Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 3, 2025

SOLAR PHOTOVOLTAIC TECHNOLOGIES AND APPLICATIONS: A CASE STUDY OF PAKISTAN

Nadir Mehran[1], Kifayat Ullah Khan[2], Muhammad Farhan[3]

[1]*MS Electrical Engineering, Department of Electrical Engineering, Abasyn University Peshawar.*
[2]*MS Electrical Engineering, Department of Electrical Engineering, Sarhad University of Science and Information Technology Peshawar.*
[3]*MS Civil Engineering, Department of Civil Engineering, CECOS university Peshawar.*

[1]*engrnadir23@gmail.com*, [2]*kifayat.suit@gmail.com*, [3]*engrfarhan23@gmail.com*

DOI:https://doi.org/

Keywords
Solar photovoltaic, renewable energy, Pakistan, energy policy, solar technology, sustainable development

Article History
Received on 20 January 2025
Accepted on 20 February 2025
Published on 27 February 2025

Corresponding Author: *

Abstract

This research paper analyzes the situation of the development of solar photovoltaic (PV) technologies and their usage, paying particular attention to the outstanding absorption of solar energy in Pakistan. It has become one of the world's fastest-growing solar markets, and solar additions contributing to about a third of the national total generating capacity were completed in 2024 alone. This paper examines the different PV technologies comprising monocrystalline, polycrystalline, and thin-film solar panels, as well as their efficiency qualities and how specific technologies can be used in the wind and solar energy sector in Pakistan. The article examines the factors that are causing the solar explosion in Pakistan: they include unreliable supplies of electricity, increasing energy prices, and government policy. This paper examines some PV technologies such as monocrystalline, polycrystalline, and thin-film solar panels, their efficient nature, and their particular application in the Pakistan energy sector. The paper discusses the factors that have fueled the solar boom in Pakistan, and they include an unstable electricity supply, an increase in the cost of electricity, and favorable government regulations. This work analyzes market data, policy guidelines, and technology applications in detail to give implications of how developing countries can adopt the use of solar PV technology to improve energy security issues. The results show that the solar market in Pakistan has been increasing since 2023 when it reached 2.9 GW of imports, 16 GW in 2024, and by 2024, it is recommended that the country becomes a global leader in solar energy consumption, as the case with Pakistan. The vast majority of solar is being added on the frontier of renewable installations; Pakistan is one of the fastest-growing solar markets in the world, with solar providing a share of about a third of the entire generating capacity added in 2024 alone. By conducting a detailed study of the market trends, policymaker regulations, and technological execution, this study gives a clear idea of how the Third World countries can use solar PV technology to meet energy security issues. The conclusion shows that the solar market of Pakistan increased during the year 2024 (16 GW of imports) in comparison to 2023 (2.9 GW of imports), making the country one of the global leaders in adopting solar energy

despite the issues with the economy.

INTRODUCTION

The process of switching the world to renewable energy sources has gained momentum in recent years, and the most prominent stage of this transformation is the use of solar photovoltaic (PV) technology (Nijsse et al., 2023). The photovoltaic effect exploited by solar PV directly produces electricity in response to sunlight emission and can provide clean, renewable, increasingly affordable electricity to meet our high energy needs. The drive toward renewable sources of energy can hardly be more timely as nations are dealing with the issues of climate change and energy contention, as well as the increase in electricity rates.

Pakistan has become one of the unforeseen leaders of solar implementation in the world of developing countries, proving that the energy crisis can become crucial in the implementation of renewable technologies very fast. Traditionally, the energy sector of Pakistan has experienced long-term power shortages, a lack of a stable grid, and an overreliance on foreign petroleum products. These issues have resulted in unusual situations on the market as distributed solar PV systems are not only a possible alternative but a necessity for many consumers and businesses.

The solar market in the country has grown in unimaginable dimensions, with installations coming at levels of those in developed countries despite the economic tightenings (Mehran, Khan, & Farhan, 2025). The emerging issue of solar power in the Pakistani context has been occasioned by several factors that also interconnect; these include policy decisions by the Pakistani government, the interest played by the private sector, and the declining cost of solar technology. This development is an excellent comparative study to the other developing countries aspiring to exploit renewable sources of energy.

General Solar PV Technology

Solar PV technology works on a basic but efficient idea. The direct sunlight passing through a photovoltaic cell excites electrons, producing an electric current (Bagher, Vahid, & Mohsen, 2015). This is effective, quiet, and does not emit any emissions during operation; hence, one of the cleanest sources of energy today is solar PV. There are various PV technology that forms part of these solar cells, namely the monocrystalline, polycrystalline, and thin-film solar cells, where each has its positive and negative aspects regarding efficiency, cost, and applicability.

