

# ***Digital Economy Empowering China's Photovoltaic Industry Transformation: Effects and Contributions to Sustainable Economic Development***

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**Abstract.** China's economy has entered a stage of high-quality development. As a core pillar of the green economy, the photovoltaic (PV) industry has embraced new opportunities under the "Dual Carbon" goals, and the digital economy has become the core driving force for the transformation and upgrading of the PV industry. Through literature analysis and indicator comparison, this paper explores the mechanisms of the digital economy advancing PV industrial transformation and its value for sustainable development. The research shows that artificial intelligence mainly empowers quality inspection and production scheduling in PV manufacturing workshops, big data optimizes supply-demand inventory across the whole industrial chain, and digital twins focus on the operation and maintenance of PV power stations. These three digital technologies significantly improve the overall efficiency of the full PV industrial chain from production, circulation and operation dimensions respectively. Digital transformation not only accelerates industrial structural upgrading, but also exerts positive effects on carbon emission reduction and economic growth, providing references for the digital development of new energy industries.

**Keywords:** Digital economy, photovoltaic industry, industrial transformation, sustainable economic development, dual carbon goals

## **1. Introduction**

China has clearly put forward the "Dual Carbon" strategic goals of peaking carbon dioxide emissions before 2030 and achieving carbon neutrality before 2060. The 14th Five-Year Plan for Renewable Energy Development proposes that the power generated by renewable energy will account for around 33% of the total social electricity consumption by 2025. Featuring wide resource distribution, low development costs and mature technologies, the PV industry has become a core instrument for China's energy transition and a central pillar of the green economy.

Studying the enabling effect of the digital economy on the PV industry can enrich theoretical research on the digitalization of green industries and offer practical basis for corporate practice and policy formulation. This paper follows the logic of "current situation – mechanism – value – suggestions", sorting out the development status of the industry, analyzing the functional paths of

digital transformation, discussing its economic value and putting forward countermeasures and suggestions.

The digital economy has gradually penetrated physical industries, offering new development paths for the PV industry trapped in transformation bottlenecks, and digitalization has become a core means for the PV sector to break through developmental constraints and consolidate global competitive advantages. At present, digital technologies have covered the whole industrial chain of PV. On the production side, leading enterprises including LONGi Green Energy and Jinko Energy have built smart factories, boosting production efficiency and product yield through equipment interconnection and AI quality inspection, while cutting unit energy consumption and material loss. On the operation side, digital twins and intelligent operation & maintenance are widely applied; PV power stations realize power generation forecasting and fault early warning via digital monitoring systems, greatly lowering operation and maintenance costs and raising power generation efficiency. On the supply chain side, big data technology is adopted for demand forecasting and inventory management to strengthen industrial chain stability. Overall, industrial digitalization has shifted from single-point pilot projects to full-chain promotion. Nevertheless, small and medium-sized enterprises (SMEs) lag noticeably in transformation due to restrictions on cost, technology and talent, leading to prominent unbalanced digital development across the industry.

Scholars at home and abroad have carried out extensive research on the integration of the digital economy and the PV industry. Transnational comparative research by Garcia and Rodriguez pointed out that digital transformation serves as the core driving force for renewable energy industries to realize sustainable economic growth [1]. Based on empirical data of Chinese power stations, Liu and Wang found that digital twin technology can lift the power generation efficiency of PV stations by 8%–12% [2]. Chen et al. sorted out application scenarios of artificial intelligence in the PV industry and argued that it delivers remarkable economic value in cost reduction and efficiency improvement [3]. Smith and Thompson analyzed supply chain volatility and bullwhip effect within global PV manufacturing networks [4]. Domestic scholars Wang and Li indicated that the digital economy empowers high-quality development of the PV industry through two core paths: technological innovation and efficiency enhancement [5]. Zhang and Liu demonstrated that digital transformation can substantially improve the carbon emission efficiency of the PV industry [6]. Chen and Zhao analyzed the economic effects of digital twin technology applied in PV power station operation [7]. In general, existing studies mostly focus on the application effects of a single technology or a single industrial link, leaving room for supplementary research on the systematic mechanism of the digital economy empowering full-chain PV transformation and its multi-dimensional value for sustainable economic development.

