Technology Review for Carbon Neutrality

Perspective

The significance, challenges, and policy recommendations for the photovoltaic industry: a twenty-year retrospective from a global industry leader

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ABSTRACT

This paper reviews the twenty-year development path of LONGi, a leading global photovoltaic (PV) supplier, to distill the critical significance, defining characteristics, and key challenges of the PV industry. It subsequently proposes policy recommendations and international cooperation initiatives to ensure the sector's sustainable future. The PV industry has developed at a pace exceeding all expectations, establishing itself as a high-efficiency, low-cost cornerstone of the global energy transition. In particular, for vast regions with limited or unreliable access to electricity, hybrid PV-plus-storage systems have become a superior alternative to fossil-fuel-based systems in both cost and speed of deployment. Over the past two decades, the industry has navigated a series of major policy-driven and market-driven crises, revealing its inherent traits of high policy sensitivity and rapid technological iteration. To navigate these dynamics, companies must prioritize financial resilience and sustained technological leadership. To bolster the industry's sustainable development, this paper proposes that China's PV sector elevate product and technical standards for downstream solar cell production. Furthermore, it is essential for grid operators to expedite the introduction of policies supporting energy storage and to drive the technical reform of grid operations, thereby creating the conditions for broader participation in green power trading. Finally, this paper calls for deepened international cooperation, leveraging China's comprehensive industrial ecosystem to accelerate global progress toward carbon neutrality.

This paper reviews the twenty-year development of LONGi to examine the defining characteristics, challenges, and resilience of the global photovoltaic industry amid policy and market fluctuations. It further proposes policy reforms and international cooperation mechanisms to support the long-term, sustainable role of photovoltaics in the global transition toward carbon neutrality.

KEYWORDS

Photovoltaic industry; energy transition; technological innovation; China's photovoltaic (PV) policy; international cooperation

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1. The rapid development and significance of the photovoltaic industry

The climate crisis is unfolding faster than anticipated. Similarly, the development of the photovoltaic (PV) industry—a key part of the solution—has progressed at a pace that has surpassed many expectations. Over the past two decades, the annual outlook reports[1] from the International Energy Agency (IEA) have consistently provided conservative forecasts for PV development, with deviations sometimes reaching 30%–40%[2]. Under the IEA's Net Zero Emissions by 2050 Scenario (NZE), renewables are projected to generate 73%–88% of global electricity, representing approximately 80% of total worldwide power capacity. Solar PV alone is expected to account for 65% of all renewable capacity and 52% of total global power generation capacity, positioning it as the central growth engine for electricity capacity expansion worldwide[3]. Examining the situation in China, which accounts for about 30% of global electricity generation, the share of wind and PV power in China's total electricity generation has been increasing by roughly 4 percentage points annually. This share was 20% in the first half of 2024, 23.7% in the first half of 2025, and is likely to reach 27% in the first half of 2026. The author confidently predicts that China's share of electricity generated from wind and PV is highly likely to exceed 49% before 2035, indicating that renewable energy still possesses immense potential for future demand and development.

Technological advances have significantly reduced the energy consumption in photovoltaic production while continuously enhancing its lifetime energy yield and Energy Return on Investment (EROI). If we calculate the energy consumed from mining raw materials to manufacturing the final PV module, it is approximately 0.4 kWh per watt[4]. In comparison, a PV module generates an average of 1.5 kWh of electricity per watt annually. Multiplying this by a service life of over 30 years, its total energy output exceeds its energy input by more than 100 times[3]. Consequently, while questions about the energy efficiency of PV were common several years ago, they are seldom raised today because this issue has been effectively resolved.

Meanwhile, the rapid cost reduction of both photovoltaics and energy storage has effectively resolved the cost challenges associated with the energy transition. We attended the 2015 Paris Climate Conference, where representatives from 192 countries and regions engaged in intense debates, with the core dispute centering on who should bear the costs of the energy transition. However, driven by the rapid development of China's PV and energy storage industries, global PV costs have declined by over 90% in the past decade[5], while electrochemical storage costs have fallen by 93% over the past 15 years. Even during the difficult two years the storage industry faced, its costs still decreased by 50%[6]. This breakthrough has resolved the energy "trilemma" of balancing energy security, energy equity, and environmental sustainability[7], thereby transforming the energy transition into a self-sustaining endeavor.

