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Opportunities and Challenges in the Solar PV Supply Chain: A Strategic Focus on Morocco's Energy Transition

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ABSTRACT

Energy is the cornerstone of modern civilization, with solar energy, particularly photovoltaic (PV) systems, driving the renewable energy transition. By 2024, the global PV market exceeded 1,000 GW of installed capacity, highlighting its rapid growth and potential. The PV solar energy supply chain is central to this transition, involving raw material extraction, manufacturing, distribution, and installation of PV systems. This paper examines the PV supply chain, focusing on key components like raw material sourcing, PV cell and module production, and logistical challenges. Through a detailed literature review, the study identifies technological advancements, market trends, and barriers to sustainable growth.

The methodology involves reviewing academic journals, industry reports, and market data to synthesize current knowledge and identify gaps. Preliminary results show advances in production efficiency and cost reduction, increasing solar energy's accessibility and competitiveness. However, challenges persist, such as supply chain disruptions due to geopolitical tensions, raw material shortages, and environmental concerns about the PV lifecycle. Key findings stress the importance of risk management strategies, recycling technologies for PV systems, and supportive policy frameworks. Future research should focus on integrating advanced technologies, assessing environmental impacts, and exploring regulatory frameworks for sustainability and resilience in the PV supply chain. Addressing these issues will enhance the industry's growth and sustainability.

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الفرص والتحديات في سلسلة توريد الطاقة الشمسية الكهروضوئية: تركيز استراتيجي على التحول الطاقي في المغرب

هاجر راجي، بوداود عبد الغاني، عاقل منعيم.

ملخص: الطاقة هي حجر الزاوية للحضارة الحديثة، حيث تقود الطاقة الشمسية، ولا سيما الأنظمة الكهروضوئية، عملية التحول إلى الطاقة المتجددة. وبحلول عام 2024، تجاوز حجم السوق العالمية للطاقة الكهروضوئية 1,000 جيجاواط من القدرة المركبة، مما يسلط الضوء على نموها السريع وإمكاناتها. تُعد سلسلة توريد الطاقة الشمسية الكهروضوئية أمرًا محوريًا في هذا التحول، حيث تشمل استخراج المواد الخام وتصنيعها وتوزيعها وتركيب الأنظمة الكهروضوئية. تتناول هذه الورقة البحثية سلسلة توريد الطاقة الشمسية الكهروضوئية، مع التركيز على المكونات الرئيسية مثل مصادر المواد الخام، وإنتاج الخلايا الكهروضوئية والوحدات الكهروضوئية، والتحديات اللوجستية. وتحدد الدراسة من خلال مراجعة مفصلة للأدبيات في هذا المجال التطورات التكنولوجية واتجاهات السوق والعوائق التي تحول دون النمو المستدام. وتتضمن المنهجية مراجعة المجلات الأكاديمية والتقارير الصناعية وبيانات السوق لتجميع المعرفة الحالية وتحديد الثغرات. وتظهر النتائج الأولية تقدماً في كفاءة الإنتاج وخفض التكلفة، مما يزيد من إمكانية الوصول إلى الطاقة الشمسية وقدرتها التنافسية. ومع ذلك، لا تزال هناك تحديات قائمة، مثل اضطرابات سلسلة التوريد بسبب التوترات الجيوسياسية، ونقص المواد الخام، والمخاوف البيئية المتعلقة بدورة حياة الطاقة الشمسية الكهروضوئية. وتؤكد النتائج الرئيسية على أهمية استراتيجيات إدارة المخاطر، وتقنيات إعادة التدوير للأنظمة الكهروضوئية، وأطر السياسات الداعمة. يجب أن تركز الأبحاث المستقبلية على دمج التقنيات المتقدمة، وتقييم الآثار البيئية، واستكشاف الأطر التنظيمية للاستدامة والمرونة في سلسلة التوريد الكهروضوئية. وستعزز معالجة هذه القضايا نمو الصناعة واستدامتها.

الكلمات المفتاحية – الطاقة الكهروضوئية، سلسلة التوريد الكهروضوئية، الطاقة المتجددة، الأنظمة الكهروضوئية، النمو المستدام.

1. INTRODUCTION

The global photovoltaic (PV) supply chain is characterized by its unique dynamics and rapid evolution. It is heavily influenced by government policies, subsidies, and geopolitical factors [1]. According to recent market research conducted by the Custom Market Insights (CMI) team [2], the global Solar PV Supply Chain Market is projected to experience a compound annual growth rate (CAGR) of 13.1% from 2023 to 2032. In 2022, the market size was estimated at USD 127.5 billion, and it is anticipated to reach a valuation of USD 326.2 billion by 2032. This significant growth underscores the increasing adoption and expansion of solar photovoltaic systems worldwide, driven by advancements in technology, supportive government policies, and a growing emphasis on sustainable energy solutions [2]. In comparison, the Solar PV Panels Market is expected to grow at a CAGR of 8.6%, reaching USD 292.32 billion by 2030, while the Solar PV Market is projected to grow at a CAGR of 8.3%, reaching USD 306.16 billion by 2030, according to the same report.

Over the past 15 years, China has emerged as the dominant player in the PV value chain, driven by intangible assets and intellectual property (Carvalho et al., 2023) [3]. Globalized supply chains in the solar PV industry have been shown to generate cost savings, benefiting PV installers in countries like the United States, Germany, and China, with estimated savings in the billions of dollars over a decade compared to scenarios with localized manufacturing [4]. At the end of 2021, Africa had 10302 MW of installed solar PV capacity, an increase of 6.2% compared to 2020, but representing only 1.2% of the world's total available PV capacity. Despite its great potential in the region, solar energy has only been deployed on an industrial scale by a handful of African countries. Morocco is located in an area with high solar potential, and is well endowed in terms of direct sunshine. According to the Moroccan Agency for Sustainable Energy (MASEN), our country ranks 9th in the world in terms of sunshine levels. The country enjoys between 2800 and 3400 hours of sunshine a year. The country's technical solar potential is therefore estimated at 20000 MW.