## **2. Specific impacts of the digital economy on promoting PV industrial transformation**

### **2.1. Intelligent manufacturing improves production efficiency**

Intelligent manufacturing constitutes the core scenario of digital transformation in PV manufacturing. Its essence lies in running data elements through the whole production process to build a closed-loop management and control system of "perception – analysis – decision-making – execution", transforming PV manufacturing from "experience-driven" to "data-driven".

In terms of production execution, digital production lines collect real-time technological parameters such as temperature, pressure, speed and tension through sensors and industrial cameras, and upload data to cloud platforms via industrial internet. Combined with historical optimal data and real-time operating status, AI algorithms dynamically adjust process parameters to maintain

production within optimal ranges. For instance, in the silicon wafer cutting process, digital control systems adjust feed speed and tension in real time according to silicon material hardness and wire saw wear, controlling silicon wafer thickness deviation within  $\pm 2\mu\text{m}$ , effectively reducing material loss and improving product consistency. In quality control, AI visual inspection replaces manual quality testing to achieve high-precision and high-efficiency defect identification. For production scheduling, digital production planning systems automatically generate optimal production schedules combining order demand, equipment status and material inventory, cutting waiting time caused by equipment switching and material shortage. Meanwhile, digital energy consumption monitoring systems track energy data of each link in real time, optimize energy allocation and reduce energy consumption per unit product. On the whole, intelligent manufacturing transforms PV manufacturing from a labor-intensive sector to a technology-intensive one, achieving multiple targets of cost reduction, quality improvement, efficiency growth and consumption cutbacks.

## 2.2. Big data optimizes supply chain management

The PV industrial chain is long and multi-layered, covering silicon materials, silicon wafers, cells, modules, inverters, brackets and power station operation. Scattered upstream and downstream production capacity layout, coupled with fluctuations in market demand, raw material prices and policies, easily trigger supply chain volatility and the bullwhip effect [4]. By integrating multi-source data to build forecasting models and breaking information barriers between upstream and downstream participants, big data technology effectively enhances supply chain stability and collaborative efficiency.

In demand forecasting, big data integrates multi-dimensional information including macroeconomic trends, new energy policies worldwide, installed capacity plans, meteorological data and historical sales volume to construct accurate demand forecasting models. It predicts PV product demand in different regions and periods, guiding enterprises to rationally arrange production capacity and plans, avoiding idle capacity from blind expansion or supply shortages amid demand surges. In supply chain collaboration, digital supply chain platforms break information barriers among suppliers, manufacturers, distributors and logistics providers, realizing real-time sharing and synchronous updating of inventory, order and logistics data. Upstream and downstream enterprises can collaboratively adjust production and delivery plans in response to market changes, lowering risks of inventory backlog and stock-outs arising from information asymmetry.

## 2.3. Digital twins boost power generation efficiency of PV stations

Digital twin technology stands at the core of digital operation for PV power stations. It constructs virtual mirrors corresponding to physical power stations to realize "virtual-real mapping, virtual-real interaction and virtual-real collaboration", comprehensively lifting power generation efficiency and operation & maintenance standards of PV stations.

A complete digital twin system for PV power stations consists of three layers. First, the perception layer collects real-time data such as component temperature, irradiance, wind speed and equipment operating status via PV component monitors, meteorological stations and drone inspection devices. Second, the model layer builds digital models of core equipment including components, inverters and combiner boxes based on physical mechanisms and data-driven approaches, restoring the spatial layout and operation logic of power stations. Third, the application layer delivers practical functions such as power generation forecasting, fault diagnosis and optimized scheduling based on virtual models.

