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A Comparative Evaluation of Distributed Photovoltaic Power Generation Costs and Economic Effects Across Different Regions

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Abstract

In the context of the dual challenges posed by global environmental pollution and the energy crisis, traditional centralized power generation models are increasingly inadequate to meet the demands of modern society. Distributed photovoltaic (PV) power generation, characterized by its modularity, low investment requirements, and advantages of being pollution-free and highly efficient, has gradually emerged as a critical source of electricity worldwide. As the leading nation in photovoltaic power generation, China has invested substantial financial resources in distributed PV technologies and implemented favorable policies to support their development. However, due to regional variations in solar energy resources, the costs and economic returns of distributed PV projects differ significantly across various areas. This paper analyzes the primary cost sources and components of distributed PV projects, calculating the levelized cost of electricity (LCOE) and internal rate of return (IRR) for different regions. It provides a comprehensive exploration of how regional differences impact the economic performance of distributed PV projects and the trends associated with these variations.

Keywords

Distributed Generation; Photovoltaic Power Generation; Regional Generation Costs; Internal Rate of Return; Economic Benefits

Introduction

The global energy sector is currently facing a dual challenge. On the one hand, there is increasing pressure on securing affordable and reliable energy supplies, as access to energy has become more constrained. On the other hand, the use of traditional high-polluting energy sources, such as oil and coal, has led to significant environmental issues, particularly irreversible damage to the global climate. With the rapid rise in energy prices and geopolitical instability in recent years, the availability of energy has become even more crucial for economic growth and human development [1]. At the same time, the global energy system is vulnerable to supply shortages, making energy security a central concern in international political agendas. While traditional energy sources may satisfy current energy demands, the environmental risks associated with them cannot be ignored. In particular, an over-reliance on fossil fuels has exacerbated crises such as climate change and environmental pollution. Therefore, achieving the dual objectives of ensuring energy security while protecting the environment has become a critical global challenge.

In response to this situation, governments and stakeholders worldwide must engage in deep collaboration and intervention to promote energy transitions and develop a sustainable, low-carbon energy system. The growth of renewable energy and distributed generation technologies, particularly distributed photovoltaic (PV) power generation, has emerged as a major energy solution in many countries due to its low investment, high efficiency, and low environmental impact. According to data from the China Photovoltaic Industry Association, as the world's leading PV power producer, China's newly installed PV capacity reached a record 216.88 GW in 2023, representing an annual growth rate of 148.12%. The

Chinese government has also provided substantial financial and policy support to promote distributed PV power generation. This paper will explore the characteristics of distributed PV power generation, focusing on the costs of distributed PV in different regions of China and analyzing the economic benefits of government support for distributed PV projects.

1. Distributed Photovoltaic (PV) Power Generation

Distributed photovoltaic (PV) power generation refers to the installation of solar PV systems directly at or near the user's location, such as on the rooftops or walls of residential, commercial, or industrial buildings. The electricity generated by these systems can be used to meet the user's own demand, with any excess power fed back into the grid. As a form of distributed generation, distributed PV power offers significant advantages such as high modularity, zero emissions, small land use, and low investment costs, making it an increasingly important component of modern power systems [2, 3].

Unlike traditional centralized power generation, distributed generation typically relies on renewable energy sources, such as solar or wind, or relatively cleaner fossil fuels like natural gas. Because distributed generation systems are usually located close to the point of electricity consumption, they reduce long-distance transmission losses and improve the efficiency of electricity use. This proximity to users not only lowers transmission costs but also enhances the reliability and flexibility of the power system.

Distributed PV power generation is particularly well-suited to densely populated urban areas or commercial zones. PV systems generate no pollutants or harmful gases during operation, ensuring no adverse health impacts on nearby residents or workers. Moreover, the modular nature of PV systems allows for flexible installation based on different needs, from small-scale residential applications to large-scale commercial projects. This clean, renewable form of power generation not only aligns with global efforts to reduce carbon emissions but also plays a critical role in the transition to more sustainable energy systems.

Overall, distributed PV power systems, with their pollution-free and highly scalable characteristics, have become an essential component of renewable energy applications. Their potential is especially evident in urban and industrial areas, where both the range of applications and the economic benefits are becoming increasingly prominent.