The study is motivated by the increasing significance of renewable energy in addressing global energy demands and environmental concerns, particularly in the context of climate change. This research seeks to fill existing knowledge gaps and provide valuable insights into the challenges and opportunities within the photovoltaic (PV) solar energy sector. Specifically, the paper examines the evolution of the PV solar energy supply chain, focusing on technological advancements, historical milestones, and current market trends. The objective is to deliver a comprehensive overview of the global PV solar energy supply chain, critically assessing recent methodologies and identifying key areas that remain underexplored. These include global and regional dynamics, policy impacts, and long-term sustainability challenges. The research aims to address the following key questions:

- What are the key opportunities and challenges in the global photovoltaic (PV) energy supply chain?
- How can African markets leverage these insights to promote the growth and adoption of solar energy?
- What strategies and recommendations can be implemented to address the unique challenges faced by the African solar PV market, while capitalizing on its potential for growth in the renewable energy sector?

To achieve a thorough understanding of the solar energy supply chain, the study employs a methodology that integrates both narrative and critical analysis. This dual approach enables a balanced exploration of historical developments, current market trends, and technological advancements. It provides a broad contextual framework while offering a detailed examination of key studies, highlighting their strengths, weaknesses, and existing gaps in the literature. The study is structured as follows: Section 1 introduces the topic and outlines the study's objectives. Section 2 provides an overview of the global PV solar energy supply chain. Section 3 details the methodology, combining narrative and critical analysis. Section 4 focuses on the Moroccan PV energy supply chain. Section 5 presents results and discussions, emphasizing opportunities, challenges, and barriers. Finally, Section 6 concludes the study with key findings and recommendations.

2. GLOBAL PV SUPPLY CHAIN: FROM SUNLIGHT TO ELECTRONS

The solar PV supply chain market involves interconnected stages of producing, assembling, distributing, and installing solar photovoltaic systems, as indicated in Figure 1 below. This complex market encompasses various elements, including raw materials, manufacturing processes, logistics, installation, and maintenance activities [5]. This PV energy supply chain follows Four main phases and seven stages to transform sunlight to electrons energy.

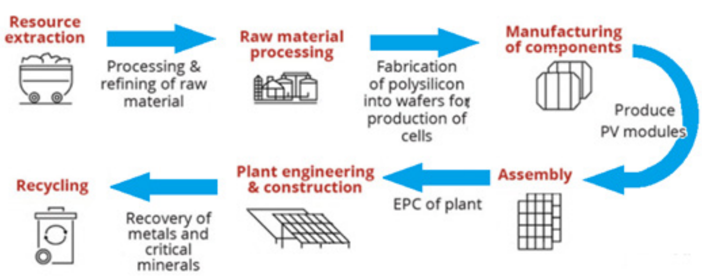

Figure 1. PV Solar Energy Supply Chain.

Phase 1: Inbound Logistics as The Backbone of Supply Chain

Stage 1: Setting the Stage and Procurement:

Site Selection and Development: the identification of optimal locations for solar PV construction is a significant task [6]. Identifying locations with high solar irradiation levels is a crucial aspect of optimizing solar photovoltaic (PV) system efficiency and energy output. Moreover, the selection of solar power plant (SPP) sites involves factors like local weather, terrain, and environmental considerations [7]. Focusing on the Environmental impact assessments are crucial for mitigating ecological harm during project development, while securing land and necessary permits lays the groundwork for commencing construction.

Sourcing Raw Materials: The supply chain begins with the extraction and processing of raw materials, primarily metallurgical-grade silicon (MGS), which is refined into high-purity polysilicon. Other critical materials include glass, resins, and various metals like silver and copper. The supply chain for concentrating solar power (CSP) technologies primarily consists of commodity materials like steel, aluminium, and glass, with specialty components, such as mirror panels, constituting a significant portion of total system costs [8].

Transportation and logistics in the PV solar inbound logistics: In the realm of PV solar energy, inbound logistics play a pivotal role in sourcing raw materials like polysilicon, silicon wafers, aluminium, and glass from various global locations to manufacturing facilities. Challenges such as bulk transportation, supply chain disruptions, and environmental impacts necessitate a strategic approach. Leveraging effective logistics strategies encompassing supplier management, inventory control, and mode selection is paramount for ensuring cost-efficiency and sustainability within the solar energy industry. Research emphasizes the importance of optimizing transportation volumes across different segments of the PV industry chain to enhance supply chain efficiency and reduce environmental footprints [9]. Furthermore, addressing vulnerabilities in the solar supply chain through policy interventions and sustainable manufacturing practices is crucial for mitigating disruptions and maximizing the benefits of solar investments [10]. However, the integration of cloud computing and blockchain technology presents a novel framework for enhancing PV logistics, optimizing various components like transportation and supply chain coordination to minimize costs and enhance overall efficiency [11].

Phase 2: PV Solar Energy Internal Logistics

Stage 2: Manufacturing Process:

Manufacturing Stages: The manufacturing stages of photovoltaic (PV) systems involve several critical processes, beginning with polysilicon production, where silicon is purified and prepared for further processing. Silicon is the predominant material used in PV cells due to its abundance and favorable properties. The production processes for solar-grade silicon, including the conversion of metallurgical-grade silicon, are well-established but energy-intensive [12]. Following this, polysilicon is melted to form ingots, which are subsequently sliced into wafers. The crystallization and wafering processes are vital in the manufacturing chain, with monocrystalline and multicrystalline methods offering distinct advantages in terms of efficiency and cost [12]. These wafers are then transformed into solar cells, which convert sunlight into electricity. The final stage involves module assembly, where solar cells are integrated into modules, the final product used in solar installations. The integration of solar cells into modules and the importance of Balance of System (BOS) components, particularly inverters, are crucial for the performance and cost of PV systems [12]. Advances in module manufacturing have led to decreasing costs, but further innovation is necessary to enhance sustainability and recyclability [12].

Logistics and transportation: The logistics and transportation part of solar component distribution involves strategic planning and efficient execution across various modes of transport [13]. This phase is crucial for optimizing routes, minimizing delays, and reducing costs in the solar industry [11]. The integration of advanced technologies, such as cloud-enabled blockchain, enhances real-time data access and decision-making in PV logistics operations [11]. Solar energy has gained significant traction in the logistics sector, particularly in warehouse rooftop installations, leading to reduced logistics costs and increased competitiveness [14]. The adoption of solar energy in logistics extends beyond warehouses to transportation activities, with ongoing R&D efforts focused on solar-powered vehicles and infrastructure [14].

