Clean Energy to the People: How Solar PV Became One of the Most Affordable Energy Sources

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Abstract. This study analyzes the declining cost trends of solar photovoltaic (PV) installation and its impact on electricity generation affordability worldwide. Secondary data from the International Renewable Energy Agency (IRENA), specifically from the Renewable Capacity Statistics 2024 report, is utilized to examine global trends in solar PV deployment, cost reductions, and market expansion. A descriptive statistical approach is employed to assess historical and recent data, identifying key patterns and investment trajectories influencing solar energy growth. The findings reveal that from 2010 to 2022, the capital expenditure (CAPEX) for solar PV installation dropped from $5,124 per kW to $876 per kW, marking an 83% cost reduction. Over the same period, the capacity factor increased from 14% to 17%, and the levelized cost of electricity (LCOE) decreased from $0.445 per kWh to $0.049 per kWh, an 89% decline. The study highlights that 81% of global solar PV capacity is concentrated in just 10 countries, with China leading (43.16%), followed by the United States (9.75%), Japan (6.17%), Germany (5.79%), and India (5.15%). Additionally, the LCOE of solar PV became less than half the cost of fossil fuel-based power generation by 2022, where fossil fuel LCOE ranged between $0.15 to $0.16 per kWh. The total installed solar PV capacity grew from 40,277 MW in 2010 to 1,046,614 MW in 2022, demonstrating exponential growth. Moreover, over the last 22 years, solar PV contributed to fuel cost savings of $27.16 billion, accounting for 16% of total savings from all renewable sources. These results underscore the increasing economic viability of solar PV and its crucial role in global energy transitions. The study provides valuable insights for policymakers, investors, and energy planners, supporting data-driven decision-making for expanding solar energy infrastructure and achieving sustainable energy goals.

Keywords: Solar energy, photovoltaic, renewable, clean energy, sustainability.

1. Introduction

The rapid advancement of solar PV technology has transformed it into one of the most viable and affordable sources of clean energy [1]. Once hindered by high installation costs and efficiency limitations, solar power has now emerged as a key driver of the global energy transition. According to data from the IRENA, solar PV capacity has expanded significantly in recent years, driven by technological advancements, economies of scale, and declining capital expenditure (CAPEX) requirements [2]. This trend signals a crucial shift in the global energy landscape, where solar power is becoming increasingly competitive with traditional fossil fuel-based electricity generation (see Figure 1). In 2023, solar energy accounted for 16% of the total electricity capacity installed across all renewable and non-renewable sources, reaching 1,419 GW. Notably, 99.5% of this solar capacity (1,412 GW) came from solar PV systems, highlighting PV's dominance in the solar energy sector.

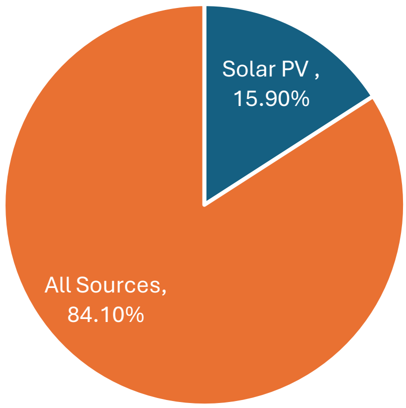

Figure 1. Electricity installed capacity across the globe from Solar PV [2]

Historically, solar PV deployment faced several challenges, including high upfront investment costs, lower efficiency rates, and limited policy support in many regions [3]. However, continuous research and development, combined with market-driven reductions in CAPEX, have significantly improved the affordability and accessibility of solar-based electricity generation. Today, solar energy is not only environmentally sustainable but also economically viable, making it a key solution for governments and investors aiming to achieve energy security and decarbonization.

This study aims to analyse the declining cost trends of solar PV installation and its impact on electricity generation affordability worldwide. The study also explores the role of leading solar markets, and their policy interventions in shaping the current solar energy landscape.

This study employs descriptive statistical analysis using secondary data from IRENA to assess global trends in solar PV deployment and cost reduction. By examining historical and recent data, the research identifies patterns, regional variations, and investment trajectories influencing solar energy growth. Descriptive statistics provide a clear and quantifiable assessment of key indicators, making the findings easily interpretable for governments, private investors, and policymakers [1].

Using secondary data from a globally recognized source like IRENA ensures reliability and accuracy in assessing solar energy trends. The descriptive statistical approach allows stakeholders to make data-driven decisions, helping governments design effective renewable energy policies, investors assess market potential, and policymakers implement cost-efficient energy transition strategies.