Monocrystalline solar panels are the most efficient and have a long life span; therefore, they are ideal to use at home and for commercial purposes in places with limited spaces. The polycrystalline panels are achieved at a lower cost and slightly lower efficiency, which is the reason why they are commonly used in larger installations where cost is more of a factor. Thin film solar cells are less popular and present flexibility and lightness features, and thus, they can be creatively used in diverse settings.

The Energy Grandeur of Pakistan

The energy situation in Pakistan is represented by a combination of energy production methods with hydropower, thermal, and renewable energy generating sources (Shakeel, Takala, & Shakeel, 2016). The nation has been struggling with a lasting energy crisis as it has been experiencing energy shortages both in rural and urban settings. The given situation has been worsened by such factors as population growth, industrialization, and insufficient infrastructure that has caused regular blackouts and the necessity to rely on costly foreign fuels.

In this regard, the rise in solar energy has given hope in this regard. Solar installations have become very affordable within the last ten years of operations, making competing extremely affordable to consumers as well as businesses. Pakistan's government has been able to realize the potential of solar energy and has formulated a number of policies to encourage the use of solar energy. Examples of such are financial incentives, tax breaks, and net metering policies under which the consumers can sell back to the grid excess electricity.

Research Problem

Migration toward renewable energy is one of the global strategies in the bid to tackle climate change and energy security. Nonetheless, solar photovoltaic (PV) technologies have serious obstacles to their implementation in many developing countries such as Pakistan. Pakistan has become a pioneer in the usage of solar energy, and it is therefore important to look into the factors that are behind the trend. The purpose of this research is to determine the technical, economic, and policy-related considerations affecting the expansion of solar PV technologies in Pakistan and how these reasons can be used to create more renewable energy technologies in other identical situations.

Research Questions

1. What are the technical attributes of different solar photovoltaic technologies that are in the process of being used in Pakistan?
2. What are the reasons that led to a boom in solar PV in Pakistan?
3. What roles do the government policies and incentives play in adopting solar energy in Pakistan?

4. What are the problems that Pakistan experiences when trying to incorporate solar energy into the existing grid?
5. What can the experience of the adoption of solar in Pakistan teach other developing countries?

Delimitation

This paper shall revolve only around solar photovoltaic technologies and their uses within the framework of Pakistan. It will not deal with other renewable energy sources, including wind or hydropower. Future research will focus on the current trends in the solar market by taking into account the analysis of the development since 2010. The analysis in the study will also mainly focus on grid-tied and off-grid solar systems and not the other technologies in the energy or the energy sector as a whole, which are irrelevant to solar PV.

Importance of the study

This study is important because it presents valuable insights into the effective implementation of solar PV technologies in the context of developing countries. The analysis of the Saudi solar market dynamics can help policymakers, stakeholders of the industry, and researchers determine successful methods to deploy renewable energy solutions in Pakistan. The results can be used to answer some of the popular challenges of implementing solar energy, which so far include technological challenges, policy constraints, and market factors. Moreover, this research will promote the international discussion of renewable energy options in terms of how developing countries can use the problems in their regions as the catalyst of sustainable energy shifts. The research can act as a guideline to direct other countries that experience the same energy problems as Pakistan by sharing the success stories and what was learned.

2. Literature Review

2.1 Solar Photovoltaic Technology Overview

Work started on commercial solar PV technology in the 1950s when the Bell Laboratory discovered the first commercially viable silicon solar cell that had achieved efficiency rates of about 6% (Green, 2015). Further development of technology has further resulted in historic gains in efficiency since then, with current commercial solar cells that use silicon having efficiencies above 20% and those that are in the laboratory having a value that is greater than 26% of single-junction silicon cells (Contreras et al., 2023).

Studies have consistently indicated that the array of PV technology should be selected depending on many factors such as cost, efficiency needs, space, and environmental factors. Monocrystalline silicon panels are generally the most efficient, though at an expensive rate, but polycrystalline panels are the average combination of high efficiency and low cost (Fthenakis, 2025). Thin-film technologies, such as cadmium telluride (CdTe) and copper indium gallium-selenide (CIGS), are cheaper to manufacture and can perform well under some conditions but are not as efficient in general as crystalline silicon technologies.

2.2 Solar Energy generation in developing nations

Several reasons have motivated the absorption of solar energy in developing nations, among them being the need to access energy, economic growth, and sustainability. The International Renewable Energy Agency (IRENA, 2023) cited above that developing countries have experienced excellent growth in renewable energy capacity, with solar PV as the most significant contributor.