Phase 3: PV Solar Energy Outbound Logistics

Stage 3: Building the Solar Farm

Building a solar farm involves several key steps. During site preparation, land clearing and leveling are essential for optimal panel placement, while the installation of electrical infrastructure, such as underground cables and inverters, is crucial [15]. Subsequently, crews meticulously position and secure the solar panels on mounting structures to maximize sun exposure, ensuring efficient energy generation [9]. It is important to consider the impact of solar farms on the environment, as studies have shown that utility-scale solar farms can increase soil erosion due to changes in land use and hydrological behaviors, especially in hilly regions like the Loess Hilly Region of China [16]. Proper design and commissioning of the earthing system are also critical to ensure safety and compliance in large-scale solar farms [17]. By following a detailed plan and considering various factors like climate suitability, technical requirements, and legal aspects, countries can efficiently harness solar energy through optimal solar farm placement [18].

Stage 4: Power Generation and Transmission:

In the process of converting sunlight into electricity, photovoltaic systems play a crucial role. Sunlight hitting solar cells generates electricity through the photovoltaic effect [19]. This direct current (DC) electricity produced by the panels is then converted into alternating current (AC) by inverters for compatibility with the power grid [20]. Additionally, transformers are employed to adjust the voltage to levels suitable for efficient transmission over long distances [20]. The integration of these components ensures that the power generated from sunlight is efficiently conditioned and seamlessly integrated into the grid, enabling the widespread distribution of renewable energy to meet the increasing demands of modern power systems.

Stage 5: Distribution and Consumption:

In the realm of energy distribution and consumption, high-voltage transmission lines play a crucial role in efficiently transporting electricity over long distances, serving as the backbone of the power grid [21]. As electricity nears its final destination, step-down transformers come into play, reducing the voltage to levels suitable for residential and commercial use [21]. Ultimately, the electricity reaches consumers, powering their appliances and lighting systems, highlighting the final stage of the distribution process [21]. Understanding consumer types is essential in modern power systems, as different sectors like residential, commercial, and industrial exhibit varying energy needs and demand behaviors, impacting the overall electricity system [22]. Analyzing consumption behaviors and similarities among consumers aids in implementing green energy trends and demand response activities effectively, ensuring grid stability and flexibility [22].

Stage 6: Operations and Maintenance:

In the operation and maintenance stage of solar farms, continuous monitoring is crucial for optimal performance and issue identification [23]. Regular cleaning of solar panels to remove dust and debris is essential for maximizing sunlight absorption and maintaining efficiency [24]. Skilled technicians play a vital role in performing preventative maintenance and addressing technical issues promptly to ensure the solar farm functions efficiently [25]. Implementing maintenance strategies such as corrective, preventive, and predictive maintenance is key to sustaining the reliability and performance of solar photovoltaic systems, ultimately boosting consumer confidence in solar energy [25]. Additionally, the development of innovative maintenance curricula and the use of artificial intelligence technology for preventive maintenance can further enhance the effectiveness of maintenance activities in solar energy systems. The integration of artificial intelligence (AI) technology for preventive maintenance in solar energy systems can significantly enhance maintenance activities by enabling early defect identification, predictive maintenance, and energy management [26].

Phase 4: Reverse Logistics and Sustainability in PV Solar Energy

Stage 7: Circularity and Sustainability:

The integration of sustainability, recycling, and circular strategies in the design of PV supply chain networks is crucial for addressing environmental concerns and promoting resource efficiency [27]. The PV industry is evolving towards circularity, with a focus on areas such as product end-of-life management, stakeholder relationships, and circular business models [28]. Additionally, the transition towards renewable energy sources like solar PV has led to a growing interest in the exploitation of renewable energy resources and sustainable development within the energy industry chain and supply chain [29]. The integration of renewable energies, particularly solar energy through PV systems, has become crucial due to the finite nature of fossil fuel resources and the associated environmental concerns [27].

3. METHODOLOGY

The methodology employed in this study involves a comprehensive review of the evolution of the solar energy supply chain, highlighting key developments and technological advancements. It begins with an overview of the historical context, followed by a summary of the current landscape, including major players, technologies, and market trends. The selection criteria focused on recent studies and reports from reputable sources, ensuring the inclusion of peer-reviewed articles and authoritative industry analyses. A critical analysis of key studies was conducted to evaluate the strengths and weaknesses of their methodologies, data quality, and conclusions. This review also identifies gaps in the literature, such as underexplored regional supply chain dynamics, the impact of policy changes, and long-term sustainability challenges. The combination of a narrative overview with critical analysis provides a balanced and comprehensive understanding, offering both a broad contextual framework and a detailed examination of specific insights within the solar energy supply chain. Combining a narrative overview with critical analysis can provide a comprehensive understanding of a topic by synthesizing a wide range of studies and offering an interpretative lens [30]. Narrative reviews, such as state-of-the-art, critical, and integrative reviews, allow for a subjective examination and critique of literature, offering insights on advancing the field and providing new perspectives [30]. Critical reviews, in particular, involve an interpretative process shaped by theory or critical viewpoints, enhancing the analysis of diverse studies [30]. By integrating narrative elements with critical perspectives, researchers can offer a readable, relevant synthesis of literature while advancing new ideas and interpretations in the field [30].

The study uses content analysis to examine the selected academic papers, proceedings, and reports. This involves categorizing and analyzing key themes, trends, and challenges related to the PV solar energy supply chain, as explained in Figure 2 below. The content analysis process enables the identification of patterns in the literature, allowing the study to pinpoint recurring barriers and opportunities. To conduct a content analysis of the PV solar energy supply chain, we begin by defining clear research questions and objectives, such as identifying the key opportunities and challenges within the global PV energy supply chain and determining how African markets, like Morocco, can leverage these insights for growth. We then gather data from various sources, including peer-reviewed articles, industry reports, and government publications from 2006-2024. Next, we develop a coding scheme based on themes such as supply chain components, challenges like raw material shortages, opportunities like technological advancements, and the role of regulations and policies. After selecting appropriate units of analysis, such as paragraphs or figures from the reports, we apply the coding scheme to categorize the data. Once the data is coded, we analyze it to identify patterns, such as common challenges like supply chain disruptions, or gaps in research, such as the lack of studies on lifecycle management in PV systems. Based on these findings, we draw conclusions, linking them back to our research questions. We then present the results in a structured form. To ensure the coding process's reliability, we cross-check it by having another three researchers independently review a sample. Finally, we conclude by highlighting recommendations and implications for future research. This approach allows us to systematically explore the literature and provide valuable insights into both regional and global dynamics of the PV solar energy supply chain.