This study is expected to highlight:

a. The significant cost reduction in solar PV installation and its implications for energy affordability.
b. The leading countries driving solar PV expansion and their investment patterns.
c. The role of policy and market forces in accelerating solar adoption.

d. Insights for governments, private investors, and policymakers to implement solar energy for sustainable economic growth.

By shedding light on these aspects, this research contributes to a better understanding of the implementation feasibility of solar PV, reinforcing its role as a cornerstone of future energy systems.

2. Methodology

This study employs a descriptive statistical approach to analyse the declining costs of solar PV installation and its impact on electricity generation affordability. The methodology consists of three key stages: data collection, data preparation, and data cleaning.

The study utilizes secondary data from the IRENA, specifically from the *Renewable Capacity Statistics 2024* report [2]. This dataset provides global and regional solar PV capacity trends, investment patterns, and cost variations over time.

The collected data is structured into relevant categories, including Installed solar PV capacity by year and region, CAPEX trends for solar PV installations., Cost per megawatt (MW) of installed capacity across different markets, and Solar PV market share among leading countries.

To ensure accuracy and consistency, the dataset undergoes: Removal of missing or inconsistent values, ensuring reliable trend analysis, Standardization of units (e.g., converting costs to a uniform currency if necessary), and filtering out outliers, such as extreme cost deviations that could distort statistical analysis.

3. Results and Discussion

This study finds that, from 2010 to 2022, the CAPEX for solar PV installation significantly decreased from $5,124 per kW to $876 per kW, marking an 83% cost reduction. This decline is primarily due to technological advancements, economies of scale, and improved manufacturing efficiencies, making solar energy more affordable.

At the same time, the capacity factor, which indicates the reliability and efficiency of solar power plants, improved from 14% to 17%. This increase suggests that solar PV systems are becoming more efficient, generating more electricity per installed unit over time.

Additionally, the LCOE (the average cost per unit of electricity generated over the plant's lifetime) dropped from $0.445 per kWh to $0.049 per kWh, representing an 89% reduction. This dramatic decline highlights the economic competitiveness of solar PV, making it one of the cheapest energy sources available today.

This study reveals that 81% of the 1,412 GW of solar PV electricity is installed in just 10 countries. The detailed results are presented in Table 1.

Figure 2 highlights that China is leading with 43.16%. China's dominance is driven by strong government policies, large-scale solar farms, and cost-effective solar manufacturing. The United States (9.75%) follows as the second-largest solar PV market, benefiting from tax incentives, corporate investments, and state-level renewable policies. Japan (6.17%) and Germany (5.79%), both early adopters, have well-established solar industries supported by government incentives and policy frameworks.

India (5.15%) is rapidly expanding its solar capacity through large-scale government-led projects and falling PV costs. Brazil (2.65%) and Australia (2.39%) also show significant growth, with Brazil focusing on private-sector investments and Australia leading in residential rooftop installations. Italy (2.11%), Spain (2.03%), and South Korea (1.92%) complete the list, benefiting from favorable policies and increasing investments in solar energy.

Table 1. Top 10 Countries by Installed Solar PV Capacity (2023)

Country	Electricity from Solar PV (MW)	% of Total
China	609350.80	43.16%
United States of America	137725.28	9.75%
Japan	87068.00	6.17%
Germany	81737.00	5.79%
India	72766.84	5.15%
Brazil	37449.21	2.65%
Australia	33680.00	2.39%
Italy	29789.25	2.11%
Spain	28712.26	2.03%
Republic of Korea	27046.23	1.92%
Grand Total	**1145324.86**	**81.11%**

