ENERGY AND CLIMATE
PANORAMA

Indigenous Manufacturing of Solar PV Modules in Pakistan

Policy Gaps, Barriers and Way Forward

About Us

Who we are

We are a dedicated team of researchers and experts who recognize the urgent need for action in addressing climate resilience and energy transition in Pakistan. Our mission is to develop and implement effective policies for cleaner, renewable energy sources like solar and wind, aligning with Pakistan's 2030 goal of 30% renewable energy in its electricity mix. As a multidisciplinary team, we leverage expertise in three key disciplines of study—Energy Systems Engineering, Thermal Energy Engineering, and Electrical Power Engineering—to drive our mission forward. We are united by a shared vision of creating a sustainable and resilient future for Pakistan, where cleaner energy sources play a pivotal role in reducing the nation's vulnerability to climate-related challenges.

What we do

We conduct in-depth, evidence-based research to analyze and improve energy policies in Pakistan. Our focus is on advancing renewable energy solutions and engaging stakeholders to ensure effective policy implementation. Our methodology involves a critical examination of current energy policies to pinpoint areas of improvement and formulate strategies for the widespread adoption of renewable energy sources across various levels.

In line with our commitment to fostering sustainable practices, we have established a fellowship program as part of our broader initiatives that aims to facilitate evidence-based research for promoting energy transition in Pakistan. Through research studies, surveys, and forecasting, we plan to assess various aspects of energy transition, including the adoption of renewable energy technologies and their impact on climate change. Our approach involves active engagement with stakeholders to address their concerns and facilitate the effective implementation of policies, fostering the growth of renewable energy manufacturing and marketing facilities.

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1. Introduction

1.1 Background and Rational of the Report

Pakistan, a country renowned for its various terrain and ample solar irradiance, possesses a distinct advantage in leveraging the revolutionary potential of solar energy. The country has a significant potential for the usage of solar energy due to its yearly average of over 300 bright days. However, while this inherent advantage, the solar energy industry in Pakistan continues to be predominantly undeveloped, with a substantial proportion of solar photovoltaic (PV) modules procured from foreign sources. The dependence on imported goods not only imposes a strain on the country's foreign currency reserves but also signifies a lost prospect in relation to domestic employment generation, technical progress, and the development of a robust and independent energy infrastructure.

The transition on a worldwide scale towards renewable and sustainable energy sources is not only a crucial environmental necessity but also holds significant economic implications. Nations that allocate resources towards the advancement of their domestic renewable energy sectors are poised to reap substantial advantages in terms of enduring energy stability, diminished carbon footprints, and the emergence of novel economic prospects. The development of domestic solar panel production in Pakistan has the potential to play a pivotal role in establishing a sustainable energy landscape, offering significant advantages in the short and long term.

Pakistan may accomplish several goals by promoting the development of a domestic solar PV manufacturing sector. These aims include diminishing reliance on fossil fuels, mitigating carbon emissions, generating employment opportunities in the renewable energy field, and fostering technological advancements. Additionally, by implementing an appropriate legislative framework and providing incentives, the nation has the potential to attract both local and foreign investments, thereby enhancing its economic growth.

In current scenario, there emerges a need to comprehensively review the existing solar PV policies, current status of Solar PV Module Manufacturing in Pakistan, identifying technological, financial, policy & regulatory barriers to indigenous manufacturing, evaluating skill and capacity constraints and hence proposing policy measures for overcoming these identified barriers and constraints.

1.2 Importance and Relevance of Solar Energy for Pakistan

- **Cost**

Solar energy holds significant potential for cost-effective power generation in

Pakistan. While the initial setup costs may be relatively higher, the long-term benefits include reduced dependence on imported fossil fuels and a potential for grid parity as technology advances. The solar policy should aim to create conditions for driving down costs and achieving grid parity over time. Indigenous manufacturing of PV modules starting would support the long-term plans of the country.

- **Scalability**

Pakistan has abundant solar energy resources, with its geographical location ensuring substantial sunlight throughout the year. This makes both solar thermal and solar photovoltaic technologies viable for large-scale implementation. The policy recognizes the scalability of solar energy, particularly in meeting rural electrification needs and supporting decentralized off-grid applications.

- **Environmental Impact**

Solar energy aligns with Pakistan's commitment to environmental sustainability. By generating electricity with zero emissions, solar power can significantly reduce the country's carbon footprint and mitigate the adverse effects of traditional fossil fuel-based power generation. The solar policy underscores the environmental benefits of transitioning to cleaner energy sources.

- **Security of Source**

Solar energy offers a secure and locally available source of power for Pakistan. The country's solar potential provides an opportunity to diversify its energy mix, reducing reliance on imported fuels and enhancing energy security. As Pakistan aims to meet its energy demand and reduce vulnerability to international energy market fluctuations, solar energy emerges as a reliable domestic resource.

The solar policy recognizes the imperative of harnessing solar energy's potential to address Pakistan's energy challenges, promote sustainable development, and ensure a resilient energy future.

1.3 Objective of the Report

The objective of this report is to present a comprehensive plan for the advancement and growth of indigenous solar panel manufacturing in Pakistan. By implementing a range of strategic initiatives, regulatory frameworks, and financial incentives, the main objective is to facilitate solar industry in harnessing its solar energy potential and establishing itself as a significant participant in the international renewable energy sector. The report also summarizes the way forward for PV module manufacturing, where indigenization should come in phases; starting from assembling of PV modules and bringing in the complete manufacturing chain at a later stage to split the gross investment cost required for complete industry establishment.

2. Reviewing Solar PV Policy of Pakistan

2.1 Renewable Energy Policy of 2006

The Renewable Energy Policy of 2006 was a significant step towards promoting renewable energy sources such as wind, solar, and small hydropower in Pakistan [1]. It primarily focuses on the policy goals, objectives, and incentives for promoting renewable energy projects, including independent power projects (IPPs), captive power projects, and grid-connected projects using renewable resources. The policy recognized the variability of renewable resources and allocated associated risks between IPPs and power purchasers. It also outlined fee structures, licensing requirements, and other regulatory aspects to facilitate renewable energy development.

2.2 National Power Policy 2013

The National Power Policy of 2013 outlined the government's vision for the power sector, including renewable energy [2]. The policy provides incentives and mechanisms like feed-in tariffs, tax exemptions, and competitive bidding processes, which were designed to stimulate renewable energy project development. The policy also addressed issues related to the energy sector's governance, efficiency, and financial sustainability. While the National Power Policy of 2013 highlights the potential for renewable energy projects to generate employment and stimulate local economic development, it did not specify measures for PV manufacturing. The policy concentrated on energy security, sustainability, and affordability but did not elaborate on supply chain localization for PV products.