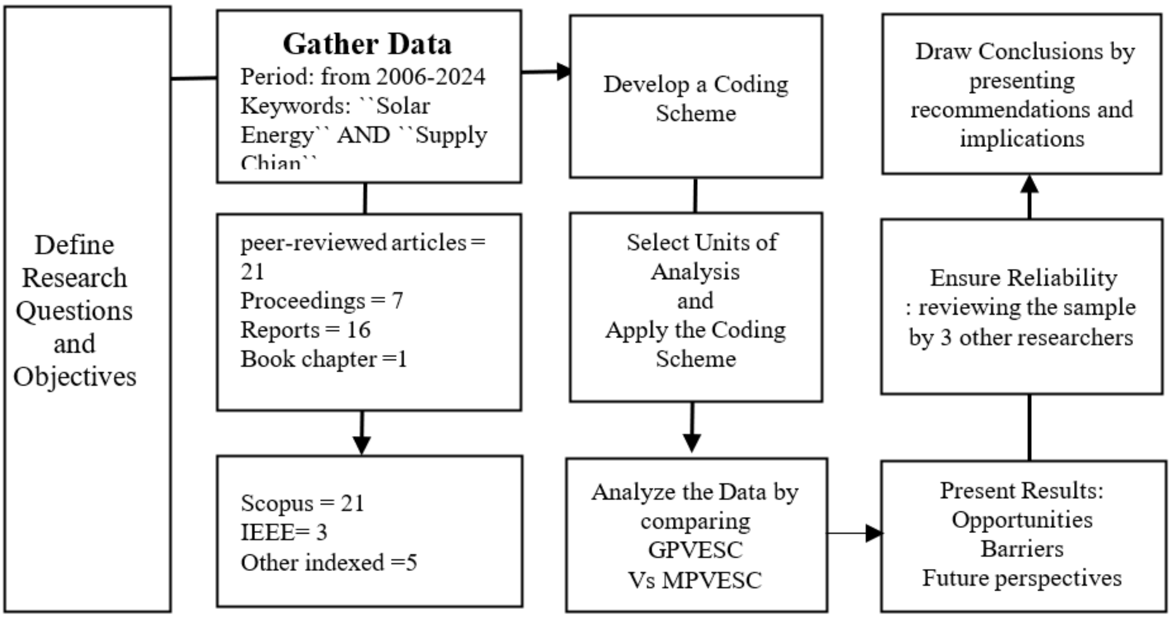

Figure 2. Literature Review Methodology Steps.

4. MOROCCO'S SOLAR ENERGY POTENTIAL

4.1. Energy production in Morocco

Since the mid-2000s, Morocco has launched major renewable energy projects, benefiting from year-round sunshine for solar projects. This rapid growth in the renewable energy sector has enabled the country to gain energy independence and has brought prosperity to some inhabitants of rural and isolated areas. The government plans to add 9.6 GW of capacity by 2027, including 7 GW of renewable energy [31], [32], [33].

Morocco's electricity supply is shown in figure 3 below. These graphs show Morocco's electricity production by type between 2000 and 2020. While there has been spectacular growth in renewable energies, there has also been a sharp increase in hydrocarbons. [31] [34] [35].

According to the Global Energy Monitor, Table 1 illustrates the development of Morocco's installed energy capacity in 2023. Table 2 provides the projected outlook for future energy capacity. Electric power plants in Morocco, which run on fuel oil, heavy fuel oil, diesel, and crude oil, generate a total of 1,031 MW.

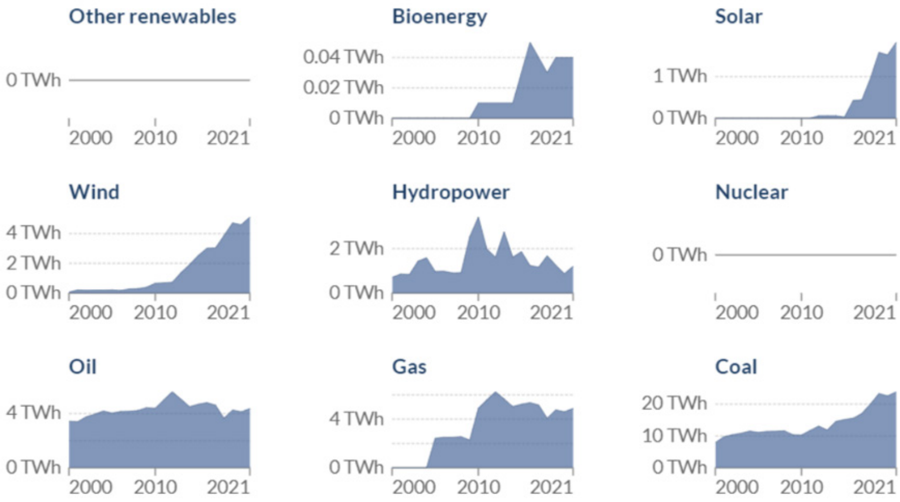

Figure 3. Evolution of Morocco's energy production [31].

Table 1. Breakdown of energy installations in Morocco [31].

Energy Source	Installed Capacity	Plant number	Percentage
Coal	4257 MW	4 plants (14 units)	49.77 %
Gas	870 MW	2 plants	10.17 %
Hydropower	1395 MW	7 plants	16.31 %
Solar	740 MW	6 plants	8.65 %
Wind	1291 MW	16 plants	15.09%

Table 2. Prospective Capacity [31].

Energy Source	Announced	Pre-construction	Construction	Total
Gas	3700 MW		457 MW	4157 MW
Hydropower		128 MW	935 MW	1063 MW
Solar	12500 MW	15209 MW	1321 MW	29030 MW
Wind	17500 MW	7773 MW	698 MW	25971 MW

4.2. Solar energy in Morocco

Solar energy in Morocco is made possible by the fact that the country has one of the highest sunshine rates of any country - around 3,000 hours of sunshine a year, but up to 3,600 hours in the desert. Morocco has launched one of the world's largest solar energy projects, estimated to cost $9 billion. The aim of the project is to create 2,000 megawatts of solar production capacity by 2020 [31] [35]. Five solar power plants are to be built, using both photovoltaic and concentrated solar power technology. The Moroccan Solar Energy Agency (MASEN), a public-private company, has been set up to manage the project. Once completed, the solar project will provide 38% of Morocco's annual electricity production.

In 2009, Morocco launched a new national energy strategy aimed at supporting the energy sector as a whole in making the transition to a low-carbon society and reducing its energy dependency. Table 3 and Table 4 provide the capacities of existing installations and those of prospective installations.