Some research works have documented the main reasons for the adoption of solar power in developing countries. Kumari, Singh, and Kumar (2022) pointed out that the idea behind solar deployment is mainly motivated by energy security issues, the falling cost of the technology, and favorable policy environments. This decentralized grid power, which can be beneficial in remote locations by enhancing access to electricity in developing countries of the world with poor grid infrastructure, makes solar PV technology especially in developing countries particularly viable because centralization in the transmission of electricity to the outposts is a significant challenge to the power generation system as a whole.

Studies involving renewable energy policies in the developing world have indicated that effective deployment of solar energy needs an amalgamation of regulatory-, monetary stimulus, and market-friendly policies to ensure proper deployment of solar energy. Ahmad and Satrovic (2023) cast light on the issue of establishing enabling environments to confront the obstacles to the adoption of renewable energy, like high costs in the implementation, insufficient financing methods, and low technical capacity.

2.3 Energy Sector Context of Pakistan

The energy sector in Pakistan has drawn so much research, both of the incessant troubles in the sector and the current events in the country. Fossil fuel has been the dominant source of energy in the country, with natural gas, oil, and coal generating most of the electricity (Jacob et al., 2023). Nevertheless, the industry has had to contend with a number of recurring problems characterized by imbalances between supply and demand, circular debt, and reliance on the importation of energy.

Mirza et al. (2009) focused on the potential of renewable energy in Pakistan. They found the potential of solar energy to be significant, with the possibility of 4-7 kWh/m (2) /day of solar energy in Pakistan. It is with this potential that the adoption of solar energy is low except

within the last few years because of the initial huge cost, inadequate supportive systems, and insufficient publicity.

Recent literature records the growth of the solar market in Pakistan. According to Shahzad et al. (2022), policy changes such as net metering policies and the availability of incentives for renewable sources also created an enabling environment for the adoption of solar. The paper emphasized the implications of the increasing electricity tariff and unreliable power supply, which has, in turn, increased the preferability of solar PV systems to residential and commercial customers.

2.4 International trends in the Solar market

The total number of installations of solar PV has grown exponentially across the world as of 2022 and reached more than 1,000 GW (IEA, 2023). This has led to a catastrophic fall in prices, with the prices of solar PV falling by about 90 percent in the last decade, from 2010 to 2022. The learning curve effect, economies of scale, and technological wave have made solar PV the cheapest source of electricity in most areas.

Through market analysis, it has been revealed that solar systems that deal with distributed solar systems, such as small-scale systems and rooftop systems, make up a large share of the deployment of solar around the world. This is especially the case in countries with expensive electricity and favorable policies toward distributed generation (Mirza & Qurat-ul-Ann, 2025).

Solar PV with energy storage has become one strategic trend, and the intermittency of solar energy is one of the factors to be solved. It has been demonstrated that solar PV and battery storage are compatible, and the resulting power can offer reliable, dispatchable renewable energy that competes well with conventional generation (Ullah et al., 2025).

3. Methodology

The study is conducted on a mixed-methods research design that will involve both a quantitative analysis of the market data and a qualitative approach to evaluate policy structures and the use of technology within the solar industry in Pakistan. The methodology aims to give an extensive picture of solar PV technologies and how they apply in the unique situation of Pakistan.

3.1 Data gathering

These data will be obtained through publications of official authorities and organizations of the industry, such as market analysis by established global companies such as the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and the Alternative Energy Development Board (AEDB) of Pakistan. The secondary data is collected through company illustrations, market intelligence services, technical reports, and acclaimed academic publications.

Analysis of the market data is concentrated on the installation capacity of solar, import, and electricity production data for 2020-2024. This period includes the most recent solar boom in Pakistan and well represents it with enough data points to analyze the trend. Import statistics by popularity are a revelation of the imports statistics by the customs authority in Pakistan, and industry bodies are rank revelations to the increase in the market and the technology being used.

Policy analysis will entail the exploration of regulatory systems such as the net metering policy, renewable energy targets, and fiscal incentives. Policy papers, government reports, and regulatory statements are studied in getting the enabling environment towards the development of solar.

3.2 Framework of Analysis

The study uses a multi-dimensional analytical model discussing technical, economic, and policy dimensions of implementing solar PV. Technical analysis entails a comparison of the various PV technologies in terms of efficiency, performance features, and the aptness to suit the climatic conditions in Pakistan.

Economic analysis will aim at cost trends, manner of financing, and market forces that have fuelled the implementation of solar in Pakistan. This involves analyzing tariff structures of electricity, the costs of solar systems, and the return on investments of various user categories.

Policy analysis assesses the success of policies and governmental programs in ensuring the adoption of solar energy. These are the evaluation of the net metering policies, renewable energy goals, and establishment of institutional mechanisms in favor of solar development.