2.3 Renewable Energy Policy of 2019

The Renewable Energy Policy of 2019 built upon the earlier policies, primarily focuses on the procurement and development of renewable energy projects, including various technologies such as solar (PV and thermal), wind, biomass, and others [3]. It set ambitious targets for renewable energy capacity, including a substantial increase in solar and wind power generation. The policy emphasized net metering for distributed generation, enabling consumers to install small-scale renewable systems and feed excess electricity into the grid. Additionally, it introduced competitive bidding to drive down tariffs and attract cost-effective renewable energy projects.

The Renewable Energy Policy of 2006 laid the groundwork, while the Renewable Energy Policy of 2019 aimed to expand renewable capacity with ambitious targets and innovative approaches like net metering and competitive bidding. National Energy Policy of 2013 aimed to provide a comprehensive framework for Pakistan's overall energy sector addressing energy security, diversification of energy sources, efficiency and conservation, infrastructure development, sustainability and energy access. However, till date no policy has discussed the manufacturing of PV cells or modules which is typically a separate aspect of renewable energy development and often requires its own set of policies and incentives to encourage domestic production.

To promote indigenous PV manufacturing, future policies may need to explicitly include strategies and incentives to encourage local production, such as research and development support, tax incentives, or tariff structures that favor domestic manufacturers.

3. Approach and Methodology

3.1 Literature Review

A methodical strategy was employed in the development of a comprehensive solar policy. The research commenced with a comprehensive analysis of the literature, utilizing internet sources to acquire knowledge on current solar energy policies, legislation, and exemplary approaches. This review provided the basis for the development of questionnaires.

3.2 Questionnaire Development and Distribution

To collect primary data, a meticulously designed structured questionnaire was employed. The involvement of subject matter experts in the collaboration process meant that the questionnaire was designed to be both pertinent and comprehensive. This was achieved by adding a well-balanced combination of closed-ended and open-ended questions, which effectively captured both quantitative and qualitative insights.

- **Online Distribution**

The technique of collecting data was characterized by multiple facets in order to guarantee a sample that is both diverse and representative. Various online distribution strategies, such as the utilization of email surveys and web-based forms, were implemented in order to effectively engage a wide-ranging demographic.

- **Hard Copies Distribution**

Concurrently, physical copies of the questionnaire were disseminated among certain individuals and organizations, to stimulate the data collection process.

- **Targeted Outreach and Interview sessions**

Furthermore, pertinent actors within the solar energy industry were identified and contacted for face-to-face interviews, facilitating comprehensive conversations and qualitative data acquisition.

- **Time Frame for Data Collection**

To uphold consistency and protect the integrity of the study, a designated period for data collection was established, accompanied by rigorous protocols to safeguard the anonymity and confidentiality of participants. This facilitated the elicitation of sincere and truthful answers.

3.3 Data Analysis and Validation

Following this, a dual-pronged methodology for data analysis was implemented. The quantitative data underwent statistical analysis utilizing specialist software. Charts and graphs were utilized as visual aids to facilitate the interpretation of data. The qualitative data, which was collected through open-ended replies, was subjected to thematic analysis in order to discover recurring themes. To support the qualitative findings, pertinent quotations were utilized.

The approach was significantly influenced by the inclusion of data validation, which involved the careful examination and comparison of both quantitative and qualitative findings to guarantee internal consistency. The interpretation of results was validated by the utilization of peer review and expert consultations.

3.4 Providing Policy Recommendations

The research endeavor reached its apex with the formulation of a collection of policy suggestions that were grounded in thorough knowledge and understanding. The prioritization of these recommendations was determined by examining their potential impact and feasibility, as well as their alignment with best practices and current policies, all of which were informed by the synthesis of survey and interview findings.

3.5 Ethical Considerations

Ethical principles were consistently maintained throughout the duration of the study. The researchers acquired consent from the participants, ensuring their awareness of the study's purpose and protecting their privacy. Robust data security protocols were implemented, ensuring the protection of sensitive information. Additionally, individuals were given the option to voluntarily participate in the study. The study was carried out in a manner that maintained impartiality, adhering to ethical principles. These standards prioritize the values of respect for individuals, beneficence, and justice.

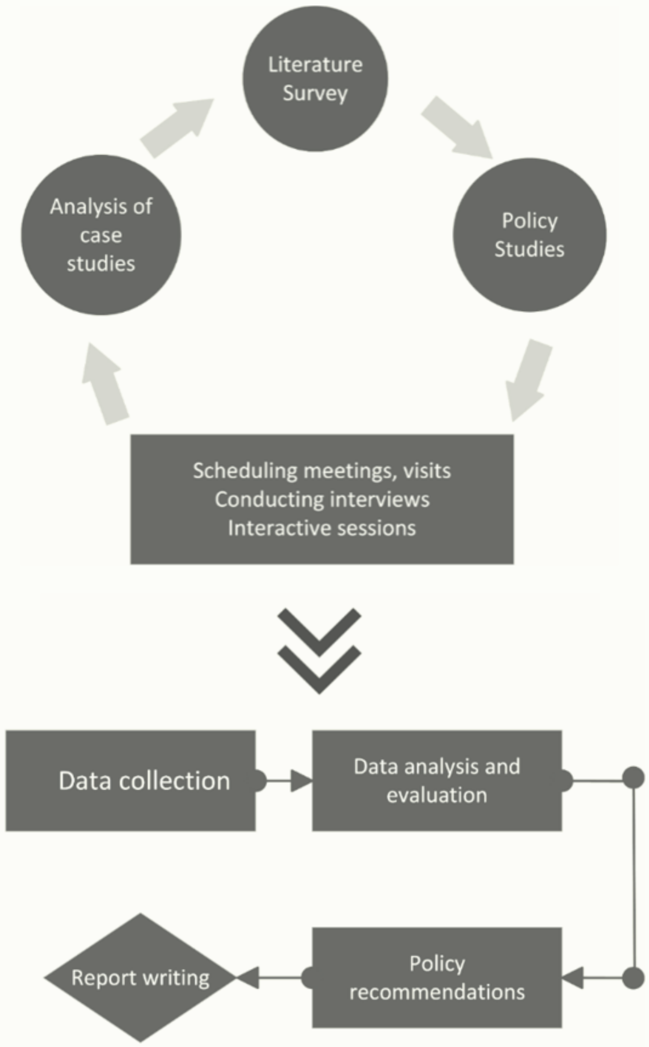

Figure 1: *Layout of the Report Methodology*

4. Solar PV Module Manufacturing in Pakistan: Current Status, Barriers, and Measures

4.1 Overview of PV Module Technologies

A solar PV module is a device that converts the incoming light energy from the sun into electrical energy, through a process known as the Photovoltaic Effect. The solar cells are made up of semi-conducting materials such as Silicon. Traditionally Silicon was the first and most widely used semi conducting material for the solar cell fabrication. However, with the ongoing research and development, various new semi conducting materials have been developed using different types of fabrication methods in addition to Silicon giving rise to the different generation of Photovoltaic technologies. Therefore, solar PV cells are categorized majorly into three generations depending upon their technology.