2. Costs of Distributed Photovoltaic (PV) Power Generation

As the world's largest photovoltaic (PV) power producer, China has witnessed a rapid increase in newly installed PV capacity since 2014, with PV power generation gradually becoming one of the country's primary sources of electricity. This remarkable growth is largely driven by the Chinese government's continuous policy support and substantial financial investments in the PV sector. According to statistics from the China Photovoltaic Industry Association and related research institutions, by 2023, China's total investment in PV power generation exceeded 500 billion yuan, with distributed PV accounting for nearly 60% of the total. This rising proportion not only reflects the increasing market demand for distributed PV but also highlights the strong influence of policy direction in driving its development.

With the rapid expansion of distributed PV power generation, understanding its cost structure and economic viability has become increasingly important. In the following sections, we will provide an in-depth analysis of the costs associated with distributed PV power generation, examining the key components of its cost structure and the evolving trends in generation costs.

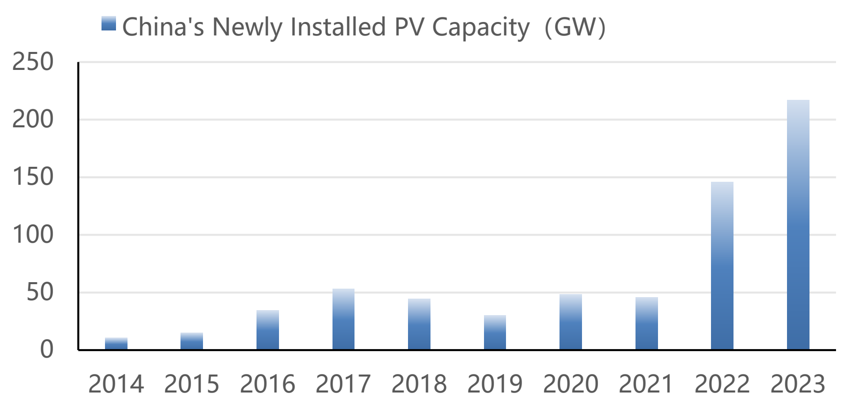

Figure 1. China's Newly Installed PV Capacity (Source: National Energy Administration of China).

2.1 Cost Structure of Distributed Photovoltaic Power Generation

The costs associated with distributed photovoltaic (PV) systems primarily include investment costs, operational and maintenance (O&M) costs, and financial costs [4]. Understanding these costs is crucial for evaluating the feasibility and profitability of distributed PV projects.

Investment costs consist of several components, particularly the costs of PV modules, balance of system (BOS) costs, and other expenses related to project implementation. Among these, the cost of PV modules is the most significant component, heavily influenced by raw material prices, especially the price of silicon. Specifically, the costs of PV modules include expenses related to cell processing, manufacturing, and module assembly. Currently, for traditional distributed PV projects, the overall investment cost is approximately 5 yuan per watt. The cost of PV modules accounts for 46% of the total investment cost, making it the largest single-cost item. This proportion reflects the complexity of the supply chain, which involves the manufacturing stages of silicon materials, wafers, and solar cells.

BOS costs represent 30% of the total investment cost, with significant contributions from key components such as combiner boxes, distribution cabinets, and grid connection infrastructure. Other costs account for 24% of the investment costs; however, accurately assessing these costs can be challenging due to the ambiguous definition of site characteristics, often necessitating individual analyses for specific projects. Additionally, larger capacity projects may require further investment in cables, substations, and local grid infrastructure.

Operational and maintenance costs primarily consist of depreciation costs, labor expenses, spare parts costs, and routine maintenance expenses. For systems with a capacity below 10 kW, maintenance costs are typically negligible. However, for megawatt (MW) scale power plants, maintenance costs generally range from 1% to 3% of the total investment [5]. Currently, there are three main O&M models available: asset entrustment, comprehensive service entrustment, and service agency entrustment. Each model has unique advantages and challenges, potentially impacting the overall effectiveness of project management.