Table 3. Operating solar Energy Project [31].

Project Name	Energy Type	Installed Capacity	Operating Year
Ben Guerir solar farm	Solar PV	18MW	2021
Noor Ouarzazate solar farm	Solar PV	72 MW	2018
Noor Tafilalt Erfoud Solar	Solar PV	40MW	2020
Noor Tafilalt Missour Solar	Solar PV	40MW	2021
Noor Tafilalt Zagora Solar	Solar PV	40MW	2021
ISCC Ain Beni Mathar solar farm	Solar Thermal	20MW	2010
Noor Ouarzazate solar farm	Solar Thermal	510MW	2016

Table 4. Planned solar energy projects [31].

Project Name	Energy Type	Status	Capacity
Noor Midelt solar farm	Solar Thermal	Construction	400 MW
Noor PV II solar farm	Solar PV	Announced	67 MW
GPM1 solar farm	Solar PV	Construction	34 MW
Noor Midelt solar farm	Solar PV	Construction	400 MW
Ain Beni Mathar solar farm	Solar PV	Pre-construction	69 MW
Bejaad solar farm	Solar PV	Pre-construction	48 MW
El Hajeb solar farm	Solar PV	Pre-construction	36 MW
Green Power PV Plant solar farm	Solar PV	Pre-construction	30 MW
Guercif solar farm	Solar PV	Pre-construction	48 MW
Jerada-Marco Photovoltaique solar farm	Solar PV	Pre-construction	10 MW
Kelaa Sraghna Solar	Solar PV	Pre-construction	48 MW
Morocco-UK Solar Power	Solar	Pre-construction	7000 MW
Noor Atlas Ain Beni Mathar solar farm	Solar PV	Pre-construction	42 MW
Noor Atlas Bouanane solar farm	Solar PV	Pre-construction	30 MW
Noor Atlas Boudnib solar farm	Solar PV	Pre-construction	42 MW
Noor Atlas Boulmane (Enjil) solar farm	Solar PV	Pre-construction	42 MW
Noor Atlas Outat El Haj solar farm	Solar PV	Pre-construction	36 MW
Noor Atlas Tan Tan solar farm	Solar PV	Pre-construction	36 MW
Noor Atlas Tata solar farm	Solar PV	Pre-construction	36 MW
Sidi Bennour Solar	Solar PV	Pre-construction	48 MW
Taroudant Solar	Solar PV	Pre-construction	36 MW
Total Eren-Guelmim-Oued Noun Solar	Solar PV	Pre-construction	5000 MW

5. PV SUPPLY CHAIN IN MOROCCO

5.1. PV Solar Energy Supply Chain Stakeholders

In the aim to accelerate the deployment of renewable energy projects in the country, MASEN (Moroccan Agency for Sustainable Energy) was created in 2010. It is the national agency responsible for the development and promotion of renewable energy in Morocco. It partners with several international and national investors, institutional and private. The financing of the Moroccan Solar Plan takes different forms: preferential rate loans, guarantees, donations, [36] [37].

Research and development of solar energy is carried out by several Moroccan universities. In addition, the government has created IRESEN Institute (Institut de Recherche en Energie Solaire et Energies Nouvelles), which is a research institute focused on solar energy and new energy technologies. Its missions are to conduct applied research, transfer technologies to the private sector and support the development of technologies. It collaborates with research laboratories in the universities, and industrial partners both in Morocco and internationally to advance research and development in renewable energy. Other key institutional players are as follow:

• ONEE (electricity division):
Is responsible for managing and satisfying the country's total electricity demand as well as developing renewable energies.

• Ministry of Energy, Mines, Water and the Environment:
Renewable Energy and Energy Efficiency Department supervises the development and implementation of the national strategy for the development of renewable energies and the improvement of energy efficiency;

• ANRE (National Electricity Regulatory Authority) :
Ensures that the market functions properly by setting the rules and tariffs for use of the national grid.

5.2. Main components of PV system

The electrical energy generated by photovoltaic modules undergoes a series of transformations before reaching the grid. The main components used in a large PV system are given in the following figure 4.

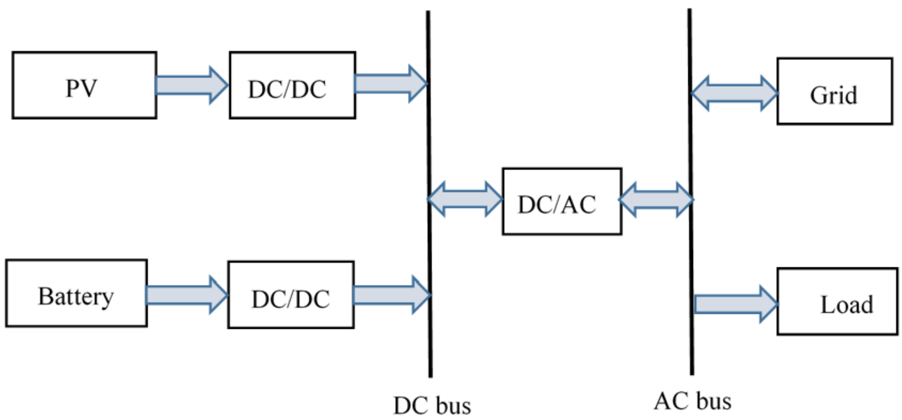

Figure 4. Main structure of a PV system.

The role of the main elements can be described as follows:

- DC-DC converters are used to boost or buck the DC voltage. As a result, the solar array voltage can be selected independently of the load voltage.
- Inverters are devices that convert direct current from solar modules into alternating current (required by the grid) and are essential components of any photovoltaic system. Inverters convert direct current from batteries or solar modules into 60 or 50 Hz alternating current.
- Batteries are used in many types of photovoltaic systems to provide energy when sunlight is low (night-time or low irradiation). In addition, batteries are necessary in solar systems due to the fluctuating nature of photovoltaic production.

5.3. PV energy supply chain in Morocco

The PV value chain in Morocco is structured according to 5 segments [38] [39] [40] as shown in Figure 5:
- Inbound of the PV energy value chain;
- Manufacturing and assembly;
- Import and distribution;
- Installation and services;
- Outbound of the PV energy value chain.

