbonization strategies, yet the effectiveness and durability of this transition are increasingly shaped by the structure of PV manufacturing supply chains. High levels of geographic, technological, and firm-level concentration have delivered cost reductions and accelerated deployment, but they have also introduced systemic vulnerabilities that threaten supply security, affordability, and sustainability. Understanding concentration dynamics within PV supply chains is therefore essential for deriving actionable lessons for clean energy transitions as illustrated in Figure 1.

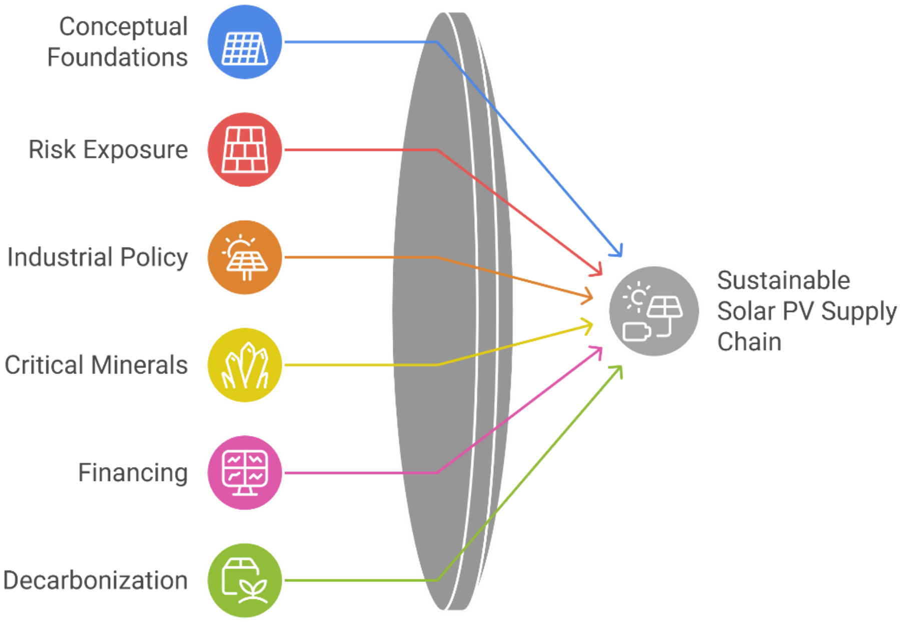

Figure 1. Key Lessons for Clean Energy Transitions from Solar PV Supply Chain Concentration.

The following agendas synthesize key dimensions, ranging from risk exposure and industrial policy to critical materials, financing, and manufacturing decarbonization, that collectively inform how solar PV supply chains can be scaled in a manner consistent with resilient and net-zero-aligned energy systems.

A. **Conceptual Foundations of Supply Chain Concentration in Clean Energy Technologies**
This agenda develops the theoretical and analytical basis for understanding concentration in solar PV supply chains and, by extension, other clean-energy technologies. It distinguishes among geographic concentration (production clustered in a small number of countries or provinces), firm-level concentration (dominance by a small number of companies), and stage-wise concentration (bottlenecks in upstream segments such as polysilicon, ingots, and wafers). It also clarifies how concentration affects market structure, bargaining power, price formation, learning-by-doing, and innovation diffusion, while providing metrics for empirical assessment (e.g., Herfindahl–Hirschman Index, import dependency ratios, supplier-tier mapping, and single-point-of-failure analysis). The outcome is a coherent framework that links concentration patterns to transition-relevant outcomes such as deployment speed, cost trajectories, and systemic resilience.

B. **Risk Exposure and Systemic Vulnerability under Concentrated PV Manufacturing Structures**
This agenda investigates how concentrated manufacturing creates cascading risk across the PV value chain. It analyzes disruption channels, including energy shortages, logistics bottlenecks, natural hazards, cyber/industrial accidents, policy shocks, and labor constraints, and explains how failures at upstream nodes can propagate downstream to module supply, project commissioning, and grid integration. Particular emphasis is placed on single-facility and single-region dependencies, where disruptions can have outsize global effects due to limited redundancy. The agenda also evaluates consequences for price volatility, lead times, inventory practices (just-in-time vs. strategic buffering), contract structures, and the bankability of PV projects. It culminates in risk-reduction strategies such as multi-sourcing, regional redundancy, supplier qualification regimes, and stress-testing of supply-chain networks.