Financial costs encompass the financing costs incurred during the investment period and the tax burdens arising post-generation. For investors with limited funding, financing costs are particularly critical when considering the investment in distributed PV stations. Therefore, careful evaluation of these costs is essential during financial assessments to ensure a comprehensive understanding of the project's economic viability. Through an in-depth analysis of these cost elements, stakeholders can better evaluate the overall potential and sustainability of distributed PV projects within the evolving energy landscape.

2.2 Cost Variation Trends of Distributed Photovoltaic Power Generation

As the market for distributed photovoltaic (PV) power generation continues to develop and mature, the inherent value of investing in this field is becoming increasingly apparent, attracting widespread attention from various enterprises and capital sources. However, the external environment surrounding distributed PV is undergoing profound changes, leading to uncertainties in industry development that exceed any previous period. In 2018, China's National Development and Reform Commission issued a notice titled "Notice on Matters Related to Photovoltaic Power Generation in 2018," which marked the first reduction of subsidies for distributed PV from 0.37 yuan/kWh to 0.32 yuan/kWh, while also limiting installation capacity. This policy shift signifies a major transformation in the long-term development logic of the distributed PV industry, where future growth will depend on cost parity with traditional energy sources and the natural growth of the industry's own demand.

In the context of gradually decreasing subsidies, the importance of technological advancement in the distributed PV industry has become increasingly prominent. To promote sustainable industry development, technology must accelerate progress to enhance efficiency and further reduce costs. The impact of technological advancements on the cost reduction of distributed PV can be analyzed from two aspects: First, the decline in photovoltaic module prices will directly lower investment costs. Photovoltaic modules have a high learning rate, meaning that as production experience accumulates, costs will continue to decline. Second, improvements in module conversion efficiency mean that fewer modules are needed to achieve the same generation capacity, thereby indirectly reducing balance of system (BOS) costs and operation and maintenance (O&M) costs. Research indicates that if the efficiency of photovoltaic modules increases by 1%, the overall cost of the photovoltaic power generation system could decrease by approximately 17%.

Moreover, due to the different methods for improving efficiency at each stage, the pathways for cost reduction in the distributed PV industry chain exhibit unique characteristics. For instance, in the silicon material segment, the cost reduction pressure is relatively small due to expanded production capacity and advancements in purification technology, particularly considering its high-profit margins. In the silicon wafer segment, cost reductions primarily depend on decreasing silicon material prices and the application of diamond wire cutting and crystal growth technologies to meet cost reduction requirements. For the cell segment, employing PERT (Passivated Emitter and Rear Cell) and PERC (Passivated Emitter and Rear Cell) technologies is crucial for improving efficiency, while multi-wire technologies are utilized to reduce silver paste consumption, thereby lowering costs.

In the module segment, promoting advanced module packaging technologies can significantly increase the energy yield per watt over the entire lifecycle, thus reducing final investment costs. For the balance of system costs, the use of tracker technology to enhance performance ratios is primarily aimed at cost reduction. These technological innovations and optimization strategies will lay a solid foundation for the sustainable development of distributed PV, enabling it to play a more significant role in the future energy landscape.

3. Cost and Economic Benefits Assessment of Distributed Photovoltaic Power Generation

3.1 Cost Assessment of Distributed Photovoltaic Power Generation

Currently, the primary basis for measuring the economic efficiency of power generation units in the market is the cost investment of the project and the resulting electricity output. This paper utilizes the Levelized Cost of Electricity (LCOE) as an economic indicator to comprehensively evaluate the average electricity generation cost of distributed photovoltaic power generation throughout its entire lifecycle. The specific calculation method involves determining the ratio of the total lifecycle cost of a power generation project to its total electricity output over the lifecycle.

The calculation of LCOE takes into account not only the initial investment cost but also includes operational and maintenance costs, equipment depreciation, financing costs, and other factors, distributing these costs across the total electricity output during the project's lifecycle. By discounting all costs and revenues over time, this method effectively assesses the economic viability of photovoltaic power generation projects and provides a standardized benchmark for cost comparisons among different technologies and energy projects.