- **1st Generation**

Mono-crystalline solar cells and poly-crystalline solar cells (as shown in Figure 2) are categorized as 1st generation PV. This technology is most commercially used due to its higher efficiency. This generation has achieved maximum efficiency of 24.7% in the lab and 22.7% when tested in the form of a module.

1st generation solar cells are produced on wafers and if the whole wafer is only one crystal, it is called mono-crystalline solar cell. And if the wafer consists of very little impurities or crystal grains, it is called poly-crystalline solar cell. These two types of solar cells are also shown in the figure. Although, mono-crystalline solar cells have higher efficiencies compared to poly-crystalline solar cells, the latter is more commonly used in various applications because of its easier production and lesser cost.

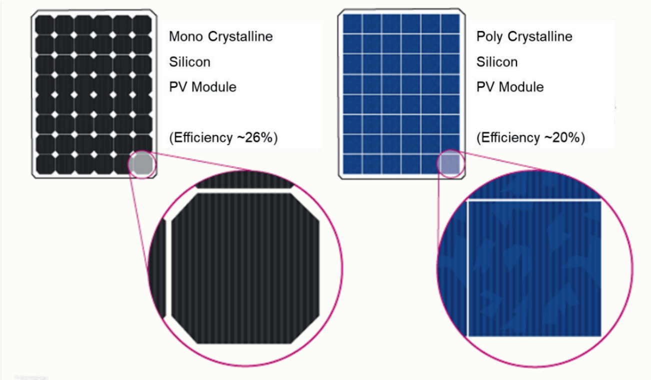

Figure 2: *Monocrystalline and Polycrystalline Solar PV Modules*

- **2nd Generation**

Amorphous silicon solar cells, Copper Indium Gallium Selenide (CIGS) solar cells, Cadmium Sulphide (CdS) solar cells, and Cadmium Telluride (CdTe) solar cells are categorized as 2nd generation PV. They are less efficient than other generations of solar cells, but they are comparatively cheaper to manufacture. This generation has achieved maximum efficiency of about 23% for the lab scale [4]and 18% when tested in the form of a module [5].

Third-Generation technologies are not proven yet commercially but are promising and novel. These include polymer based solar cells, Dye sensitized solar cells, Perovskite solar cells, Organic solar cells and Nanocrystal based solar cells. Among all the most developed ones are Dye-sensitized solar cells, Perovskite solar cells, Organic solar cells and Tandem Solar Cells. The Dye-sensitized cell technology has achieved beyond 15% efficiency [6] and the organic solar cells are credited with a maximum recorded efficiency of 18.07% inside the lab [7] and still improvements are being made. Another promising technology is Perovskite solar cells that has emerged within a decade's time to achieve efficiency beyond 26% in single junction structure [8] and comparable to Monocrystalline Silicon solar cells. Whereas Perovskite solar cells has recorded an efficiency of 33 % when fabricated in a tandem structure [9]. This technology has potential to be commercialized soon in near future.

Having higher cost of the manufacturing for the first generation in addition to issues of toxicity and material availability for the second generation, the third generation of solar PV modules is getting attention of solar PV researchers and industrial community.

4.2 Current State of PV Module Manufacturing in Pakistan

The most developed and mature technology among all types of PV modules are the ones based on Crystalline Silicon The process of manufacturing crystalline silicon solar modules involves four stages:

1. Making Solar Grade Silicon, a highly pure form of elemental silicon starting from raw material like Quartz.
2. Converting Silicon Crystals into Mono/Poly crystalline Silicon wafers.
3. Processing wafers into solar cells.
4. Assembling solar cells into modules.

Currently, Pakistan has no manufacturing capacity for the first three stages. Pakistan is, therefore, heavily reliant on solar PV imports. While new policy measures will increase this share, the volume of imports are also expected to rise further up the supply chain. The current situation of manufacturing presents multiple challenges, as discussed below:

- First, due to significant import reliance, Pakistan is highly exposed to supply chain shocks. These can become a bottleneck for Pakistan's solar deployment targets as the global demand for solar products scales up. For instance, the years 2022 and 2023 saw significant disruption across the solar supply chain, delaying deliveries and raising prices.
- Second, without a robust technology ecosystem, manufacturers must rely on technology developed in other nations.
- Third, Pakistan is missing out on significant opportunities for job creation. It is estimated that 10 GW of fully integrated solar manufacturing capacity (Mono/Polysilicon to modules) can create 10,500 jobs in plant operations alone [10]. Further jobs will be created in ancillary requirements and bill of materials manufacturing.

- **Overview of existing manufacturing units**

There are few PV module assembling units in the country, where the installed capacities are limited and the assembled PV modules are facing issues in supply chain management. A list of PV modules assembling units is given in the Table 1 below, including the active links of the company profiles.

Table 1: *List of PV module production industries including type and quality of locally produced modules.*

Name	PV products	Power Range (W_p)	Link
Akhtar Solar	Monocrystalline, Polycrystalline	5-320	https://www.facebook.com/akhtersolarlimited/
Comtec Energy	Monocrystalline, Polycrystalline	60-270	https://comtec-energy.com/
PV Silicon Technologies	Monocrystalline, Polycrystalline	5-325	https://www.enfsolar.com/pvst
Shaan Technologies	Monocrystalline	5-100	http://www.shaantech.com/
Solar Electrical Technologies	Monocrystalline, Polycrystalline, Thin-Films	235-260	https://www.selectpk.com/
Sunlife Solar	Monocrystalline, Polycrystalline	15-300	https://www.sunlifesolar.com.pk/
Tesla PV	Monocrystalline, Mono-PERC	440-660	https://tesla-pv.com/pages/solar-panels
Supreme Solsun Energy	Monocrystalline, Polycrystalline, Mono-PERC	160-540	www.supremesolsunenergy.com
Maxell Power (Pvt) Ltd.	Monocrystalline, Polycrystalline	170-400	https://www.maxpower.com.pk/product-category/solar-panels/

- **Assessment of awareness and acceptability of solar PV indigenization**

For the benefit of future investors of the PV module manufacturing industry, the assessment of acceptability and market demand for the locally assembled PV modules has been conducted, where the respondents of the questionnaires were diversified including academia, industry, private and public sector organizations. Based on survey it is assessed that Pakistan's solar sector showcases a diverse technological landscape. The majority i.e., "68%" of respondents being businessmen or industrialists, are linked with first-generation solar technologies, which are the foundational technologies in the solar PV sector. In contrast, 20% are exploring the newer, third-generation technologies, which encompass a range of advanced solar solutions. The remaining 12% are engaged with second-generation technologies, bridging the gap between the foundational and advanced solutions.