Currently, PV-plus-storage systems have reached cost parity with fossil fuels, particularly in regions without established fossil fuel infrastructure. China's low-cost fossil energy system benefits from extensive existing infrastructure: numerous coal-fired power plants, railways and highways that facilitate coal transport, and a robust grid that minimizes transmission costs. However, across many parts of Southeast Asia, Middle East, Africa, and South America, grids remain underdeveloped or non-existent. In contexts lacking comprehensive infrastructure—reliable roads, railways, or new power networks—deploying PV-plus-storage with microgrids proves more efficient than establishing new fossil fuel systems[8]. Furthermore, solar and storage solutions can electrify underserved areas within mere months.

Therefore, solar power holds transformative significance for vast regions lacking reliable electricity, fundamentally reshaping local development trajectories. This impact embodies the "Economics of Goodness" philosophy[9] that LONGi has long upheld. Photovoltaics enable communities to leapfrog directly into electrification by supporting mobile communication, education, healthcare, and clean water access, thereby breaking cycles of poverty and disease.

In agriculture-dependent regions, particularly across the Middle East and Africa, solar-powered irrigation systems are increasingly deployed. PV-enabled water pumping provides reliable and affordable irrigation during drought periods, significantly reducing food insecurity[10,11]. At broader scales, PV microgrids now support not only households but also industrial parks, mines, and essential infrastructure, delivering rapid and scalable access to electricity in regions previously constrained by weak or absent grids[a,12,13].

2. The volatile history and challenges of the photovoltaic industry

The photovoltaic industry has experienced significant volatility over the past two decades, navigating four major crises. The first three crises were primarily triggered by abrupt policy shifts that many companies struggled to adapt to. The initial wave of global PV development followed the 2004 revision of Germany's Renewable Energy Sources Act (EEG), which permitted grid connection for solar power and offered attractive feed-in tariffs[14]. This policy shift also marked China's initial entry into the global PV market. However, rapid technological advancement led to steep subsidy reductions, and when the 2008 financial crisis hit, fixed subsidies became unsustainable, causing installation volumes to decline[15]. The second crisis emerged in 2012, when subsidy reductions coincided with the United States imposing anti-dumping and countervailing duties against Chinese PV products[16], creating another sharp market disruption. The third crisis occurred in 2018, when China abruptly slashed subsidies for grid-connected PV projects[17].

The landscape of industry leadership has also shifted significantly through each crisis. In the early years, Japanese firms like Sharp and Panasonic held dominant market shares. Prior to the first industry downturn, German enterprises experienced rapid growth, propelled by domestic subsidy policies. However, their ascendancy was short-lived, as Chinese manufacturers surpassed them within just a few years (Fig. 1). Consequently, the 2012 crisis primarily impacted leading Chinese companies, including former industry pioneer Wuxi Suntech. Following the third crisis, China's PV sector achieved a remarkable transformation. It evolved from its initial state of near-total external dependency—relying on overseas equipment, raw materials, and markets—to achieving comprehensive self-sufficiency across the entire manufacturing chain. Today, China accounts for approximately 50% of global PV installations and about 80% of the world's module manufacturing capacity[18]. Furthermore, Chinese-manufactured PV products are globally recognized for their superior quality and reliability, a reputation built upon adherence to stringent European quality standards from the industry's inception.

The ongoing fourth crisis, which began in 2024, differs fundamentally from previous downturns. Unlike earlier policy-driven shocks, this cycle is primarily rooted in structural overcapacity arising from misaligned expectations about technology transitions and downstream demand growth. Several mechanisms jointly contributed to this imbalance. First, firms systematically underestimated the speed at which new cell technologies would commoditize, leading to excessive, synchronized capacity expansion. Second, short-term profitability during earlier demand surges reinforced optimistic expectations and encouraged herding behavior. Third, in some regions, soft budget constraints and local government support delayed market exit of inefficient producers, slowing the natural process of industry consolidation. As a result, financial losses observed in 2024–2025 are not merely cyclical fluctuations, but manifestations of deeper coordination and incentive problems within the industry. The global PV sector now operates largely without subsidies, with the notable exception of manufacturing incentives

[a]The report Microgrids in Emerging Markets: Private Sector Perspectives[12] highlights the crucial role microgrids are expected to play in remote and off-grid areas of developing countries. The global solar PV microgrid market was valued at approximately USD 3.2 billion in 2024, with projections indicating a compound annual growth rate (CAGR) of around 20.3% from 2025 through 2034.