3.3 Directed Case Study

To study the Pakistani solar industry at length, the case study methodology has been utilized, and the information can be applied to other developing nations that have the same energy issues as Pakistan. The use of the case study approach will enable a detailed examination of the complex relationship existing among technology, policy, and market forces that shaped the solar development in Pakistan.

Analysis of other countries that have witnessed rapid growth in the use of solar energy helps to give more context and find best practices and lessons that have been learned. Other countries that will be incorporated in the comparative analysis include India, Bangladesh, and Vietnam, as they are facing similar development problems and solar potential.

5. Case Study: Pakistan's Solar Revolution

5.1 Market Overview and Growth Trajectory

The solar Photovoltaic business in Pakistan has grown beyond expectation to be the mainstream energy solution

in only a few years, as compared to the previous niche technology. The market path shows the rate at which rapidly developing countries can be able to implement renewable energy technology in case the market conditions support policy and economic incentives.

The growth figures are outstanding on any measure. The rate of growth in Pakistan of solar module imports was over 450 percent, with the import going up from 2.9 GW in 2023 to an estimated 16 GW in 2024. This rate of growth is ranked among the highest-growing solar markets in the world, with an installation rate that is similar to other economies like Germany and India, which are much higher than Pakistan.

The localism of the Pakistan solar installation is one of its key distinctions compared to most markets. The solar boom in Pakistan has been primarily due to residential, commercial, and small-scale industrial installations compared to those countries where utility-scale installations prevail. The most significant majority of new capacity has been attributed to rooftop systems, ground-mounted systems in agricultural land, and solar pumping systems.

The market research shows that in 2024, the contribution of solar power to the total electricity of Pakistan was about 14.3 percent, almost twice the amount of China with 8.4 percent and much more than India with 7.4. Such a fast pace of adding solar power to the energy mix shows how quickly the technology can ramp both to meet the current market needs and due to enabling conditions.

The spatial distribution of solar is highly focused on Punjab and Sindh provinces with the most significant electricity demands and favorable solar potential. Installations, however, are expanding to other provinces, such as Khyber Pakhtunkhwa and Balochistan, in cases where awareness and the availability of financing options have improved.

Analysis of the imported data shows a favorable tendency for the use of monocrystalline technology, which comprises about 70 percent of the imported panels. This is a market demand because rooftop implementations are primarily conducted in urban settings where the market preference requires efficiency and optimization of space. The Chinese manufacturers control the supply chain, and manufacturers like JinkoSolar, Trina Solar, and Canadian Solar are the most prominent manufacturers that supply the Pakistani market.

5.2 Solar Adoption Drivers

In Pakistan, the recent trend in the adoption of solar technology has been a result of the convergence of factors that made the deployment of renewable energy very favorable in that country. By studying this set of drivers, it is possible to get some inspiration about what developing nations can do to speed up their renewable energy transition.

Concerns about the reliability of electricity supply have been one of the primary triggers of solar usage. The national grid of Pakistan faced constant system failures due to power cuts, power fluctuations, and the interruption of supply, which have adversely affected domestic well-being and business performance. Solar PV systems are a necessity for ensuring energy security by many consumers and not an alternative environmental option.

A special impetus to adopt solar has been the so-called load-shedding crisis under which power utilities engage in planned blackouts to control supply-demand misalignments. Even in the middle of the summer, in some regions, there are up to 12-18 hours of daily load shedding, and solar with battery backup is not only an appealing opportunity but a fairly imperative one to sustain a minimal level of living standards and commercial activity.

Electricity tariffs are on the increase, which has provided a high economic incentive for the adoption of solar energy. The electricity prices in Pakistan have by far risen in the last few years following declining terms on the currency, rising fuel prices, and financial issues in the utility sector. The tariff of electricity has increased by more than twice since the year 2020, which makes solar installation very exciting economically for all categories of consumers.

The introduction of the net metering policy has established an important regulatory environment that allows the use of solar power. With this policy, consumers are allowed to put back the excess solar electricity into the grid and get credits for their electricity bills. The policy has enabled the cost of solar systems to be affordable even with no battery storage, which is lowering the overall cost of the entire system to the consumers.

The reduction in the costs of a solar system has led to the introduction of technology to more consumers. The impact of the decline in international prices of the panels, the presence of a greater number of local players as system installers, and economies being achieved through bulk procurement have lowered the cost of a solar system by around 40-50 percent in the last three years.

Due to increased access to financing, banks and microfinance institutions have emerged together with solar financing companies that offer solar-specific loan products. The financing of solar power has been financed through competitive interest rates provided by financial institutions due to the refinancing schemes by the State Bank of Pakistan on renewable energy projects.

Government policies have been supportive, although inconsistent in terms of renewable energy development. A

supportive policy environment aids in the form of tax exemption on solar equipment imported, ease of approval procedures, and renewable energy targets.