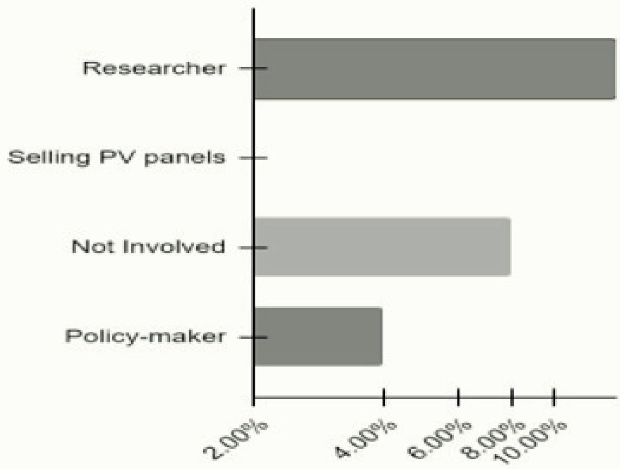

Figure 3: *Respondent's profile*

The duration of employment for specialists in the photovoltaic panel manufacturing industry in Pakistan exhibits variability. Approximately 37% of individual respondents have been actively involved with initial iterations of technology for a duration ranging from 1 to 3 years, suggesting a notable increase in interest or available prospects within this field in the very recent past. It is noteworthy that an additional 37% of individuals have acquired familiarity with the industry within a duration of less than one year, indicating the presence of a recent influx of experts or enterprises. In contrast, a relatively small proportion of individuals, namely 8.3%, have devoted a period beyond five years, so highlighting the early developmental phase of the business in Pakistan.

The push and need for indigenous PV module manufacturing in Pakistan is driven by multiple compelling reasons. A dominant 85.2% of respondents view it as a strategic move to bolster the renewable energy sector, reducing dependency on imported solutions. Over half believe that local manufacturing can democratize energy access, especially in remote regions, by making it more affordable. The potential for job creation, economic stimulation, and meeting the energy demands of Pakistan's burgeoning population also emerged as strong motivators. Furthermore, the environmental perspective was evident, with many respondents highlighting the role of PV panels in reducing greenhouse emissions and promoting sustainable energy.

4.3 Barriers to Indigenous PV Manufacturing

Like any emerging sector, indigenous PV manufacturing in Pakistan faces its set of challenges. The most prominent challenge, as highlighted by ~40% of survey respondents, is the perceived lack of robust government support through policy and regulatory framework. Additionally, the availability of quality raw materials, technical expertise, and infrastructural challenges were underscored. To counter the influx of subpar PV products, respondents advocate for a multi-pronged approach, including strengthening regulatory measures, promoting local manufacturing, and establishing stringent quality standards. The major barriers can therefore be divided into the following categories.

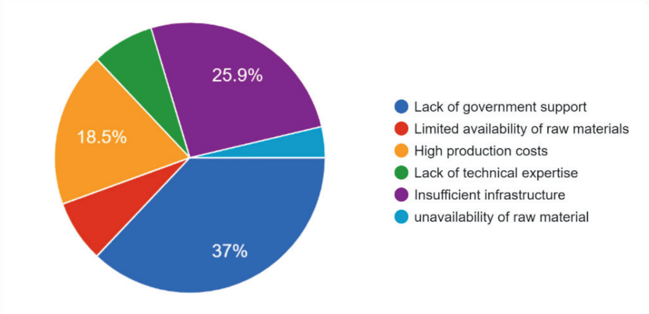

Figure 3: *Barriers to PV indigenization, as weighed by survey respondents.*

- **Technological Barriers:**

Pakistan's solar industry faces several critical technological barriers. Firstly, the absence of local manufacturing capabilities hinders self-reliance and increases dependency on imports. Secondly, limited investment in research and development stifles innovation within the sector. Moreover, the low quality of imported solar cells, susceptible to damage during shipping and due to mishandling, poses a significant challenge. Suboptimal lamination quality, issues with interconnects, ribbons, and other PV components further undermine module durability and performance. The challenges associated with sourcing raw materials for PV panel manufacturing in in Pakistan are multifaceted. Nearly half, 48.1%, of the respondents have faced issues related to the high cost of raw materials. Inferior quality is a concern for 37%, while 44.4% have encountered tax, duties, and custom clearance related issues. A smaller percentage, 3.7%, have experienced long lead times. Others believe that no supply chain exists for these materials.

To regulate the supply chain of raw materials needed for PV manufacturing, a significant 59.3% of respondents believe the government should encourage local production of raw materials. Additionally, 33.3% see the importance of implementing quality control processes throughout the supply chain. Investment in research and development of alternative materials is favored by 25.9%, while 29.6% advocate for improving the supply chain infrastructure. Interestingly, 29.6% believe that all the aforementioned measures should be adopted to effectively regulate the supply chain.

Quality assurance is paramount. A significant 63% of survey respondents emphasized the importance of adhering to international quality standards, ensuring that the PV modules produced in Pakistan are reliable and efficient. Such adherence not only ensures product longevity but also positions Pakistani PV modules favorably in the global market. From an environmental standpoint, the majority believe in sustainable manufacturing practices.

Reducing waste and enhancing resource efficiency are seen as essential steps to ensure the industry's growth doesn't come at the planet's expense.

Quality concerns extend to inverters and allied equipment, which are essential for effective energy conversion. Lastly, inadequate machinery, equipment, and skills for PV module manufacturing impede progress. Overcoming these barriers necessitates targeted efforts to promote local manufacturing, increase R&D investment, improve component quality, and elevate manufacturing processes and expertise. Hence quality assessment becomes mandatory particularly for locally produced PV modules, therefore establishment PV module testing laboratories should also be under spotlight in parallel to PV module manufacturing industry.

- **Economic and Financial Barriers**

Establishing local PV manufacturing facilities in Pakistan encounters significant economic and financial barriers. Despite a growing availability of alternative energy providers in the country, many solutions heavily rely on imported solar components. The existing tariff and tax structure, categorized under the same Harmonized System (HS) Codes for PV modules and cells, favors imports, with most of the imported modules being of potentially low quality and posing safety risks. While a considerable portion of imports originates from China, limited quantities come from Tier 1 solar PV Original Equipment Manufacturers (OEMs) in other countries. However, the issuance of SRO 604(I)/2019 has mandated the import of solar PV modules certified according to IEC 61215 and IEC 61730 [11]. These barriers also complicate the establishment of a local PV manufacturing industry, necessitating careful consideration and policy adjustments to incentivize domestic production and ensure quality standards.