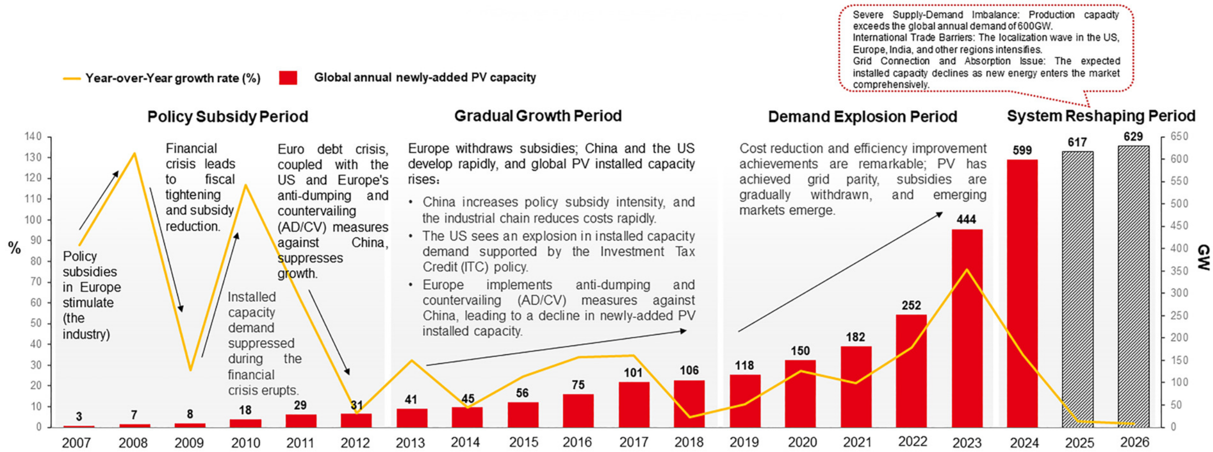

Fig. 1. Panoramic overview of China's PV industry.

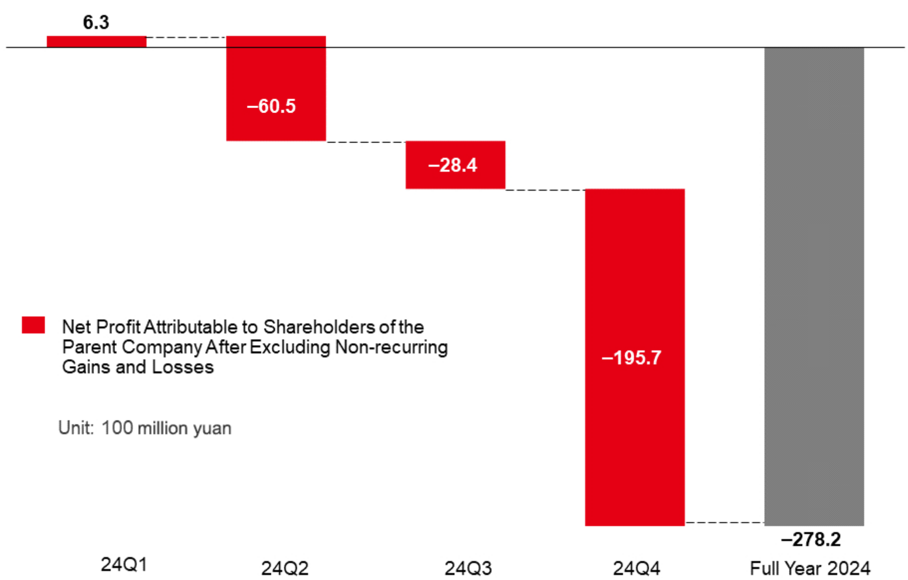

Fig. 2. Quarterly net profit status of 16 major enterprises in the photovoltaic industry in 2024 in China.

in the United States[b,19-21]. The industry's financial performance in 2024 has been severely challenging, with 16 major companies collectively reporting annual losses totaling RMB 27.8 billion (Fig. 2)[22]. These losses expanded significantly in the first half of 2025 compared to the same period in 2024[23], reflecting the persistently difficult conditions facing the entire industry.

[b]Inflation Reduction Act of 2022 (IRA) provisions:
• United States Environmental Protection Agency. Solar for All – Greenhouse Gas Reduction Fund Overview. Washington, DC: EPA, 2024. "Under the US$7 billion Solar for All program ..."
• U.S. Department of Energy. Energy Act of 2020 or CHIPS and Science Act Federal Tax Credits for Solar Manufacturers. Washington, DC: DOE, May 2024. "The program began accepting concept papers on May 22 2024 for a second round of US$6 billion in credits..."
Solar for All (United States Environmental Protection Agency introduced solar subsidy program for low-income communities)
• U.S. Internal Revenue Service. Residential Clean Energy Credit. Washington, DC: IRS (2024 version accessed). "The Residential Clean Energy Credit equals 30 % of the costs of new, qualified clean energy property..."