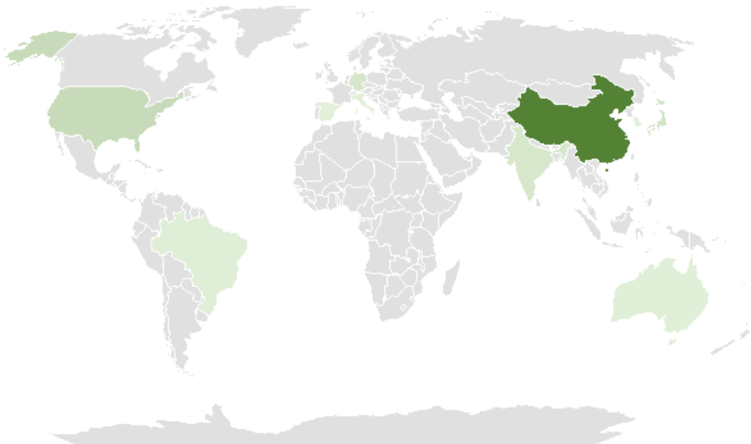

Figure 2. Concentration of solar PV only in 10 countries

Figure 3 shows that in 2012, the LCOE from solar PV was significantly higher than that of the two cheapest fossil fuel-based power plants: coal power plants and combined cycle gas turbine (CCGT) plants. However, by 2022, the LCOE of fossil fuel-based power generation was approximately 0.15 to 0.16 USD per kWh, which was more than twice the LCOE of solar PV.

The decline in the LCOE for solar PV and the rise in fossil fuel-based power generation costs from 2012 to 2022 can be attributed to several factors. Solar PV costs have significantly decreased due to advancements in manufacturing, improved efficiency, economies of scale, and policy support through subsidies and incentives. In contrast, fossil fuel prices have surged due to supply chain disruptions, geopolitical tensions, and inflation [4]. Stricter environmental regulations, carbon pricing, and rising operation and maintenance costs for coal and gas plants have further increased their LCOE. Additionally, advancements in solar technology, including more efficient panels and declining battery storage costs, have enhanced the competitiveness of renewables. As a result, solar PV has become a more cost-effective and sustainable energy source compared to fossil fuels.

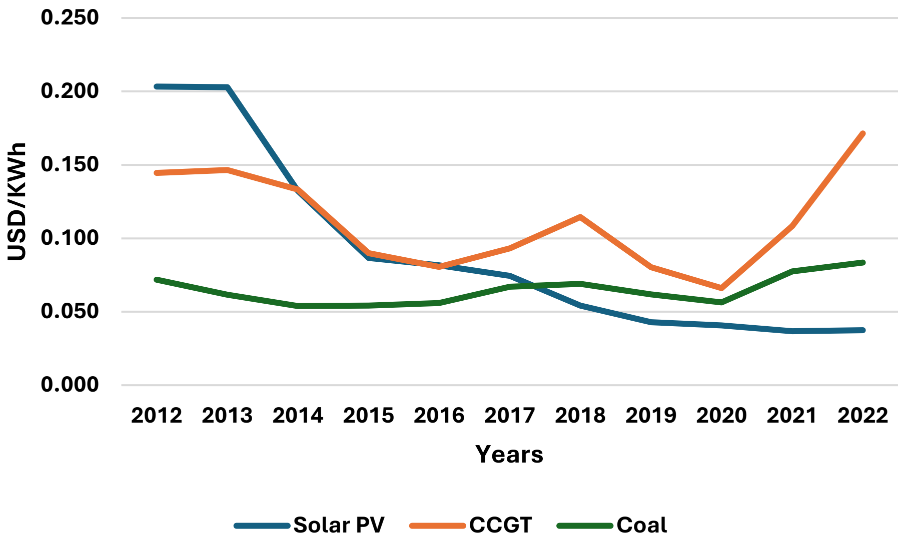

Figure 3. Declining LCOE of Solar PV vs. Rising Costs of Fossil Fuel Power

Table 2 shows the rapid increase in installed solar PV capacity from 2010 to 2022. In 2010, the capacity was around 40,277 MW, which increased steadily each year. By 2022, it reached 1,046,614 MW, demonstrating exponential growth in solar energy adoption. This result also highlights the decreasing trend in the installation cost of solar PV. In 2010, the installation cost was $5,124 per kWh, which continuously dropped each year. By 2022, the cost reached $876 per kWh, reflecting technological advancements and economies of scale. Besides, the data illustrates the decline in the LCOE, which measures the cost of electricity generation over a plant's lifetime. In 2010, LCOE was $0.445 per kWh, which significantly reduced to $0.049 per kWh by 2022. This indicates that solar energy has become increasingly cost-competitive compared to conventional energy sources.

Table 2. Trend of installed capacity, installation cost and LCOE for solar PV

Year	Existing Solar PV (MW)	Installation Cost (USD/KWh)	LCOE (USD/KWh)
2010	40277	5124	0.445
2011	72030	4392	0.332
2012	101511	3343	0.248
2013	135740	2935	0.191
2014	171519	2652	0.172
2015	217243	2016	0.129
2016	290961	1833	0.113
2017	383598	1586	0.089
2018	483078	1355	0.075
2019	585868	1120	0.066
2020	713918	983	0.059
2021	855162	917	0.051
2022	1046614	876	0.049

In the last 22 years, Solar PV has contributed to fuel cost savings of $27.16 billion, which accounts for 16% of the total savings from all renewable sources. This reduction is primarily due to the widespread adoption of solar PV, technological advancements, and decreasing costs of solar installations. As solar energy replaces fossil fuel-based electricity generation, it lowers dependency on expensive and volatile fuel markets, leading to substantial economic and environmental benefits.