The demonstration effect has been significant in the development of the markets. When the first adopters experienced successful outcomes in solar systems, the neighbors and business associates also took up the same trend, which has developed into a viral adoption pattern, especially in the commercial and industrial sectors.

5.3 Segmentation of market and usage

The solar market in Pakistan is highly segmented into residential, commercial, industrial, and agricultural settings that have different properties, demands, and growth accelerator characteristics. Such division indicates the versatility and applicability of the technology in various scenarios and conditions based on the economy.

The residential market constitutes the most significant part of the Pakistan solar market in terms of installations, although not in terms of capacity. Most residential systems are 3kW-10kW, with 5kW being the most common system size. Most of these systems are installed on urban and suburban rooftops, and the homeowner is driven by the desire to lower the cost of the electric bill and have power in excessive cases of power failures.

Utility-scale installations are also a minority in Pakistan's solar market, not because of technical or economic issues but because of policy and regulatory problems. Although several utility-scale development projects have been made through power purchase agreements, most of the solar infrastructure in Pakistan is composed of spread systems.

5.4 Technology Preferences and Market Dynamics

The market in Pakistan has its technology preferences, including functionality requirements, budget requirements, and the situation in domestic markets. The knowledge about these preferences gives insights into the pattern of technology adoption that arises in the developing market.

The monocrystalline technology is predominant in the Pakistani market, and it contributes about 70 percent to panel importation. This is due to various reasons, which are: it has higher efficiency, especially on rooftops where there are space-constraining factors, it improves performance in high temperatures, and it has reduced price premium over polycrystalline substitutes.

The efficiency superiority of the monocrystalline panels has a significant role in the case of Pakistan, where the rooftop area available is limited, and it is critical to ensure that maximum generation is done using each unit area. High-efficiency panels are cost-effective, particularly in urban centers where population density is high and there is not a lot of roof space to work with in Karachi, Lahore, and Islamabad, and tend to pay off in the long run.

The competitive environment incorporates a combination of foreign firms, domestic distributors, and system integrators. Chinese firms control the panel supply chain, whereas European and Japanese firms are represented more in inverter and balance of system components. The services to be offered by local companies are mainly on distribution, installation, and system integration.

6. Technical Analysis and Performance Evaluation

6.1 Characteristics of Performance in the Climate of Pakistan

Varying climatic conditions in Pakistan serve as an excellent natural laboratory to assess the performance of solar PV relative to different environmental parameters. The nation has a highly high fluctuation in its temperature, amount of humidity, and solar radiance, providing information on the functionality of various technologies in varying conditions.

Irradiance levels throughout the Pakistan region are quite adequate for solar PV applications, and the majority of the regions get 4.5-6.5 kWh /m 2 / day of global horizontal irradiance quantum. In Balochistan and southern Sindh, the coefficient of irradiance is high, and in the area of mountains to the north, the coefficient is low but sufficient. The resource potential of this solar is good when compared with top solar markets around the world.

The problem of temperature influence on solar panel work is especially topical in the context of Pakistan when the ambient temperatures are so high in summertime. The temperatures in most areas are usually above 40 0 C, and in some, it is up to 50 0 C. These factors have a significant effect on the performance of solar panels and their durability.

Monocrystalline panels perform better in terms of temperature than polycrystalline options, with average temperature coefficients of -0.35%/C in comparison with -0.40%/C in polycrystalline panels. In high-temperature conditions of Pakistan, this difference can lead to a 2-4 percent increase in the generation of energy in peak summer months with monocrystalline panels.

6.2 Design considerations of the systems.

Pakistan Solar PV system design should take into consideration the local conditions, performance requirements as well as economics of the design. Design optimization is a balance of various factors such as energy production, cost of the system, system reliability, and maintenance needs.

The choice of the mounting system makes a considerable contribution to performance and cost. The most common type of PV mounting system on rooftops is fixed-tilt (also known as stationary mounting), with maximum tilting angles of 24-30 o depending on the latitude. Single-axis tracking can be used on ground-mounted systems to raise

energy production, but the extra complexity and cost ought to be called out by more energy production.

The sizing and selection of inverters need to be analyzed, taking into consideration the load patterns and requirements of the grids. The inverter-to-panel ratios of grid-tied systems are usually 0.8-0.9 in order to balance cost and reasonably good performance. Hybrid systems that need the use of battery backup have lower ratios to provide sufficient charging capability when the irradiance is low.

Design of battery storage systems requires compromises among cost, performance, and reliability. The increased preference for lithium-ion batteries is seen by superior efficiency, lifespan, and other characteristics despite higher first-purchase prices. System sizing very often offers 4-8 hours of backup power to critical loads, giving compromises between cost and effectiveness.