Beyond China, policy frameworks in other major economies continue to shape global PV deployment and manufacturing dynamics. The European Union's Green Deal and Fit for 55 packages have reinforced long-term demand certainty for renewable energy through binding decarbonization targets. In the United States, the Inflation Reduction Act (IRA) has significantly altered investment incentives by providing long-term tax credits for both PV deployment and domestic manufacturing. While these policies support global PV growth, they also contribute to regionalized manufacturing patterns and new forms of industrial competition.

A retrospective analysis reveals two defining characteristics of the photovoltaic industry that pose significant challenges for corporate management. First, its high sensitivity to policy shifts. During periods of product shortage, companies often engage in aggressive capacity expansion. However, a single policy change can cause markets to contract abruptly. Organizations operating with high financial leverage in such conditions can rapidly face existential crises. Second, the pace of technological iteration is exceptionally rapid. The previous generation Passivated Emitter and Rear Cell (PERC) technology, for instance, had a commercial lifespan of merely seven years[3] from its initial scale deployment in 2016 to market obsolescence by 2023. We further observe that Tunnel Oxide Passivating Contact (TOPCon) technology, the current mainstream, progressed from initial market penetration to oversupply in just two years. This acceleration is particularly challenging given the massive capital investments required—factories that were traditionally planned for 10–20 years operational horizons now face potential closure within 3–5 years of commissioning. This pattern has become commonplace in the PV sector: numerous companies, observing competitors' profitability, rush to expand capacity only to encounter market oversupply before their new production lines even become fully operational, immediately jeopardizing their financial viability.

LONGi has addressed these challenges through two core countermeasures: financial discipline and the principle of "no expansion without technological leadership." While conceptually straightforward, both entail substantial execution challenges in practice.

Slower and more selective capacity expansion can reduce short-term market share and delay revenue growth, especially during industry upcycles. However, LONGi deliberately accepts these trade-offs to preserve financial flexibility, avoid stranded assets, and maintain long-term innovation capacity.

In practice, the principle of "no expansion without technological leadership" is implemented through a multi-dimensional internal assessment framework. Capacity expansion decisions are guided not only by laboratory efficiency records, but also by manufacturability, cost-reduction potential, reliability under mass production, and the expected longevity of the technology relative to competing pathways. Only when a technology demonstrates a clear and sustainable advantage across these dimensions does it qualify for large-scale investment.

Industry-wide, many firms form overly optimistic expectations about technology transitions due to short-term profitability signals, peer imitation, and competitive pressure to avoid losing market share. Such short-termism often leads to premature or excessive investment in transitional technologies, increasing the risk of rapid obsolescence. By contrast, LONGi's experience suggests that disciplined patience and a willingness to forgo short-term gains are critical to navigating periods of rapid technological change.

LONGi's own growth trajectory serves as an instructive case study. In 2005, the company remained a small enterprise with annual revenue of just several tens of millions of RMB. From that period until 2015, the global PV industry was dominated by multi-crystalline technology, which offered marginally lower efficiency than mono-crystalline at a significantly reduced cost, making it the preferred option based on cost-performance[24]. However, LONGi's thorough analysis concluded that multi-crystalline technology possessed inherent efficiency limitations that would prevent it from achieving the cost reductions necessary for mass adoption, and thus could not evolve into an economically viable industry at scale. The company firmly believed that mono-crystalline represented the definitive direction for technological progress in photovoltaics. Consequently, LONGi committed exclusively to mono-crystalline technology, developing numerous advancements in this field rather than pursuing short-term gains through policy subsidies or market trends. Today, the global industry still widely employs two pivotal technologies developed during LONGi's early commitment: the Recharged Czochralski (RCz) crystal growth method and diamond-wire wafer slicing (Fig. 3). These two technological breakthroughs alone are credited with contributing approximately 70% of the overall cost reduction in PV manufacturing[5].

LONGi achieved critical technological breakthroughs starting in 2015, and through this technological leadership, ascended to become the world's top PV module supplier by shipment volume in 2019. In 2021, while the company pioneered the development of TOPCon technology, our assessment concluded it offered only marginal improvements over the previous generation and lacked long-term viability. Consequently, we chose not to commercialize this transitional technology, instead redirecting R&D resources toward the more promising, nearly mature next-generation Back Contact (BC) technology. Indeed, while competitors began mass-promoting TOPCon in 2022, the market for TOPCon products reached a state of oversupply within just two years, validating our strategic decision.