4. Role of Policy and Market Forces

The declining cost of solar PV and its global expansion are driven by supportive policies and market dynamics. Government incentives like the Investment Tax Credit (ITC) in the U.S. [5], feed-in tariffs in Germany [6], and China's solar subsidies [7] have significantly boosted installations. Large-scale auctions in India and Brazil have driven competitive pricing [8], while economies of scale and technological advancements, such as bifacial solar panels and high-efficiency perovskite cells, have further reduced costs. Corporate commitments, like Google and Amazon's renewable energy targets, and carbon pricing in the EU Emissions Trading System, have also fuelled demand [9]. Microbial Fuel Cells (MFCs) can complement solar PV in the future by providing continuous power at night, enabling hybrid renewable energy systems, and offering sustainable energy storage solutions [10]. Together, these factors have made solar PV a cost-effective and rapidly growing energy source worldwide.

5. Insights for Governments, Private Investors, and Policymakers

The exponential growth and declining costs of solar PV present unprecedented opportunities for governments, investors, and policymakers, particularly in developing countries [10]. The following insights are grounded in the study's findings and offer actionable strategies to accelerate solar adoption and maximize economic and environmental benefits.

For Governments,

- Subsidies and Tax Incentives: Introduce phased subsidies (e.g., 20–30% upfront) paired with VAT exemptions to lower entry barriers for households and SMEs.
- Auction Mechanisms for Large-Scale Projects: Implement competitive bidding to attract private investment while ensuring cost transparency.
- Grid Modernization and Storage Integration: Developing nations often lack grid infrastructure to absorb variable solar power [11]. Pair solar projects with battery storage (e.g., Nigeria's 100 MW solar + 50 MWh storage project) to stabilize supply.

For Private Investors,

- Focus on High-Return Markets: Invest in off-grid solar for industries (e.g., textiles, agriculture) to replace costly diesel generators.
- Utilize Corporate Power Purchase Agreements: Partner with multinationals seeking Environmental, Social, and Governance (ESG) compliance to secure long-term revenue streams.
- Localized Manufacturing: Setting up panel assembly in low-labour-cost countries (e.g., Indonesia, Ethiopia, Bangladesh) can reduce CAPEX compared to imports.

For Policymakers,

- Simplified Permitting: Adopt India's "single-window clearance" model, which cut approval times to 30 days [12].
- Prioritize Rural Electrification: Use blended finance (public + donor funds) to deploy solar home systems.
- Carbon Pricing and Fossil Fuel Phase-Out: Carbon tax can be generated and reinvested in solar microgrids for remote communities.

6. Conclusions

This study underscores the remarkable transformation of solar photovoltaic (PV) technology into one of the most affordable and accessible energy sources globally. Key observations include an 83% reduction in CAPEX and an 89% decline in LCOE between 2010 and 2022, driven by technological advancements, economies of scale, and supportive policies. Solar PV's LCOE is now less than half the cost of fossil fuel-based power, reinforcing its economic viability.

The research successfully met its objectives by:

- Quantifying cost reductions and efficiency gains (e.g., capacity factors rise from 14% to 17%).
- Identifying market leaders, with China (43.16% of global capacity) and the U.S. (9.75%) dominating due to policy incentives and large-scale investments.
- Highlighting policy impacts, such as feed-in tariffs and auctions, which accelerated adoption.

The implications of the findings are far-reaching. Solar PV contributed $27.16 billion in fuel cost savings over 22 years. Expanding solar infrastructure fosters employment in manufacturing, installation, and maintenance. Solar PV's affordability supports universal energy access, particularly in developing nations, while also reducing carbon emissions, thus contributing to SDG 7 (Affordable and Clean Energy).

Limitations include reliance on secondary data (e.g., IRENA reports) and a focus on macro-level trends without detailed regional analyses. Future research could explore decentralized solar solutions for off-grid communities, integration challenges (e.g., grid stability, storage) in emerging markets, and the lifecycle environmental impacts of solar panel production and disposal.

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