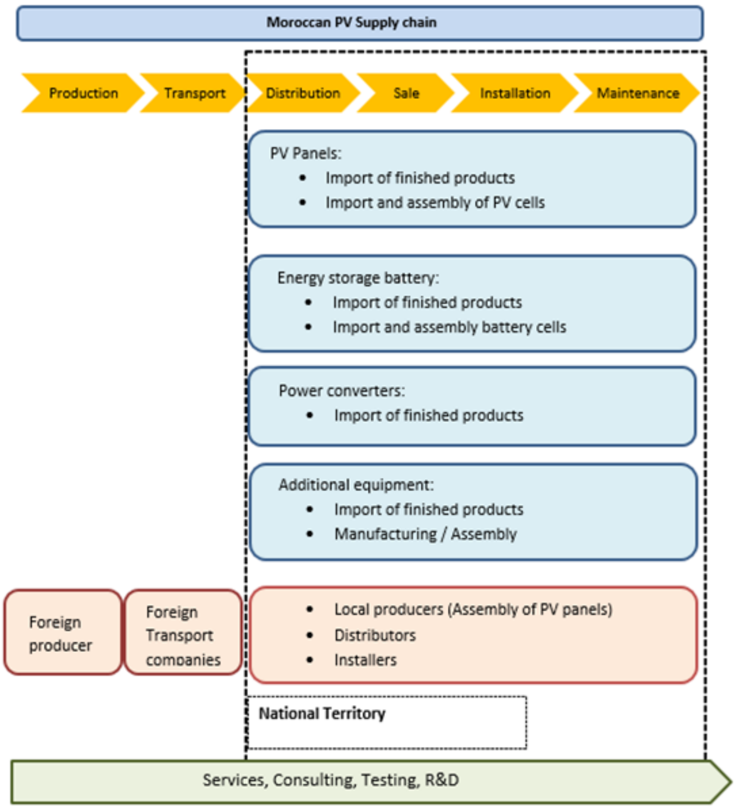

Figure 5. Moroccan PV energy supply chain.

5.3.1. Inbound of PV supply chain

a- Production of solar-grade silicon

Silicon does not exist in a free state. It is obtained by an electrometallurgical process in which a mixture of quartz, coal and wood is heated to a very high temperature in a furnace. To obtain metallurgical silicon, the silicon obtained must be almost 99% pure. Next, metallurgical silicon needs to be chemically purified. Numerous processes have been developed by the world's silicon producers. Finally, the purification process produces silicon ingots that are 99.99% purified. World production of silica sand for industry is dominated by the United States and the Netherlands [39].

b- Production of Wafers

Once it has cooled, the silicon ingot enters a process that produces circular wafers from which the components used in all electronic devices are made. In other words, the silicon ingots obtained at the end of the solidification stage are then sawn into thin wafers. The sawing stage is a determining factor in the production cost of photovoltaic cells. Worldwide, wafer production is dominated by Asian countries. The top three wafer producers are Taiwan, South Korea and Japan. China is in fifth place behind the United States [39].

c- Production of photovoltaic cells

The cell is the basic element of solar panels. It consists of a wafer of silicon (or another semiconductor) covered with a layer of glass and an anti-reflection film. Photovoltaic solar energy comes from the direct conversion of part of the sun's rays into electrical energy. This energy conversion takes place via a so-called photovoltaic cell, based on a physical phenomenon known as the photovoltaic effect, which consists of producing a current when the surface of the cell is exposed to light. Worldwide production of photovoltaic cells is dominated by four countries: China, Germany, Japan and the United States.

The above-mentioned links in the PV energy value chain are not yet present in Morocco.

5.3.2. Manufacturing and assembly

In Morocco, local production of solar collectors (assembly and installation) is gradually expanding. Local producers are companies that assemble solar collectors from solar cells imported from abroad; their activities are limited to assembling the various components used in designing the final product. The main producers of photovoltaic panels on the Moroccan market are listed in the Table 5 below. National production of photovoltaic panels is still in its infancy, although the market has great potential and could make Morocco a leader in this field in Africa [32], [39].

Table 5. Main producers of photovoltaic panels on the Moroccan market [32], [39].

Company Name	City	Capacity of production
Almaden	Al Hoceima	300 MW
PV Industry	Skhirat	30 MW
Cleanergy	Nouaceur	15 MW
Droben Energy	Nouaceur	10 MW
	Total	355 MW

5.3.3. Import and distribution

The majority of SMEs import equipment themselves in order to maximise their profit margins. Currently, the emphasis is on importing equipment from China, as this is the most accessible market, with a wide range of products varying in price and quality. In most cases, SMEs import a whole container, as the minimum quantity of photovoltaic panels that can be imported is 50 KW [39].

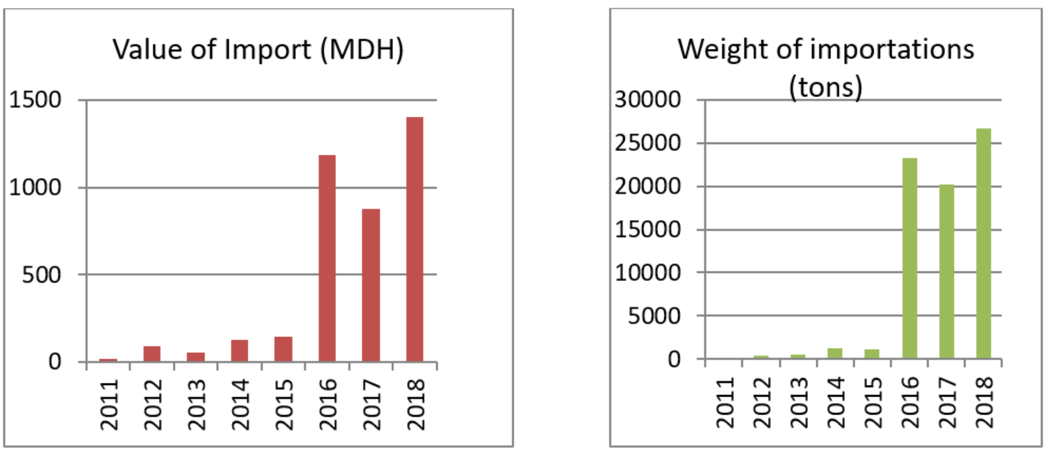

Figure 6. Evolution of import of solar photovoltaic panels.