As a standardized economic evaluation tool, LCOE is particularly suitable for analyzing the investment returns and competitiveness of photovoltaic power generation projects under varying policy environments, subsidy mechanisms, technological advancements, and market conditions. This, in turn, offers reliable data support for project planning and investment decision-making. The calculation formula for LCOE is as follows:

$$LCOE = \frac{I+\sum_{t=1}^{n}\frac{O_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \tag{1}$$

In equation (1), $\boldsymbol{I}$ represents the initial investment cost of the distributed photovoltaic power generation project; $\boldsymbol{O_t}$ indicates the operating and maintenance costs of the project in year $\boldsymbol{t}$; $\boldsymbol{E_t}$ denotes the electricity generation in year $\boldsymbol{t}$; $\boldsymbol{r}$ refers to the discount rate; and $\boldsymbol{n}$ signifies the project's lifespan (in years).

The LCOE calculation method takes into account the time value of money by discounting the future costs and economic benefits (electricity generation) of the project to present value, thereby providing a more accurate reflection of the project's average electricity generation cost and the economic benefits it produces.

3.2 Economic Benefit Evaluation of Distributed Photovoltaic Power Generation Projects

The key driving force behind the development of the distributed photovoltaic (PV) industry lies in the internal rate of return (IRR) of PV projects. As long as operators can ensure that the IRR remains at an attractive level (for example, above the project discount rate of 8% or higher), the investment returns for distributed PV projects can be maintained at a high level, thus ensuring continuous growth in new installation demand. In this process, both manufacturers and operators stand to benefit. To further investigate the investment return situation of distributed PV projects, this paper calculates the IRR under different regional and operational models, and further analyzes the impact of benchmark grid connection prices and subsidy reductions on the IRR of distributed PV projects. Through a quantitative analysis of these factors, a more comprehensive understanding of the impact of different policies and market conditions on project economics can be achieved.

Next, this paper will reveal the changes in economic benefits generated by calculating the IRR of distributed PV projects. The specific formula is as follows:

$$NPV(IRR) = \sum_{i=0}^{T}(CF_{in,t} - CF_{out,t})(1 + IRR)^{-1} \tag{2}$$

In equation (2), $\mathrm{NPV(IRR)}$ represents the internal rate of return of the distributed photovoltaic (PV) project; $\mathrm{CF_{in,t}}$ denotes the cash inflow of the project at time $\boldsymbol{t}$, composed of its total annual revenue; $\mathrm{CF_{out,t}}$ indicates the cash outflow of the project at time $\boldsymbol{t}$, consisting of its maintenance costs, operating costs, and initial investment; $\boldsymbol{t}$ represents the year after the project's completion.

4. Case Study Analysis

China's status as the world's largest photovoltaic (PV) power producer is significantly attributed to its vast territory, which encompasses diverse terrains and climatic regions that provide abundant solar energy resources for PV projects. However, this geographical feature also results in notable disparities in solar resource distribution across different regions. Specifically, the western regions of China, characterized by low population density and high altitudes, enjoy relatively rich per capita solar resources, while the economically developed and densely populated eastern regions have comparatively less.

In response to these differences, the Chinese government has categorized distributed PV projects into three types based on the solar resource conditions and economic development levels of various regions, implementing differentiated policy subsidies to promote balanced growth of the PV industry [6].

Specifically, the first category includes cities in the northwest, which have abundant per capita solar resources but lag in economic development. For distributed PV projects in these areas, the national government offers a subsidy of 0.32 yuan/kWh, with no additional local subsidies. The second category consists mainly of industrial cities in northern China, which have higher population densities and moderate per capita solar resources. In addition to the national subsidy of 0.32 yuan/kWh, local governments provide an additional subsidy of 0.3 yuan/kWh to further encourage investment and development in PV projects. The third category encompasses economically developed regions in central, eastern, and southern China, which, despite having the least per capita solar resources, benefit from strong economic foundations that prompt local governments to provide significant policy support. In these regions, distributed PV projects can receive an additional local subsidy of 0.25 yuan/kWh on top of the national subsidy.