7. Economic Analysis

7.1 Economics and Economic Viability

In Pakistan, the economics of solar PV systems has developed beyond all recognition in the last five years due to the fall in technology prices, increasing electricity rates, and favorable financing products. The nature of cost structure and financial returns can be used to understand the fast market adoption and garner some insights that may be used in future development.

The cost of solar systems in Pakistan has been reduced by around 40-50 percent over the last two years, where the average residential system (5kW) can be installed at 3000-4000 USD. Commercial systems (50kW) have an economy of scale at a cost of a kW installed of 2,500-3,500 dollars. Such prices are competitive with those in the international markets and are indicative of competitive procurement, local installation capacity as well as attractive exchange rates on equipment imports.

The cost composition has a number of components whose ratios to each other are subject to different proportions based on the size and design of the system. The solar panels and the inverters average 4050 and 1520 of the overall system costs, respectively; mounting structures and electrical devices use 2025, and installing labor consumes 1015. With battery storage added, the total system cost may increase by 30-50 percent due to battery capacity.

7.2 Comparative Energy Economics Alternate Energy

The solar PV economics in Pakistan should be compared to all the alternatives, such as grid power, diesel gensets, and UPS batteries with batteries. This discussion shows the underlying reasons why solar has become economically viable in various market segments.

The cost of the grid electricity differs considerably among consumer types and consumption brackets, where the residential tariffs go at least between 0.05-0.15/kWh, and the commercial/industrial tariffs go up to 0.12-0.20/kWh. These tariffs have been inflated tremendously in the past few years by the factor of devaluation and increment in fuels, as well as fiscal deficits in the utility sectors.

The cost of diesel generators comprises fuel cost and maintenance cost that leads to a price range of electricity between 0.20-0.30/kWh based on the price of fuel and the efficiency of the generator. Solar with battery storage is usually a more cost-effective backup power for businesses and households that use generators when the power goes out.

8. Barriers and Obstacles

8.1 The technical difficulties

Although impressive growth has been recorded, the solar industry in Pakistan still has a lot of technical issues to work out to guarantee its sustainable evolution and the best system outputs. These issues cut across the system design, integration into the grid, maintenance, and quality assurance.

Grid integration is one of the most complicated technical issues when it comes to increased penetration of distributed solar. The Pakistan distribution systems were engineered with a one-way power flow of centralized generation, and large amounts of distributed generation will pose problems with the regulation of voltage, power quality, and protection issues.

Issues associated with voltage regulation arise when solar generation results in the voltage levels going beyond accepted levels, specifically in high generation and low load times. The Great grid infrastructure weakness in most regions adds to this problem and may lead to an inverter disconnection or electrical equipment damage.

8.2 Regulatory and Policy Challenges

There have been uncertainties and obstacles set by policy and regulatory challenges, which restrain the maximum possible development of the solar sector. These issues need the cooperation of both federal and provincial governments, regulatory authorities, and players in the market itself.

Consistency and predictability of policies continue to be an issue because renewable energy policies have changed quickly and, at times, irregularly across various jurisdictions. Uncertainty among investors and consumers is brought about by the changes in import duty regulatory frameworks, net metering regulation, and approval processes.

There are restrictions on regulatory capabilities to exercise adequate solar installation and market player control. In its case, it is thousands of small installations with hundreds of companies competing in the market, and providing them all with the appropriate provision of compliance with the requirements of safety, quality, and

procedures of grid interconnection consumes a lot of regulatory resources.

Procedures and standards among companies in the distribution of grids are differentiated, making the process to be installed by the system installer and consumers complex. These procedures would be standardized and implemented uniformly, which would suppress the cost of transactions and enhance efficiency in the market.

8.3 Barriers based on economy and finances

Although this gives favorable economics to a lot of the applications, there are still first-order economic and financial obstacles to solar usage that restrict the area applications and segments.

Finance is a problem as small consumers and businesses and people in rural areas cannot manage to access finance. The number of available financing options has grown, though the overall means of offering the financing still is a detriment to many would-be consumers, such as collateral restrictions, and owing to the stringent procedure, some would-be consumers cannot gain access to a financial institution.

The fact that it has very high upfront costs remains a barrier despite the fact that systems are getting cheaper. In spite of the availability of financing, the initial cost of making solar installations can be too high to qualify for low-income households and small businesses that operate on minimal capital.

Because it requires foreign equipment, solar installations are affected by currency risk in economics. Fluctuation of the exchange rate may have profound effects on the system cost and economics of the projects and pose a threat to both the consumers and the financing institutions.

8.4 Environmental and Social Causes

With the boom in the Pakistani solar industry, there are social and environmental issues that must be taken into consideration to provide a non-exploitative and economically viable way of growth.