LONGi has implemented a comprehensive strategic layout across the entire PV value chain, from upstream technology to diverse downstream applications, to mitigate operational risks. In upstream technology, LONGi currently holds world records in both mainstream crystalline silicon and silicon-perovskite tandem cells, with strong conviction in the latter's future commercial viability. Downstream, we have developed comprehensive product portfolios for utility-scale, commercial & industrial (C&I), and residential applications, including specialized building-integrated photovoltaics (BIPV) that feature customizable colors and marble-like textures, seamlessly blending into architectural designs. These BIPV solutions have reached commercial maturity, positioning every future building as a potential power generator. Furthermore, LONGi is advancing hydrogen equipment and green methanol solutions to address the demand for liquid and gaseous green fuels in shipping and aviation. Concurrently, we are committed to delivering green, low-carbon products throughout their entire lifecycle. Our leadership in smart manufacturing is demonstrated by operating the PV industry's first Lighthouse Factory[25], recognized for its advanced digitalization and intelligent manufacturing capabilities. We remain confident that photovoltaics will continue to play an exponentially expanding role in addressing climate change and advancing the global energy transition.

While LONGi's experience illustrates one pathway of disciplined expansion anchored in technological leadership, other global PV manufacturers have adopted different strategies. Some firms pursued rapid capacity scaling to capture short-term market share during subsidy-driven booms, while others emphasized geographic diversification or downstream integration to mitigate policy risks. These heterogeneous responses underscore that there is no single optimal strategy; however, the increasing frequency of technology transitions and market cycles has made long-term technological competitiveness and financial resilience universally critical.

3. Recommendations for the sustainable development of the PV industry

To address the current challenges facing the photovoltaic sector, we propose several measures to steer China's PV industry onto a sustainable development path:

First, implement differentiated capacity management policies for upstream and downstream segments. Upstream polysilicon production, characterized by its chemical industry attributes and stabilized technological processes, warrants supply-demand rebalancing through appropriate capacity controls. In contrast, the downstream solar cell segment remains in a phase of rapid technological iteration. Here, the focus should be on fostering innovation by elevating technical standards, enhancing quality requirements, and raising market access thresholds. Imposing capacity restrictions in this

Fig. 3. World-leading technology innovations by LONGi. (RCz (Recharged Czochralski), PERC (Passivated Emitter and Rear Cell), BC (Back Contact))

dynamic segment would inevitably stifle technological progress.

Second, the power grid sector must refine policies and undertake technical adaptations to support energy storage. In recent years, grid redundancy has been utilized to facilitate PV integration. However, the combined daytime output from solar and fossil fuel power now frequently exceeds total societal electricity demand. This new paradigm necessitates accelerated development of energy storage, requiring grid operators to implement supportive policies and complete necessary technical upgrades to enable continued growth in PV installation capacity.

Third, encourage broader participation of diverse entities in green electricity trading. China's power sector reform maintains a clear market-oriented direction. We recommend that national authorities create more market outlets for green power, enabling a wider range of participants to consume renewable electricity—beyond the current model of self-consumption or selling exclusively to the grid.

Furthermore, we advocate for enhanced international cooperation. A distinct trend toward decentralized manufacturing is emerging globally, with many countries seeking to develop domestic PV manufacturing capacity to generate employment, stimulate economic growth, and secure supply chain resilience—an entirely understandable objective. However, achieving parity with China's current levels of technological sophistication, product quality, and cost-competitiveness presents significant challenges for other regions in the short term. The PV industry constitutes a vast industrial ecosystem encompassing components, equipment, raw and auxiliary materials, and workforce expertise. Currently, no other region possesses the complete, integrated industrial chain that China has established. Therefore, deepening international collaboration is essential to accelerate global carbon neutrality progress.

At the same time, upstream capacity management should not rely solely on administrative controls. Market-based instruments deserve greater emphasis to mitigate information asymmetries and avoid entrenching inefficient incumbents. Performance-based standards—such as benchmarks for energy intensity, conversion efficiency, or lifecycle emissions—can accelerate the exit of outdated capacity while preserving competitive pressure and innovation incentives across both upstream and downstream segments.

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Baoshen Zhong is solely reponsible for this article.

Data availability

Not applicable.

Use of AI statement

None.

Declaration of competing interest

The author Baoshen Zhong is the employee of LONGi Green Energy Technology Co. Ltd.

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