C. **Industrial Policy, Trade Governance, and the Political Economy of PV Supply Chains**
This agenda examines the policy drivers behind PV supply-chain concentration and the governance trade-offs that arise when states pursue cost minimization, industrial competitiveness, and strategic autonomy simultaneously. It evaluates instruments such as subsidies, tax credits, concessional finance, export incentives, local content requirements, public procurement, and R&D support, alongside trade measures including antidumping duties, countervailing tariffs, and import restrictions. The agenda further analyzes how policy-induced fragmentation can influence investment certainty, cross-border technology diffusion, and global deployment rates, potentially increasing costs even as it strengthens supply security. A key deliverable is a set of design principles for “resilience-compatible” industrial policy that remains consistent with international trade rules while enabling diversification and avoiding destabilizing boom–bust cycles.

D. **Critical Minerals, Processing Bottlenecks, and Materials Security for Net-Zero Scale-Up** This agenda addresses the materials basis of PV manufacturing, focusing on the risk implications of rapidly rising demand for critical minerals and refined materials (e.g., silver, copper, aluminum, silicon derivatives, and specialty chemicals). It assesses concentration not only in mining, but, more importantly, in processing, refining, and high-purity material production, where capacity is often more geographically concentrated and slower to scale. The agenda incorporates lead-time economics, showing how permitting, capital intensity, and infrastructure constraints can delay supply responses, increasing the probability of shortages and price spikes. It evaluates mitigation pathways including materials substitution, thrift (reduced intensity), recycling and circularity, design-for-recovery, strategic reserves, long-term offtake agreements, and improved traceability and sustainability standards for responsible sourcing.

E. **Financing and Profitability Cycles in PV Manufacturing: Implications for Capacity Expansion** This agenda analyzes the macro-and microeconomic conditions required to scale PV manufacturing sustainably. It examines how margin compression, price competition, overcapacity cycles, and policy uncertainty shape profitability across different supply-chain stages, influencing firms' willingness and ability to invest. The agenda also assesses the sector's exposure to credit tightening, interest-rate risk, and demand volatility, and how these factors can produce bankruptcies that disrupt supply and slow deployment. It then develops stabilization mechanisms: long-term demand signals, bankable offtake contracts, credit guarantees, blended finance, insurance instruments, and public–private risk-sharing frameworks. Special attention is given to aligning finance with resilience and sustainability metrics, so that capital allocation rewards diversified, low-carbon, and transparent supply chains rather than merely lowest-cost production.

F. **Decarbonizing PV Manufacturing through Clean Power, Regionalization, and Sustainability Standards**
This agenda focuses on reducing embodied emissions and environmental impacts as PV manufacturing scales. Because electricity is a dominant energy input, it evaluates strategies to decarbonize manufacturing by shifting to low-carbon grids, deploying on-site renewables and storage, and contracting clean electricity through PPAs and green tariffs. It also examines regionalization as a dual-purpose strategy: enhancing supply security while lowering emissions when production relocates to jurisdictions with cleaner power mixes. The agenda further develops sustainability governance through life-cycle assessment (LCA), product carbon footprints, environmental product declarations (EPDs), traceability systems, ESG due diligence, and end-of-life regulations to support recycling and circularity. The deliverable is a practical roadmap for scaling PV manufacturing in a manner that is resilient, affordable, and demonstrably aligned with net-zero objectives.

To sum up, these agendas demonstrate that concentration dynamics in solar PV supply chains represent both an enabler and a constraint for clean energy transitions. While concentrated production has historically supported rapid cost declines and learning effects, excessive dependence on limited regions, firms, and materials exposes the transition to economic, geopolitical, and environmental risks. Addressing these challenges requires an integrated approach that combines diversification, stable investment frameworks, responsible materials management, and low-carbon manufacturing practices. By embedding resilience and sustainability into supply-chain expansion strategies, policymakers and industry stakeholders can ensure that solar PV continues to function as a reliable, affordable, and climate-effective pillar of the global net-zero transition.

5. Conclusion

The rapid scale-up of solar photovoltaic deployment required to meet global climate and energy objectives cannot be achieved without a parallel transformation of PV manufacturing supply chains. Recent systemic shocks have exposed the vulnerabilities associated with high geographic and technological concentration, underscoring the need for deliberate diversification, strategic investment, and resilient industrial planning. Expanding manufacturing capacity across the PV value chain will require substantial and sustained capital inflows, particularly in upstream segments such as polysilicon, ingot, and wafer production, while simultaneously delivering significant employment opportunities despite ongoing automation-driven productivity gains. At the same time, aligning supply-chain expansion with power-sector decarbonization offers a critical opportunity to reduce the embodied emissions of PV technologies, thereby reinforcing their life-cycle climate benefits. Collectively, these findings indicate that a secure, diversified, and low-carbon PV manufacturing ecosystem is not merely a supporting condition but a central pillar of a credible and cost-effective net-zero transition.

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