- **Regulatory and Policy Barriers**

Several regulatory and policy barriers hinder the growth of the PV manufacturing industry in Pakistan. Firstly, the absence of a comprehensive policy defining module prices based on quality creates uncertainty in the market, impeding the establishment of fair pricing mechanism. This lack of clarity extends to end-users who often remain unaware of the quality-price correlation, further inhibiting informed decision-making. Moreover, the confusion regarding the required qualification tests for different module types leads to a lack of awareness and compliance, potentially compromising the safety and performance of solar installations. The absence of policy in the past has hindered the development of a structured and quality-conscious PV manufacturing ecosystem. To foster a thriving PV manufacturing sector, it's imperative for Pakistan to address these regulatory gaps by introducing policies that establish quality-based pricing, enhance end-user awareness, clarify testing standards, and encourage manufacturing excellence through robust standards and regulations.

- **Social Barriers**

Setting up industry in Pakistan at a larger scale is expected to increase the energy demand and hence bringing further environmental impact. In this scenario the transition from polluting energy resources to clean and renewable ones is crucial. On the environmental front while discussing about waste reduction and resource enhancement in PV module manufacturing, 77.8% of survey respondents believe that measures to reduce waste and increase resource efficiency are essential for minimizing the environmental impact. Additionally, 59.3% see it as crucial for the sustainability of the industry in Pakistan. These facts also lead to the idea of PV module recycling and utilization of locally available raw materials.

4.4 Measures for Overcoming Technological Barriers

- **Support for Technology Transfer**

Technology transfer refers to the sharing and adoption of advanced knowledge, methods, and technologies related to solar cell and panel production between different entities, often involving collaborations between domestic and foreign companies or organizations. Chinese government invited foreign companies to form partnerships with local firms, enabling the transfer of new solar technologies. This allowed China to access advancements while foreign investors benefited from cost advantages. China also set efficiency goals and allocated R&D funds domestically [12]. Pakistan could learn from this by collaborating with foreign firms to enhance its solar sector. This would bring in advanced technologies, boost research, and align with sustainability goals.

- **Research and Development (R&D)**

The solar technology landscape is dynamic and major shifts in solar PV production processes are typically seen in every five years, necessitating Pakistan's commitment to developing innovative manufacturing technologies and effectively introducing them to the market. However, it's important to note that currently, R&D funding in the solar sector is severely limited. To remain competitive, it's imperative for Pakistan to significantly enhance industry engagement in R&D programs, Government should also play its role, with a distinct emphasis on solar technologies.

- **Government Initiatives to boost R&D in PV**

The government, too, has a role in fostering research and development of innovative PV module manufacturing technologies in the country. A dominant 66.7% of respondents believe in the establishment of technology innovation centers for PV module manufacturing. An equal percentage see the value in offering research grants for PV module manufacturing technology development. Additionally, 37% suggest the introduction of internship programs for students to bridge the gap between academia and industry.

- **Academia-Industry Linkages**

Universities in Pakistan have a pivotal role to play in the research and development of indigenous PV module manufacturing. A significant 48.1% of respondents believe that universities should collaborate with industry partners for PV module manufacturing research. Additionally, 40.7% advocate for the establishment of dedicated research centers for PV module manufacturing within academic institutions. While 7.4% see the value in offering specialized degree programs in PV module manufacturing, a small segment, 3.7%, feels that academia doesn't have a special role in PV module manufacturing research.

- **R&D Program in Solar Energy**

A major R&D initiative needs to be taken in order to focus: first on improvement of efficiencies in traditional materials, devices and applications and on reducing costs of balance of systems, establishing new applications by addressing issues related to integration and optimization; secondly, on developing cost-effective storage technologies which would address both variability and storage constraints, and on targeting space intensity through the use of better concentrators, application of nano-technology and use of better and improved materials.

- **Network of Research Centers, Government, and International Collaboration**

A high-level research team can be formulated comprising eminent scientists, technical experts and representatives from academic and research institutions, industry, Government and Civil Society to guide the overall technology development strategy. Recognizing the importance of PV manufacturing's involvement in R&D, Pakistan needs to increase R&D investment from public and private sources. Comparative insights from other nations' approaches should also considered. Pakistan needs to start solar research grant programs funded by ministry of Science and Technology and ministry of energy and petroleum like other technology-leading nations, such as the United States, South Korea, and Singapore which award solar R&D funding through their energy ministries.

International experts in the field may also be invited to support the ongoing work. They will review and update the technology roadmap to achieve more rapid technological innovation and cost reduction. The team may also review and incorporate ongoing and proposed R&D initiatives.

- **National Centre for Photovoltaic Research**

A national center for photovoltaic research shall be established to coordinate the work of various R&D centers regarding technology development initiatives and validate research outcomes and serve as an apex center for the Indigenous Solar industry. The overall objective of the center is to promote the local manufacturing of solar panels and components to boost the domestic solar industry and reduce dependency on imports. Next goal of the center should be focused on providing intellectual support to PV Module Assembling Industry through research & development of new technologies and materials to improve the efficiency of PV panels. Establishment of R&D facilities: for advanced generation PV (Perovskite Technologies) starting from fabrication of lab-scale solar cells to industrial scale mini-module prototypes (commercially ready products), to foster the use of local reserves of Silicon/Silica for solar cell fabrication, for PV Module Recycling to explore and develop efficient Design for Recycling and Disassembling.

4.5 Measures for Human Resource Development

- **Training Modules and Skilled Workforce**

The rapid and large-scale diffusion of Solar Energy will require an increase in technically qualified manpower of international standard. Some capacity may already exist in the country, though precise numbers need to be established including engineering management and R&D roles. Skilled labor is a key requirement of the PV manufacturing industry which can be met through skill development and training programs particularly in underdeveloped regions.

- **Partnerships with educational institutions**

When it comes to developing a skilled workforce for the indigenous manufacturing of PV modules, a majority, 55.6%, believe that academic institutions should partner with the industry to provide hands-on training. Offering training programs specific to PV module manufacturing skills is favored by 25.9%, and 14.8% see the importance of providing internships for gaining practical PV module manufacturing experience. An interesting suggestion from 3.6% of respondents is the provision of foreign internships and exchange programs in PV manufacturing labs.