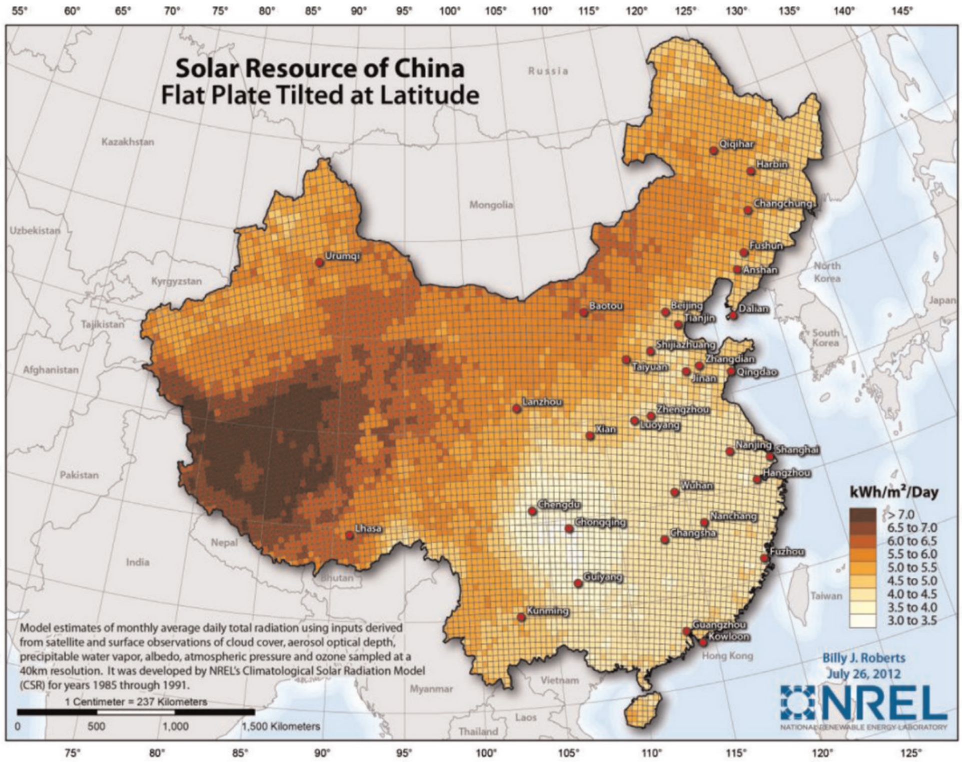

Figure 2. Distribution of China's Solar Resource (Source: National Renewable Energy Laboratory (NREL)).

Table 1. Economic Parameters of Distributed PV Power Generation Projects

Parameter	Value
Installed Capacity	1 MW
Unit Cost	5 CNY/Watt
Annual O&M Cost	2% of Initial Investment
Photovoltaic Conversion Rate	80%
Depreciation Rate	0.7%
Loan Ratio	70%
Loan Term	15 years
Loan Interest Rate	5%
Discount Rate	8%
Lifecycle	25 years

Table 2. Basic Overview of Distributed PV in Three Types of Solar Resource Regions

Electricity Price Indicators	First Category Region	Second Category Region	Third Category Region
Annual Peak Hours	1650	1514	1340
PV Power Station Electricity Price (CNY/kWh)	0.5	0.6	0.7
National Subsidy + Local Subsidy (CNY/kWh)	0.32	0.32+0.3	0.32+0.25
Duration of Local Subsidy	-	5	5
Average Industrial and Commercial Electricity Price (CNY/kWh)	0.57	0.92	0.89

Therefore, when evaluating the generation costs and internal rate of return (IRR) of distributed photovoltaic (PV) projects, it is essential not only to consider the basic cost structure of the project but also to discuss it categorically based on local subsidy policies in different regions. The level of policy support in various regions has a significant impact on the project's economic viability and investment returns.

As shown in Table 1, let’s consider a distributed PV project with an operational duration of 25 years, a capacity of 1 megawatt, a unit generation cost of 5 yuan per watt, and an annual operating cost of 2% of the initial investment. The project's depreciation rate is 0.7%, and its photovoltaic conversion efficiency is 80%. When this project is established in Lanzhou (Category 1 region), Beijing (Category 2 region), and Shanghai (Category 3 region), the economic benefits generated by the project can be analyzed by calculating its Levelized Cost of Electricity (LCOE) and IRR in different regions (specific details are presented in Table 2).