In fault operation and maintenance, AI algorithms analyze operating data from virtual models to predict problems such as component hot spots, inverter failures and loose wiring in advance, shifting the operation & maintenance mode from traditional post-failure emergency repair to pre-emptive prevention, drastically cutting equipment downtime and power generation loss. For PV stations built on complex terrains including mountainous areas, deserts and water surfaces, digital twin technology optimizes component arrangement angles and spacing combining terrain and hydrological data, improving land utilization and power generation efficiency while lowering safety risks and labor costs of on-site maintenance. In addition, digital twin technology can be applied in the preliminary design phase of power stations, simulating power generation effects under different terrains, installation plans and inclination angles to optimize design schemes and raise the full-life-cycle revenue of power stations from the source.

### **3. Value of PV industrial digitalization for sustainable economic development**

#### **3.1. Accelerating optimization and upgrading of industrial structure**

Digital transformation of the PV industry not only improves its own efficiency but also delivers prominent industrial driving effects and structural upgrading value, serving as a key starting point to promote high-end, intelligent and green development of manufacturing.

From the perspective of industrial chain extension, PV digitalization drives the development of high-tech upstream industries such as industrial software, intelligent sensors, industrial robots and computing power services, spawning new products and tracks including PV-specific MES systems, SaaS platforms for power station operation & maintenance and intelligent inspection drones. In terms of industrial spillover effects, technological experience and solutions of PV digitalization can be replicated and promoted to other energy sectors including wind power, hydropower, energy storage and power grids. For example, digital twin power station technology can be directly applied to wind farm operation & maintenance; experience in smart factory construction can be migrated to energy storage cell manufacturing; industrial internet platforms can adapt to the whole energy equipment manufacturing sector, driving digital upgrading and structural optimization of the entire energy industry.

In terms of global value chain upgrading, digitalization helps China's PV industry break away from the low-end path of price competition and shift toward high-end competition centered on technology, standards and brands [8]. Previously, China's PV industry mainly exported processed products and occupied the manufacturing segment in the global value chain. With enhanced digital capabilities, Chinese enterprises have begun to export high value-added products and services such as smart factory solutions, intelligent power station operation & maintenance services and digital standards, extending China's position in the global PV value chain toward R&D and service links, elevating China's manufacturing status in global industrial division and pushing manufacturing toward high-end development.

#### **3.2. Facilitating carbon emission reduction and environmental improvement**

PV power itself acts as a core clean energy force, and digitalization further amplifies its carbon reduction effects, supporting the realization of Dual Carbon goals and ecological environment improvement from two dimensions: carbon reduction in energy supply and carbon reduction within the industry itself.

On the energy supply side, replacing fossil fuel power generation with PV power constitutes the core path to carbon emission reduction. Digitalization raises power generation efficiency, meaning more clean electricity can be produced under the same installed capacity to substitute coal and other fossil fuels. Meanwhile, digitalization improves grid absorption capacity and curtails PV abandonment, further lifting the carbon reduction contribution of PV power. On the industrial self-carbon reduction side, intelligent manufacturing cuts energy and material consumption in production links; digital supply chains lower carbon emissions in logistics links; digital carbon footprint management realizes precise accounting and control of carbon emissions across the whole industrial chain. Full-chain low-carbon transformation not only supports domestic Dual Carbon goals, but also strengthens the international competitiveness of Chinese PV products, helping cope with international carbon tariff barriers.

### **3.3. Driving economic growth**

The PV industry is a strategic emerging industry with global competitive advantages in China. Digital transformation amplifies the economic driving effects of the PV industry by lifting industry efficiency and profitability, injecting momentum into sustainable economic development.

From the perspective of economic growth, digitalization raises the profitability and return on investment of PV enterprises, attracting more capital inflow and continuous industrial scale expansion, driving output growth in manufacturing links including silicon materials, modules and inverters. Meanwhile, PV digitalization fuels the development of related industries such as digital technology services, intelligent equipment manufacturing and power station operation & maintenance services, forming an integrated industrial cluster of "PV + digital". In PV industrial agglomeration areas such as Jiangsu, Zhejiang, Guangdong and Ningxia, digital transformation promotes regional industrial upgrading and economic growth, emerging as an important pillar for high-quality local economic development.