Moreover, in next couple of years, a targeted amount of youth should be trained under TEVTA, GIZ and other vocational training centers, so that they could provide their services for installation, operation, repair and maintenance of Solar Systems (Solar Street Light, Solar Power Plant etc.). Curriculum for the training courses also needs to be designed by keeping in view the most being used technology and the advanced future technologies in the field of solar PV.

- **Specialized Courses in Solar Energy**

Engineering universities and Higher Education Commission should be involved to design and develop specialized courses in solar energy, with financial assistance from Government. These courses should be at B. Tech, M. Tech and may also be defined for Ph. D level. Some of the engineering colleges and universities are already teaching solar energy at graduation and post-graduation level. Centers for Advanced Studies in Energy have already been set up at National University of Sciences and Technology and University of

Engineering and Technology, Peshawar under joint program of Higher Education Commission and USAID. In addition, a countrywide training program and specialized courses for technicians should be taken up to meet the requirement of skilled manpower for field installations and after sales service network like the one which is already being arranged by Atlas, Pakistan.

- **Government Fellowship Program**

Government Fellowship program to train selected engineers / technologists and scientists in Solar Energy in world class institutions abroad must be taken up. Fellowships should be awarded at two levels (i) research and (ii) higher degree in solar energy.

- **International Collaboration**

Saudi Electric Services Polytechnic (SESP) initiated a five-year training program enhancing skills for 400 recruits annually. Strategic partnerships brought global expertise, boosting training standards and the English Language and Technical Bridging Program. This comprehensive approach, industry connections and global collaboration, not only elevated workforce capabilities but also spurred socioeconomic growth, exemplifying a model for sustainable development. We can follow a similar trend to foster the development of workforce for setting up a PV manufacturing facility in Pakistan. As NUST recently partnered with the SESP to host a workshop focused on training individuals in PV installation, commissioning, and PV manufacturing techniques.

4.6 Measures for Overcoming Economic and Financial Barriers

- **Financial Incentives**

Central and local governments should provide solar manufacturers tax incentives, input subsidies, R&D grants, equity infusions, technology upgradation grants, subsidized land, and even pre-built factories. Further, the central and local governments should provide relief to companies facing financial difficulties.

To encourage the development of the PV manufacturing sector, survey respondents also suggested various government interventions including tax incentives, followed by import duty exemptions and subsidies for PV manufacturing companies.

- **Market Development Measures**

PV manufacturers, upstream raw materials and equipment suppliers should be constructed in the same area, as it could enable the ecosystem to cut costs and achieve co-development between manufacturers and their vendors [13]. Manufacturing hubs concentrate manufacturers and suppliers in the same location, driving cost reduction and innovation. Further, import tariffs on imported PV products will help the country develop a strong domestic PV modules and raw materials supply. Initially, the tariffs should only be imposed on module imports from other countries.

4.7 Measures for Overcoming Regulatory and Policy Barriers

Last but not least, the barriers and gaps related to policy and regulation are playing very detrimental role in bringing the stagnancy situation in growth of PV module manufacturing industry. All three pillars; government, industry, and academia, should play their defined role. In the realm of policy development for indigenous PV module manufacturing, universities and research centers can play a manifold role. A total of 37% of survey respondents believe that universities should collaborate with the industry to advocate for supportive policies. Conducting research and analysis to inform PV module manufacturing policy is deemed important by 25.9%, while 33.3% believe universities should provide direct policy recommendations to both government and industry stakeholders.

- **Streamlining Licensing and Approval Processes**

The government can more streamline the licensing and approval procedure for PV manufacturing through

- Setting up participating rules and compliance monitoring process
- Increased flexibility for participants
- Overcome geographical constraints
- Reduced transaction costs for RE transactions
- Enforcement of penalty mechanism
- Create competition amongst different RE technologies
- Development of all-encompassing incentive mechanism
- Defining pricing options

- **Policy support for Testing and Certification of PV modules**

A comprehensive framework for conducting fundamental post-manufacturing performance tests of PV-modules, including but not limited to I-V testing, inspection, and packaging, needs to be systematically formulated. Additionally, it is imperative that module quality testing should be done as per IEC 61215, 60904, and 62804 requirements to ensure the quality and lifetime of PV modules. Regulatory authorities should collaborate closely with already established solar PV testing laboratories to facilitate thorough testing and certification procedures for PV modules. Furthermore, there exists a critical necessity to implement oversight across all phases of PV manufacturing processes to ensure adherence to quality standards and regulatory compliance.

A National Centre of Photovoltaics shall be established to implement the technology development plan and coordinate the work of various R&D centers, validate research outcomes, and serve as an apex center for testing and certification and for developing standards and specifications for the Solar industry. Besides the quality control of locally made modules, to curb the import of low-quality PV products, most of survey respondents believe in strengthening regulatory, policy and inspection measures.

5. Roadmap to Indigenous PV Manufacturing

The manufacturers foresee a long-term strategy to retain a steady growth trajectory for solar PV sector, while increasing protection against imported panels in the long run through incentivizing local production [14]. The intention should be to develop the solar industry under the "Made in Pakistan" initiative and also to bolster other allied industries like glass, aluminum frames and adhesives, etc.

When it comes to technological preferences in PV module manufacturing, there's a clear inclination towards Monocrystalline/Polycrystalline Silicon modules and the innovative technologies are being advocated [15]. These technologies, favored by about 80% of survey respondents, are known for their efficiency and reliability. In terms of cell size, the standard 6×6 inches and their half-cut cells emerge as the ideal choice, aligning with global trends.

5.1 Proposed Roadmap for PV Module Manufacturing in Pakistan

PV module manufacturing indigenization should be adopted in stages, making it feasible with respect to required finances and infrastructure.

Stage 1 should include the following in parallel:

- Assembling of PV Modules using imported solar cells and other components
- R&D of locally available Silicon raw material
- Local manufacturing of allied materials like Glass, Aluminum, back-sheet, etc.

The initial phase involves acquiring the necessary technology and expertise for assembling silicon-based PV modules. This includes establishing assembly lines and production processes for Mono/polysilicon-based PV modules emphasizing the latest available module/cell structures like Passivated Emitter Rear Contact (PERC), Tunnel Oxide Passivated Contact (TOPCon) and Interdigitated Back Contact (IBC), etc. Concurrently, there will be a focus on research and development to assess the quality and suitability of locally available raw materials such as Quartz, Glass, Aluminum, and others. Research and development efforts will also be directed towards the exploration and potential development of 3rd generation solar cell and module technologies. This ensures that Pakistan remains competitive with the latest advancements in the global solar industry.