4.1 Analysis of Levelized Cost of Electricity (LCOE)

Focusing on Lanzhou (Category I region), Beijing (Category II region), and Shanghai (Category III region), this study conducts an in-depth analysis of the Levelized Cost of Electricity (LCOE) for distributed photovoltaic (PV) projects in these three cities. The calculated results indicate that Lanzhou's LCOE is 0.73 CNY/kWh, Beijing's is 0.81 CNY/kWh, and Shanghai's is 0.87 CNY/kWh. This trend clearly demonstrates a negative correlation between the richness of solar resources and LCOE, with Lanzhou exhibiting greater economic competitiveness in power generation due to its superior solar resource conditions.

Further observation reveals that both Beijing and Shanghai's LCOE are lower than their respective commercial and industrial electricity prices, indicating that under the current technology levels and cost structures, users can achieve parity in electricity generation compared to traditional power sources. This finding lays a solid foundation for the widespread application of distributed photovoltaic power generation, highlighting its economic advantages and market prospects amid urbanization.

In summary, distributed PV projects in Lanzhou, Beijing, and Shanghai demonstrate significant investment return potential within their respective market environments. With technological optimization and policy support, the economic benefits of distributed PV projects in these cities are expected to improve further, contributing positively to sustainable energy development.

4.2 Internal Rate of Return Analysis

Through calculations, the Internal Rates of Return (IRR) for distributed photovoltaic (PV) projects in Lanzhou, Beijing, and Shanghai are found to be 14.3%, 23.5%, and 18.4%, respectively. These figures are significantly higher than the set discount rate of 8%, indicating that distributed PV projects in all three cities have favorable economic effects. Notably, the projects in Beijing demonstrate the highest IRR, highlighting their outstanding potential for economic returns.

In contrast to the Levelized Cost of Electricity (LCOE), the IRR does not show a clear positive correlation with the abundance of solar resources. Although the solar resources in Beijing (a Type II region) and Shanghai (a Type III region) are less abundant than those in Lanzhou (a Type I region), their project IRRs exceed that of Lanzhou. This phenomenon can be attributed to the additional economic subsidies and policy support provided by local governments for distributed PV projects, which significantly enhance the economic viability of investments in these two regions. Particularly in economically developed areas, the intensity of government support and the stability of subsidy policies play a crucial role in improving project investment returns.

Therefore, despite the Type I region having relatively rich solar resources, factors such as policy support and market environment also play a significant role in determining project's economic viability. This further underscores that policy incentives and local subsidies have a critical impact on enhancing the economic feasibility of distributed PV projects, allowing them to achieve excellent investment returns even in regions with relatively weaker resources.

5. Conclusion

This study clearly demonstrates that distributed photovoltaic (PV) generation will exhibit significant investment potential and competitive advantages in the future. As the global energy transition accelerates, distributed PV has brought substantial economic benefits to existing energy generation structures worldwide. Furthermore, advancements in photovoltaic technology and reductions in production costs will serve as crucial engines for industrial development, creating new investment opportunities.

In economically developed cities like Beijing and Shanghai, the Levelized Cost of Electricity (LCOE) for distributed PV has fallen below local commercial and industrial electricity prices, indicating that user-side photovoltaic generation has achieved parity with traditional electricity sources. This phenomenon not only highlights the progress of photovoltaic technology in reducing generation costs but also confirms its sustainable economic development capability. Particularly in the context of rapid urbanization, distributed PV demonstrates strong market adaptability in energy supply and demand, showcasing broad application prospects.

Additionally, the research reveals that distributed PV projects exhibit high Internal Rates of Return (IRR) across three typical regions with significant solar resource disparities. This indicates that these projects possess strong economic viability, even in areas with limited solar resources, such as Beijing and Shanghai, where local government support and economic subsidies ensure higher returns than in more resource-rich Lanzhou. This suggests that beyond the abundance of solar resources, local policies, and subsidy levels significantly influence project economics.

In summary, distributed photovoltaic generation projects have tremendous growth potential in the current and future market environment. Although government subsidies are gradually decreasing, ongoing technological advancements, cost reductions, and continued local government support will likely sustain the long-term growth momentum and competitiveness of the distributed PV industry. Driven by policies, technology, and market dynamics, distributed PV will become an integral part of the clean energy transition in China and globally, continuing to provide robust support for optimizing energy structures and achieving carbon reduction targets.

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