The general effect of solar deployment on the environment is good, and it entails aspects surrounding land use, waste management, and manufacturing procedures. Big installations demand much land space that can conflict with agricultural or natural habitat applications.

Solar panels and batteries are new sources of end-of-life management as the first installations turn into retirement. Pakistan does not have integrated systems of recycling solar gears, and they need to be developed.

9. Prospects and Recommendations in the Future

9.1 Projections on Market Growth

Pakistan: The solar market in Pakistan is currently poised to experience healthy growth in the next ten years, sustained by a steady economic incentive, enhancement of technology, and an increase in applications. Market projections show that installed capacity maybe 25-30 GW in 2030, which is a considerable share of Pakistan's total electricity generation capacity.

The residential sector should see robust growth since costs are still reducing in the systems, and more funding avenues are being opened up. By 2030, rooftop solar installation is projected to reach between 5-8 million or 15-25 percent of households in Pakistan. This expansion will be facilitated by an increase in urbanization, electricity tariff increase, and enhancement in consumer awareness.

The most significant growth opportunity lies in the commercial and industrial segments that provide favorable economics and wide addressable markets. The manufacturing, commercial, and agricultural fields may lead to the cumulative installations of 15-20GW in the next 10 years.

The process of utility-scale installations should be gaining momentum as policy frameworks undergo maturity and grid integration capacity increases. Sun power made use of possible 5-10 GW large-scale projects, especially in provinces where there are large areas of land and great solar irradiance.

The significance of energy storage integration will also be on the rise with escalating penetration levels of solar and a steady decrease in the costs of batteries. Solar-storage systems have the potential to make up 30-50 percent of new installations by 2030, delivering grid services and greater reliability.

The market expansion in regions other than Sindh and Punjab province will diversify the market and utilize unused solar resources. In Balochistan and Khyber Pakhtunkhwa, the potential for distributed and utility-level installations is large.

9.2 Trends in technology development

The technology of solar developments is evolving very fast, and a few trends have been identified that are likely to affect the Pakistani market in the upcoming years. These trends allow for future opportunities and challenges.

The efficiency of panels will be increased further, where commercial silicon panels achieve 25-27 % efficiency by 2030. The more efficient panels will be handy in the space-starved urban markets of Pakistan and justify higher prices of superior-performing products.

Digital technologies such as artificial intelligence, IoT sensors, and predictive analytics will streamline the performance of the systems, minimize maintenance expenses, and enhance grid integration. These technologies will be a common requirement of solar installations.

9.3 Policy recommendations

The existence of favorable policies is essential for the sustainable development of the solar sector in Pakistan; the policies should facilitate existing challenges and support its further development. Some important policy suggestions are:

Creation of comprehensive-renewable-energy legislative developments that offer long-term policy certainty and coordinate federal and provincial efforts. This law must put in place specific milestones, institutional roles, and support systems for renewable energy development.

Building up grid infrastructure and preparing to allow large distributed generation. This involves upgrading distribution networks, installation of smart grid technologies as well as coming up with grid codes that can allow the adoption of renewable energy.

Inspecting quality standards and certificate schemes that guarantee the reliability of the system and consumer protection. Such programs must contain installer certification, equipment requirements, and performance monitoring.

Designing special support packages for underserved areas of the market, such as rural demeanor, low-wage individuals, and small-scale businesses. These plans may entail subsidies, concessional financing, and technical help.

Building domestic production capacity by adopting industrial policies that encourage technology transfer, skills, competence development, and addition of values. This would lessen the reliance on imports and even provide jobs.

Introduction of end-to-end options of planning and forecasting that predict future patterns in solar deployment and allow it to develop infrastructure and policy in advance.

10. Conclusion

One of the most outstanding renewable energy revolutions in recent history is that of Pakistan and solar photovoltaics. The experience of the country, which transformed into one of the fastest-growing solar markets in the world in a short period after making minimal gains in the field of solar generation, shows how developing countries may step up the renewable energy application rates rapidly when the favorable combination of the market background and policies could prompt economic benefits.

Technical analysis indicates that solar PV technology is very effective in the climate of Pakistan as it is in Pakistan; the monocrystalline silicon solar panels are of great timing; therefore, they are very appropriate to the high-temperature climatic setting of the country, the narrow places of the cities. Its versatility and adaptability have been demonstrated by the variety of applications, which flow water downstream to power residential rooftop systems, drive agricultural pumping plants, rotate overhead snuff mills, etc., each using suitable and economical equipment.