Between 2011 and 2018, Morocco imported 3,897 million dirhams worth of photovoltaic solar panels, equivalent to 73,617 tonnes of solar panels. Over the same period, exports amounted to 47 million dirhams, virtually negligible compared with imports. The following graphs (see figure 6) illustrate the evolution of imports between 2011 and 2018 [39]. Between 2011 and 2018, Morocco imported 855 MW of solar photovoltaic panels (all applications combined).

5.3.4. Installation and services

In Morocco, solar energy systems are installed by SMEs. The installation business is expanding, driven by the growing demand for solar services. However, the major challenge lies in the inadequate quality of the services offered and the absence of a regulatory framework that structures commitments and determines responsibilities. All the electrical and civil engineering work, as well as the work on the structures supporting the panels, can be carried out by locally available skilled labor, and the installation will pose no problems if carried out under the supervision of a qualified project manager. As far as servicing and maintenance are concerned, a number of technicians have the necessary skills for small and medium-sized photovoltaic installations, but maintenance and after-sales service are not guaranteed in most cases by installers [32], [39].

5.3.5. Downstream of PV energy value chain

In Morocco, there is significant activity in the downstream part of the value chain. Import and distribution, sales, engineering services, installation and maintenance companies are the links involved and the most developed [32], [39].

6. RESULTS AND DISCUSSION

Globally, the PV solar supply chain is highly advanced, with large-scale production facilities, significant investments in R&D, and the integration of cutting-edge technologies like AI and blockchain to enhance logistics and efficiency. Countries like China, the U.S., and Germany dominate the global market, investing heavily in innovation, sustainability practices, and scaling production capacity, while benefiting from strong government policies and support. These countries also prioritize environmental sustainability, focusing on recycling programs, reducing carbon footprints, and improving circularity in the supply chain. In contrast, Morocco's solar supply chain is still in its developmental stages, with a heavy reliance on imports for key components like silicon and photovoltaic cells. The local industry focuses more on assembly and installation, and R&D efforts are minimal compared to global standards. Additionally, logistical challenges, a lack of regulatory oversight, and limited sustainability practices hinder Morocco's ability to compete globally.

While global markets benefit from large-scale exports and an established workforce trained in advanced solar technologies, Morocco's PV sector is primarily focused on meeting domestic demand, with limited export capabilities. The country's solar industry faces challenges in workforce development, with a shortage of trained personnel for specialized roles and a lack of standardized training programs. Moreover, Morocco has not yet adopted new technologies like AI and blockchain at the same scale as global players, further limiting efficiency improvements in the supply chain. Although the Moroccan government has shown strong political support for renewable energy through large projects like Noor Ouarzazate, detailed policies to promote local manufacturing and improve service quality are still evolving, making the country more dependent on imports and limiting its global competitiveness.

6.1. Solar PV Supply Chain: Market Opportunities and Growth Prospects

The PV solar energy supply chain presents several promising opportunities that have the potential to significantly drive its growth and sustainability. These opportunities address the following key areas:

Technological Advancements:

• Efficiency Improvements: Research and development can lead to higher efficiency solar cells [41].

• Energy Storage Solutions: Advances in battery technology enhance energy storage capabilities [2] [42].

• Smart Grid Integration: Integration with smart grids can optimize energy distribution [43].

Cost Reductions [2] :

Scaling up production reduces costs per unit [44]. While, new manufacturing processes lower production costs [45].

Sustainability and Environmental Concerns:

• Decarbonization Efforts: PV solar energy offers a clean alternative to fossil fuels [46].

• Government Incentives: Policies promoting renewable energy can increase solar investments [2] [47].

• Electrification and Green Hydrogen: The push for electrification across various industries, coupled with the growth of solar-powered electrolysis for green hydrogen production, presents substantial opportunities for the solar PV supply chain. The creation of green hydrogen from solar electricity can serve as a critical energy source, facilitating the transition to a low-carbon economy. This integration of solar PV technology with green hydrogen production enhances energy storage capabilities and supports broader decarbonization efforts.

Market Expansion:

• Emerging Markets: Growing energy needs in developing countries create new markets [2] [48]. Emerging markets offer numerous opportunities, particularly for off-grid solar products that can provide energy access to remote and underserved communities.

• Rural Electrification: Off-grid solar solutions provide electricity to remote areas [49]. Rural electrification initiatives create a demand for distributed solar PV systems, driving the growth of the supply chain to support these projects. Expanding solar PV infrastructure in these regions not only addresses energy poverty but also fosters economic development and improves the quality of life for local populations.

Investment and Job Growth:

On one hand, expansion of the solar industry can create employment opportunities and job creation [50]. On the other hand, investment opportunities increased interest in green investments attracts capital [2].

Innovation in Applications:

Building-Integrated Photovoltaics (BIPV) highlights integration into building materials offers new opportunities [51] and agrophotovoltaics (Agri-PV) insist in combining agriculture and PV systems optimizes land use [52].

Circular Economy and Recycling:

Developing efficient recycling methods minimizes waste [4] [53]. An increasing focus on sustainability and circular economy principles is driving the demand for recycling and reusing end-of-life solar PV components. Within the supply chain, the development of effective recycling technology offers significant potential to minimize waste and maximize resource utilization. This trend not only promotes environmental sustainability but also supports the economic viability of the solar PV sector by reducing dependency on raw material extraction and mitigating disposal costs.

6.2. Challenges and Threats in the Solar PV Supply Chain

The PV solar energy supply chain faces several critical barriers that significantly impede its growth and sustainability:

Supply Chain Disruptions:
In the solar PV sector, supply chain disruptions are defined as unanticipated occurrences or conditions that impede the smooth flow of resources, components, and goods through the supply chain. These interruptions can be caused by various events, including natural catastrophes such as earthquakes, hurricanes, and floods, as well as geopolitical tensions, trade disputes, and global health crises. Such disruptions can result in delays, shortages, increased costs, and disruptions in production schedules. Consequently, manufacturers, distributors, and installers may face challenges in meeting deadlines and fulfilling orders, leading to project delays and hindering the development and adoption of solar PV technology. To mitigate these disruptions, robust contingency planning, diversification of suppliers and logistics, and effective risk management strategies are essential [2] [12].
Inventory Fluctuations [1] [54]**:**
This refers to the inconsistency in the availability of solar PV components and materials, which can lead to difficulties in maintaining a steady supply of products.
Fluctuations in inventory can disrupt production schedules, cause delays, and lead to increased costs.
Raw Material Shortages [1] [54]**:**
This challenge involves the scarcity or limited availability of essential raw materials needed for the production of solar PV components. Shortages of materials like silicon, rare earth elements, or other critical inputs can slow down manufacturing, increase prices, and hinder the overall growth of the solar PV industry.
Policy Uncertainties and Legal Challenges: Changes in government policies and incentives create an unpredictable environment for investors and developers [2]. Inconsistent regulatory frameworks across regions increase operational costs and create barriers to entry, while issues related to intellectual property protection stifle innovation and discourage investment [45].
Technological Shifts:
Rapid advancements can render existing components obsolete, contributing to market volatility [2].
Market Saturation and competition:
on one hand, oversaturation leading to decreased demand and competitive pricing pressures [2]. On the other hand, the solar PV market faces strong competition from conventional energy sources like coal, natural gas, and oil, which continue to dominate due to established infrastructure and subsidies [44].
Quality Control and Standards Compliance [12] **:**
For a product to be reliable and accepted in the market, it must adhere to established standards, such as those developed by organizations like the International Electrotechnical Commission (IEC) or Underwriters Laboratories (UL). Non-compliance can result in product recalls, damage to brand reputation, legal issues, and potential risks to end-users. Suppliers and manufacturers make significant investments in quality control to meet these standards, thereby fostering trust in the solar PV sector and promoting sustainable growth. Compliance with these standards ensures the reliability and market acceptance of solar PV products, which is crucial for the sector's long-term success.
Financial Constraints:
High initial capital costs and limited access to affordable financing, particularly in developing regions, slow the adoption of solar PV technologies [48].
Technical Challenges:
Grid integration issues, including managing intermittency and ensuring grid stability, along with current limitations in energy storage technologies, pose significant obstacles [42].

Social and Environmental Concerns:
Land use conflicts for large-scale solar farms and the environmental impact of manufacturing processes involving hazardous materials and waste generation present further complications [46].

6.3. Current Research Gaps and Future Directions in the Solar PV Supply Chain

Despite the current research conducted on the photovoltaic (PV) solar energy supply chain, significant gaps remain in the existing literature. While numerous studies have explored various aspects of the supply chain, including technological advancements, market dynamics, and regulatory frameworks, there are several underexplored areas that warrant further investigation including:

- Advanced Technologies Integration: There is limited research on the practical implementation and effectiveness of cloud computing and blockchain technologies in optimizing PV supply chain operations [11].
- Sustainability and Circular Economy: There is a lack of detailed studies on lifecycle assessments, recyclability, and end-of-life management of PV systems, with a need for frameworks promoting sustainable practices [27].
- Environmental Impact: In-depth research on the long-term environmental impacts of large-scale solar farms, including biodiversity loss and water consumption, is missing [16].
- Policy and Regulation: The role of specific regulatory frameworks in supporting the PV industry's growth and sustainability practices is not well-explored [29].
- Consumer Behavior and Demand Response: There is insufficient research on how consumer behavior can be influenced to optimize energy consumption and support demand response initiatives [22].
- Operational Efficiency and Maintenance: Detailed cost-benefit analyses of various maintenance strategies and their economic implications are lacking [25].
- Global Supply Chain Vulnerabilities: The impact of geopolitical factors and trade policies on the availability and cost of critical raw materials like polysilicon is underexplored [8].

These gaps include the nuanced impacts of regional supply chain dynamics, which vary widely and can significantly influence local and global markets. Additionally, the long-term sustainability challenges posed by evolving technologies, such as the environmental and economic implications of new innovations, have yet to be fully addressed. The interplay between policy changes and market performance also remains inadequately studied, particularly how shifts in government incentives and regulations affect different segments of the supply chain. Highlighting these gaps as future research perspectives is essential for developing a more comprehensive understanding of the PV solar energy supply chain and for fostering the continued growth and resilience of the industry. Addressing these areas will contribute to more effective strategies for overcoming barriers and enhancing the sustainability and efficiency of solar energy systems.

7. CONCLUSION

In conclusion, the solar photovoltaic (PV) industry is on a trajectory of significant growth, driven by technological advancements and increasing market opportunities. However, to fully capitalize on these opportunities and ensure sustainable progress, it is imperative to address the identified challenges and research gaps within the PV solar energy supply chain. Key barriers such as supply chain disruptions, policy uncertainties, and regulatory challenges must be mitigated through targeted strategies and robust risk management. Additionally, exploring underexamined areas, such as the integration of advanced technologies and long-term environmental impacts, will provide a more comprehensive understanding of the sector's dynamics and support its evolution toward greater efficiency and resilience. To advance the industry, several directives are essential.

Enhancing technological integration, advancing sustainability practices, and investigating the long-term environmental impacts of solar farms will contribute to a more sustainable and efficient solar energy supply chain. Evaluating policy frameworks, studying consumer behavior, and assessing operational efficiency will further support the sector's growth and stability. Additionally, examining global supply chain vulnerabilities will help mitigate risks associated with raw material availability and trade policies. By addressing these recommendations, stakeholders can foster a more robust solar PV industry, supporting the transition to a low-carbon economy and meeting the world's growing energy needs.

In recent years, Morocco has made industry a new driving force for its national economy, with sectors like automotive and aeronautics achieving remarkable results. However, this progress has not yet been mirrored in the PV energy sector, where projects often depend on the physical connection to the national electricity grid, managed exclusively by ONEE. To advance Morocco's PV industry, several recommendations have been made by stakeholders:

• Product and Service Recommendations: Speed up the signing of a program contract between the State and sector operators, focus on local production of PV components, and promote "Made in Morocco" and IMANOR certifications.

• Regulatory Recommendations: Unblock medium voltage for private solar energy, accelerate the implementation of self-generation, simplify the connection procedure for self-generating PV installations, and encourage innovation in storage solutions.

• Tax and Customs Recommendations: Strengthen tax incentives and financial aid for renewable energy adoption and introduce customs measures to promote local solar component manufacturing.

• Market-Oriented Recommendations: Build local skills for export, particularly in innovation and R&D, and enhance the capacity of national operators to explore new markets, especially in Africa.

By addressing these challenges and recommendations, stakeholders can foster a more robust and resilient solar PV industry. For Morocco, implementing these actions will help the country further integrate solar PV into its industrial landscape, contributing to national energy security, economic growth, and environmental sustainability. Globally, the solar PV industry will continue to play a pivotal role in transitioning to a low-carbon economy and meeting the world's growing energy demands. Ongoing research, targeted policy support, and technological innovation will be crucial to ensuring the sector's success and long-term viability.

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