## **4. Suggestions to promote digitalization of the PV industry**

### **4.1. Policy support and digital infrastructure construction (government perspective)**

First, the government shall set up special funds for PV industrial digital transformation, offering subsidies for projects such as smart factory construction, digital technology R&D and deployment of digital operation & maintenance systems. Policies including additional tax deductions for R&D expenses and tax incentives for high-tech enterprises shall be implemented to lower enterprises' digital investment costs. For SMEs, lightweight digital transformation subsidies and inclusive financial products shall be launched, encouraging SMEs to prioritize single-point digital applications and gradually realize full-chain upgrading to narrow the digital development gap within the industry [9].

Second, accelerate the layout of digital infrastructure and public services. Prioritize the construction of 5G private networks, industrial internet nodes and edge computing centers in PV industrial clusters to provide network and computing power support for corporate digital transformation. Build a public digital service platform for the PV industry, offering inclusive digital services including lightweight MES systems, cloud-based operation & maintenance tools and carbon emission accounting tools to reduce the digital transformation threshold for SMEs. Carry out free digital diagnosis services for enterprises to help identify transformation pain points and formulate customized transformation plans.

## 4.2. Independent transformation and innovation (enterprise perspective)

First, enterprises shall avoid blind imitation and formalistic transformation and formulate progressive digital transformation roadmaps matching their development stage, business scale and core pain points. Large enterprises can advance full-chain digital upgrading and build integrated smart factories and digital supply chain systems; SMEs can start with low-input, high-return single-point scenarios such as AI quality inspection, intelligent production scheduling and remote power station monitoring, acquire digital benefits with small investments and expand transformation scope step by step.

Second, increase R&D investment and strengthen technological and talent support. Enterprises should raise input in digital technology R&D, tackle core problems in production and operation to develop self-controllable digital solutions and avoid over-reliance on external service providers. Attach importance to building compound talent teams: cooperate with universities to train specialized talents in targeted programs, upgrade digital capabilities of existing employees via internal training, and introduce high-end professionals in algorithm and digital twin fields to provide talent guarantees for digital transformation [10].

Third, expand digital application boundaries and innovate business models. Enterprises can develop new businesses relying on digital capabilities, such as value-added services including PV + energy storage, virtual power plants and power trading based on power station operating data; export digital solutions to the whole industry and transform from single product manufacturers to comprehensive energy service providers. Leading enterprises shall actively participate in the formulation of international digital standards, promote China's PV digital technologies and experience, elevate global industrial discourse power and consolidate the international competitive advantages of China's PV industry.

## 5. Conclusion

The main conclusions are summarized as follows. First, the digital economy runs through the whole chain of PV manufacturing, circulation and power station operation, and together with new cell technologies and Dual Carbon policies, forms the core driving force for high-quality industrial transformation. Second, the digital economy empowers the PV industry via four paths: efficiency improvement through intelligent manufacturing, supply chain optimization with big data, power generation efficiency growth via digital twins, and innovation acceleration through digital platforms. Third, digital transformation of the PV industry delivers multi-dimensional positive value for sustainable development, including industrial upgrading, carbon emission reduction and economic growth stimulation.

Promoting PV digitalization requires coordinated efforts between the government and enterprises. The government should provide support in policies, digital infrastructure and standards to build a sound development environment; enterprises shall proceed from reality, increase R&D and talent investment and deliver tangible digital value. Joint efforts of both sides can lift the overall digital level of the industry and consolidate China's global advantages in the PV sector.

This paper mainly analyzes the overall industry and typical cases, with insufficient discussion on digital gaps among enterprises of different regions and scales. Follow-up research can collect micro-panel data of thousands of listed PV enterprises, build mediating effect models to quantify the carbon emission reduction contributions of digital transformation, and conduct comparative research subdivided into silicon material, module and power station sectors.

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