The case of Pakistan can serve as a source of lessons to other developing nations with given issues regarding energy problems. The identified key success factors are the following ones: the awareness of renewable energy as the solution to energy security issues, the establishment of supportive regulatory frameworks, including net metering, the establishment of relevant financing schemes, and the establishment of competitive markets leading to cost reduction and quality upgrading introduced.

Its economic contribution has been tremendous, and the number of jobs created after its introduction, as well as the development of industries and cost savings by consumers. The solar industry has created more than 100,000 direct and indirect employments and lowered energy prices for millions of houses and companies. The net foreign exchange effects are mixed, although, on the whole, favorable given the avoided importation of fuels and increase in energy security.

Nevertheless, there exist outstanding issues that are yet to be addressed to cause sustainable development. Technical issues such as grid connection, maintenance, and quality assurance should remain under the spotlight. The enforcement and policies also need to be reinforced to create certainty in the market in the long term and effective regulation. Economic access also remains a barrier to some sections of the market, especially the rural and low-income groups.

The prospects of the solar industry in Pakistan are very bright, and the industry is estimated to be growing strongly in all market segments. Advancements in technology, such as more energy-efficient panels, falling prices of batteries, and smart grid integration, will enhance the economics and efficiency of solar installation even further. This potential will be important to realize policy support, development of infrastructure, and capacity building.

The Pakistani case of the solar revolution reveals that developing nations should not wait to achieve the best conditions before starting to implement renewable energy. Instead, energy crises may be turned into agents of a swift transition towards renewable energy with the usage of corresponding policy instruments and market-based regulations. Meanwhile, the example of the country is a roadmap that other nations should follow in cutting their renewable energy transitions fast.

Its lessons are not confined within the boundaries of Pakistan and can be helpful to those working on the issue of climate change and sustainable development abroad. The fast growth of solar technology in the atmosphere of developing countries demonstrates that renewable energy

solutions might be not only economically interesting but also technically possible, even in harsh conditions.

Also, as renewable energy is practiced in Pakistan, the experience and the best practices thereof will still enlighten the whole world with the implementation of renewable energy. The solar revolution of the country is not only a national success but also a contribution in terms of sustainable development of the whole world and curbing climate change.

References

Ahmad, M., & Satrovic, E. (2023). Modeling combined role of renewable electricity output, environmental regulations, and coal consumption in ecological sustainability. *Ecological Informatics*, *75*, 102121.

Bagher, A. M., Vahid, M. M. A., & Mohsen, M. (2015). Types of solar cells and application. *American Journal of optics and Photonics*, *3*(5), 94-113.

Contreras, M. V., Li, J., Kim, M., & Green, M. A. (2023). Solar photovoltaic technologies for mitigating global climate change. In *Handbook on Climate Change and Technology* (pp. 58-81). Edward Elgar Publishing.

Fthenakis, V. M. (2025). Status and outlook of solar photovoltaics. *Energy and Climate Change*, 225-249.

Green, M. A. (2015). Forty years of photovoltaic research at UNSW. In *Journal and Proceedings of the Royal Society of New South Wales* (Vol. 148, No. 455/456, pp. 2-14).

Jacob, R., Hoffmann, M., Weinand, J. M., Linßen, J., Stolten, D., & Müller, M. (2023). The future role of thermal energy storage in 100% renewable electricity systems. *Renewable and Sustainable Energy Transition*, *4*, 100059.

Kumari, N., Singh, S. K., & Kumar, S. (2022). A comparative study of different materials used for solar photovoltaics technology. *Materials Today: Proceedings*, *66*, 3522-3528.

Mehran, N., Khan, K. U., & Farhan, M. (2025). SOLAR PHOTOVOLTAIC TECHNOLOGIES AND APPLICATIONS: A CASE STUDY OF PAKISTAN. *Spectrum of Engineering Sciences*, *3*(7), 232-241.

Mirza, F. M., & Qurat-ul-Ann, A. R. (2025). Bibliometric Assessment of Energy Research in Pakistan: Mapping of Past and Prospects for the Future. In *Geopolitical Landscapes of Renewable Energy and Urban Growth* (pp. 125-184). IGI Global Scientific Publishing.

Nijsse, F. J., Mercure, J. F., Ameli, N., Larosa, F., Kothari, S., Rickman, J., ... & Pollitt, H. (2023). The momentum of the solar energy transition. *Nature Communications*, *14*(1), 6542.

Shakeel, S. R., Takala, J., & Shakeel, W. (2016). Renewable energy sources in power generation in Pakistan. *Renewable and Sustainable Energy Reviews*, *64*, 421-434.

Ullah, H., Diao, X., Shahzad, U., & Iqbal, F. (2025). Nexus between green innovation, policy stability, and environmental sustainability on sustainable economic growth: the case of China. *Clean Technologies and Environmental Policy*, 1-22.