Stage 2 should focus on the following:

- Indigenization of Silicon-based PV Cells Manufacturing
- R&D of PV Module Recycling

The final stage focuses on establishing

domestic manufacturing capabilities for silicon-based PV cells. This strategic move aims to support the silicon-based PV module assembly industry, reduce reliance on imports, and enhance the country's energy security. PV module recycling should also be added up at the R&D scale leading to effective PV module recycling strategies.

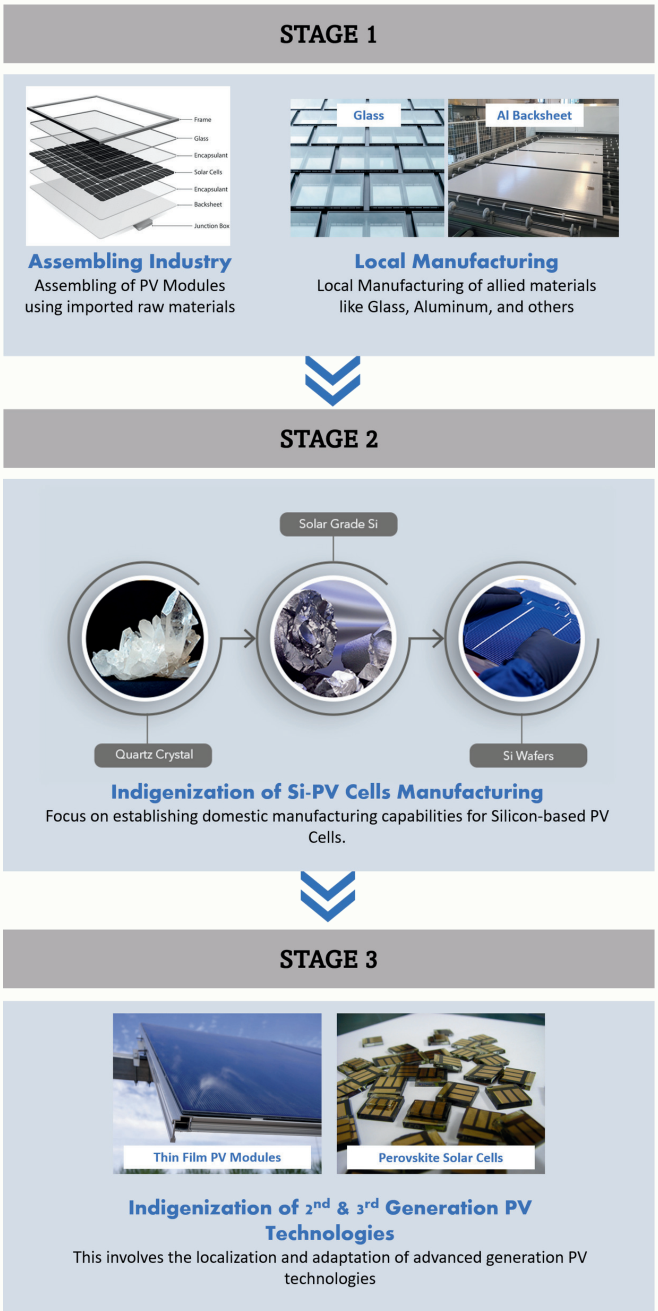

Figure 5: *Roadmap of PV Indigenization*

Stage 3: Indigenization of 2nd/3rd Generation PV Technologies

This stage involves the localization and adaptation of 3rd generation PV technologies that were researched and developed in Stage 1. The goal is to make these technologies economically viable for local production.

5.2 Establishment of National Center for Photovoltaics

In this scenario, Pakistan requires a dedicated research and development (R&D) facility not only for Crystalline Silicon (C-Silicon) based technologies but also for next-generation photovoltaics, notably Perovskite solar cells. Currently, Pakistan's efforts in this field lack substantial progress due to the absence of a specialized R&D center. Such a dedicated facility should encompass the following essential components: R&D of raw materials for C-Silicon based technologies, R&D facility for PV module recycling, encapsulation development for Perovskite solar cells/ mini modules, prototype development for industry ready products and R&D facility for technology advancement initiatives. Incorporating these elements into a specialized R&D Center would enable Pakistan to actively contribute to the indigenization of C-Silicon based PV technology as well as leading to the advancement of Perovskite solar cell technology.

Figure 6: Roadmap of R&D Center

5.3 Long-Term Plans for Sustainability of Solar Manufacturing in Pakistan

- **Global Leadership in Solar Manufacturing**

Currently, the bulk of Pakistan Solar PV industry is dependent on imports of critical raw materials and components – including silicon wafers. Transforming Pakistan into a solar energy hub would include a leadership role in low-cost, high quality solar manufacturing, including balance of system components. We need to set high targets from now on. The key framework in solar PV manufacturing should be to innovate, expand and disseminate. Policy should be designed to provide special incentives to promote PV manufacturing plants, including domestic manufacture of silicon material.

- **Infrastructure and Ecosystem**

In the absence of a coherent ecosystem, the current facilities may not be available or keep abreast of innovations and may become redundant after a few years. So, it is recommended to establish a long-term solar manufacturing technology roadmap, strategically approaching export demand creation, and supporting manufacturers in setting up and scaling up upcoming manufacturing facilities.

- **Localizing production of bill of materials (BOM) and manufacturing machinery:**

Localizing production of BOM is critical to ensure supply chain security and reducing import dependence. Further, making manufacturing equipment in Pakistan can help cut capital expenditure and improve manufacturer's access to servicing. Industry-led R&D is critical for both BOM and machinery, as Pakistani players must first develop high-quality, cost-competitive options before scaling up.

6. Policy Recommendations

6.1 Strengthening the Supply Chain for Raw Material

- Promote domestic production: Facilitate the growth of local industries engaged in the manufacturing of crucial raw materials for photovoltaic (PV) production by offering subsidies and tax incentives.
- Import Regulation: Streamline customs and duty procedures and provide tariff reductions for crucial raw materials that are not domestically accessible.
- Supply Chain Infrastructure: Establish specialized logistics and storage systems to guarantee the prompt accessibility of essential resources.
- Establishing Supplier Partnerships: Cultivate collaborative relationships with reputable foreign suppliers in order to maintain a steady and reliable stream of high-quality raw materials.

6.2 Enhancing Quality and Standards

- Local Testing Facilities: Implementation of Local Testing Labs for Photovoltaic Module Quality Control in Accordance with International Electrotechnical Commission (IEC) Standards.
- International Collaboration: Engage in collaborative efforts with reputable international quality assurance bodies to facilitate periodic audits and training sessions.
- Programme Certification: The implementation of certification programs is proposed as a means to introduce quality criteria for photovoltaic (PV) manufacturers.

6.3 Fostering Academia-Industry Collaboration

- Research Centers: Assistance must be provided to universities in the development of specialized research centers for photovoltaic (PV) module manufacture through providing support.
- Hands-on Training: Organize and conduct industry-oriented hands-on training sessions and workshops within academic institutions.
- Internship Programs: Propose the inclusion of industry internships as a compulsory component within the academic curricula of pertinent courses.
- Joint Research Initiatives: Encourage collaborative research endeavors between academic institutions and industry sectors to effectively tackle real-world issues.

6.4 Financial Incentives and Support

- Tax Incentives: Tax incentives must be provided to promote the growth of photovoltaic (PV) module manufacture and technology research. These incentives would involve providing tax discounts to enterprises engaged in these activities.

- Research Grants: Establishing a specialized research grant program to support the advancement of photovoltaic (PV) technologies.
- Low-Cost Financing: Low-cost Financing: Establish partnerships with financial institutions to provide access to affordable loans with favorable interest rates for photovoltaic (PV) businesses.
- Investment Platforms: Development of investment platforms that facilitate the connection between potential investors and photovoltaic (PV) entrepreneurs, thereby fostering private investment in this sector.

6.5 Infrastructure Development

- Special Economic Zones: Special Economic Zones (SEZs) can be established or modified to cater specifically to the manufacturing of photovoltaic (PV) modules, equipped with the essential infrastructure required for this purpose.
- Supply Chain Infrastructure: Establish resilient supply chain systems to facilitate seamless transit and ensure the consistent availability of raw materials.
- Utility Support: Development of utility support to guarantee the provision of dependable utility services, with a particular emphasis on electricity, within these designated areas.
- Technology Parks: Establishment of designated areas, known as technology parks, within these zones to facilitate advanced research and development activities.

6.6 Promoting Local PV Modules

- Government Projects: Mandate a percentage of locally manufactured PV modules in government-funded projects.
- Public Awareness: Launch nationwide campaigns promoting the benefits of indigenous PV modules.
- Local Vendor Lists: Maintain and promote lists of certified local PV module manufacturers for public and private projects.
- Quality Assurance: Offer extended warranties or other incentives for projects using local PV modules to assure quality.

6.7 Encouraging Advanced Technologies

- R&D Funding: Implementation for the allocation of certain proportion of domestically produced photovoltaic (PV) modules to be utilized in government-funded projects.
- International Partnerships: Initiate nationwide campaigns aimed at raising awareness about the advantages of utilizing indigenous photovoltaic (PV) modules.
- Technology Licensing: Compilation and dissemination of certified local photovoltaic (PV) module manufacturers' listings for both

private and public projects.

- Innovation Hubs: Provide extended warranties or additional incentives for projects that utilize locally manufactured photovoltaic (PV) modules in order to ensure and uphold quality standards.

6.8 Regulatory Measures

- Import Regulation: Enforce stringent quality inspections for imported photovoltaic (PV) products in order to verify their compliance with established standards.
- Quality Standards: It is imperative to consistently revise and implement quality standards that align with internationally recognized best practices.
- Monitoring & Compliance: Establishing a specialized entity responsible for the monitoring and enforcement of these standards.
- Penalties: Implementation of sanctions should be considered as a means to discourage non-compliance with regulations and standards for poor items.

6.9 Skilled Workforce Development

- Training Programs: Establishing partnerships with international institutions to facilitate the implementation of high-quality training programs within Pakistan.
- Foreign Internships: To establish collaborative partnerships with prominent photovoltaic (PV) manufacturing nations in order to facilitate foreign internships and exchange programs.
- Skill Development Centers: Establishing specialized centers focused on the development of skills in the field of photovoltaic (PV) production.
- Industry Feedback: Consistently collect feedback from the industry regarding identified skill gaps and take proactive measures to remedy them.

6.10 Collaboration with International Entities

- Funding & Technical Assistance: Establish partnerships with foreign organizations to secure financial resources and facilitate technical collaborations.
- Knowledge Exchange Programs: Facilitating information exchange is the implementation of knowledge exchange programs, which involve the organization of international seminars and workshops.
- Trade Delegations: Attracting investment and establishing collaborations in the field of photovoltaic (PV) production is to organize trade delegations to nations that are at the forefront of this industry, like China, Germany, US etc.
- International Exhibitions: Engage in and organize international exhibitions to present regional progress and foster collaborative opportunities on a global scale.

7. Conclusion

The potential for indigenous photovoltaic (PV) module manufacture in Pakistan is considerable, and the perspectives obtained from industry stakeholders emphasize the pressing need and significance of harnessing this potential. With the increasing worldwide emphasis on transitioning to renewable energy sources, Pakistan finds itself at a critical juncture when it has the opportunity to fulfill its energy requirements in a sustainable manner and establish itself as a prominent participant in the photovoltaic manufacturing industry.

The aforementioned policy recommendations offer a comprehensive framework for effectively addressing the difficulties and capitalizing on the opportunities within the PV module manufacturing sector. Pakistan can establish a resilient and sustainable photovoltaic (PV) manufacturing sector by prioritizing the reinforcement of the raw material supply chain, the improvement of quality standards, the cultivation of academia-industry collaboration, the provision of financial incentives, and the promotion of local PV modules.

In addition, the prioritization of international collaborations, the cultivation of a competent workforce, and the implementation of regulatory measures serve to maintain the industry's competitiveness in the global arena. The role of academia is crucial in advancing research, fostering innovation, and facilitating skill acquisition, so guaranteeing that the industry maintains its position at the forefront of technological progress.

Through the collaborative endeavors involving the government, industry, academia, and foreign collaborators, Pakistan has the potential to attain self-reliance in photovoltaic (PV) module production and establish itself as a prominent player in the global renewable energy market. The present moment necessitates prompt action, and the implementation of appropriate policies holds the potential for a favorable outlook on photovoltaic (PV) module manufacturing in Pakistan.

The indigenization of the PV module manufacturing faces the lack of financial support since huge investment is required for establishment of complete PV manufacturing chain. Therefore, this study recommends to start indigenous PV manufacturing in different phases, where assembling of PV modules based on imported raw materials should be the first step for Made-In-Pakistan module technology then the initial stages can be added up in next phases. In parallel, a specialized R&D center should be established to support not only silicon PV industry but also the indigenization of advanced generation PV technologies. This center should explore cutting edge technologies leading to high quality, advanced indigenized PV products.

The proposed strategy suggests a step-by-step approach, starting from establishment of PV module assembling industry, then start utilizing the local silicon reserves and the launching an advanced PV technology research center. The goal is to formulate a business model for indigenous PV manufacturing with active stakeholder participation.

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