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Sustainability of Photovoltaic Power Plants in Desert Environments: From Design to Maintenance Strategies

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Abstract. The deployment of large-scale photovoltaic systems in desert regions offers significant potential due to high solar irradiance and vast unoccupied land. However, these environments also present extreme challenges that impact the performance of the systems and their longevity. This paper reviews several major photovoltaic projects in desert areas worldwide, outlining their key technical characteristics and some of their environmental constraints. Two experimental platforms – ATOMOS-TEC in Chile and Green Energy Park in Morocco – are then presented as case studies for the analysis of degradation mechanisms such as soiling, delamination and thermal stress. Their findings contribute to the optimization of the design of photovoltaic modules for desert applications. The paper also examines advanced maintenance strategies, including robotic and waterless cleaning solutions, infrared thermography, electroluminescence imaging, and aerial inspection techniques using unmanned aerial vehicles (UAVs) and AI-based fault detection. These approaches are essential for maintaining efficiency and reducing operational costs in harsh climates and ensuring the long-term sustainability of the photovoltaic plants in arid environments.

1 Introduction

The deployment of photovoltaic energy production systems needs vast expanses of land. One potential solution is to use desert regions, which are largely uninhabited. A simple calculation shows that in order to capture sufficient solar energy to meet the global primary energy consumption in 2021, estimated at 19.6 TW, different surface requirements could be applied depending on the location of the energy collection. On Earth, taking an average solar irradiance at ground level around 200 W.m^{-2}, the necessary surface area without accounting for conversion losses would be approximately 98,000 km^2 – equivalent to a square of about 313 km by 313 km. When considering a photovoltaic converter with 20% efficiency, this required area increases to roughly 490,000 km^2, or a square measuring 700 km by 700 km.

In fact, deserts cover about one-fifth of the Earth's land surface and are characterized by annual precipitation of less than 25 cm [1]. Among them, hot deserts like the Sahara are

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particularly attractive for solar power owing to their high average solar irradiance, which reaches an average of 263 W.m^{-2}. The Sahara also experiences extreme temperatures, with more than 100 days per year exceeding 40°C, low nighttime temperatures that can fall below 0°C, relative humidity below 10% and average wind speeds of 5 m.s^{-1} (18 km.h^{-1}). However, these regions present highly challenging climatic conditions, making the maintenance operations of installations complex. Moreover, transporting the generated electricity over long distances would pose significant challenges, in addition to dealing with intermittency and the need to implement energy storage systems. It is also important to note that not all deserts share the same climate characteristics, as shown in Table 1, which summarizes the surface areas of the world's major deserts that have the potential to be considered for large-scale solar deployment.

Table 1. Diversity of the World's major deserts: surface areas and climate types [1].

Desert	Climate type	Surface area (km²)
Antarctic	Polar	14,000,000
Sahara	Subtropical	9,065,000
Arabian Desert	Subtropical	2,331,000
Gobi Desert	Cold continental	1,300,000
Chihuahuan Desert	Subtropical	450,000
Great Victoria Desert	Subtropical	424,000
Atacama Desert	Subtropical	104,000

The present paper reviews several major ongoing large-scale photovoltaic power plant projects or existing installations located in various desert regions around the world. It then focuses on two dedicated research platforms and examines the specific degradation mechanisms observed in desert environments, along with the implications of these findings for the design of photovoltaic modules. Finally, the paper addresses the issue of photovoltaic power plant maintenance under hot and arid climates, presenting examples of strategies already implemented, and provides a review of key maintenance operations to be considered. It also discusses the development of diagnostic tools and both existing and emerging solutions tailored to the challenges of maintaining photovoltaic systems in desert environments.

2 Major large-scale photovoltaic plants

Large-scale photovoltaic installations in desert environments represent one of the most promising solutions for producing massive amounts of renewable energy. In this section, seven major plants, either operational or under development, are reviewed providing their main specific features.

Noor Solar Complex (edge of Sahara Desert, Morocco) – The Noor Solar Complex in Ouarzazate, Morocco, includes a large-scale photovoltaic phase of around 70 MW, integrated into a broader system combining Concentrated Solar Power (CSP) and photovoltaics to exceed 580 MW in total capacity. Commissioned between 2016 and 2018, this project was located in a desert area on the edge of the Sahara [2]. The installation has to be connected to the national grid and is part of Morocco's strategy to reach 52% renewable energy by 2030.

Bhadla Solar Park (Thar Desert, India) – Commissioned in 2015, the Bhadla Solar Park is one of the World's largest solar farms, covering 57 km² and providing 2.7 GWp of capacity, with plans to expand to 3.5 GWp. Located in the arid Thar Desert, the plant faces frequent sandstorms, which can reduce its electricity production by up to 40%. Various cleaning solutions are being tested on-site to mitigate this impact and maintain its efficiency [3].

Sheikh Mohammed bin Rashid Al Maktoum Solar Park (Dubai, United Arab Emirates) – Building on this trend of ambitious projects, the Sheikh Mohammed bin Rashid Al Maktoum Solar Park in Dubai is set to be completed by 2030 (Figure 1) [4]. The installation will combine 77 km² of photovoltaic panels with a 262-meter solar tower equipped with 70,000 adjustable mirrors, aiming for a total capacity of 5 GW.

Huanghe Hydropower Hainan Solar Park (Qinghai province, China) – Moving to China, the Huanghe Hydropower Hainan Solar Park has been in operation since 2009 in the desert areas of the Qinghai province (Figure 2) [5]. With seven million photovoltaic modules, it generates 2.2 GWp and is connected to a high-voltage transmission line over 1,500 km long, enabling it to supply electricity to several Chinese provinces.

Edwards and Sanborn Solar (California, USA) – In the United States, Edwards and Sanborn Solar project with its energy storage in California has been deployed since 2022 [6]. It should feature two million solar panels for a capacity of 875 MW, combined with an energy storage system providing 3 GWh (Figure 3), underscoring the growing importance of integrated storage solutions in large-scale solar developments.

CEME1 Solar Power Plant and Oasis de Atacama projects (Atacama Desert, Chile) – Further south, in the Atacama Desert of Chile, the CEME1 plant, which relies on 882,720 photovoltaic panels to achieve 480 MW of capacity across 435 hectares, was connected to the grid in April 2024 [7]. The plant supplies electricity to half a million households, benefiting from an exceptional solar irradiation level exceeding 3,000 $kWh.m^{-2}$. This project contributes to Latin America's target of 319 GW of combined solar and wind capacity by 2030. Another project, the Oasis de Atacama one, has been deployed since 2024 with a planned total capacity of 2 GW photovoltaic generation coupled with 11 GWh of battery energy storage in seven phases over the upcoming years (Figure 4).

SunCable Project (Northern Australia) – Finally, the SunCable project in northern Australia illustrates the vision of exporting solar power across borders [8]. Planned for commissioning in 2030, the installation will provide 6 GW (4 GW for domestic use and 2 GW for export to Singapore), covering 12,000 hectares. It will be supported by battery storage with a 40 GW capacity, supplying electricity to three million households at an estimated cost of 21 billion euros.

3 Degradation modes and experimental platforms

Photovoltaic modules deployed in desert environments are exposed to severe stress factors that accelerate the degradation and reduce the performance over time. Major degradation modes include optical issues such as glass erosion, delamination, encapsulant discoloration, cracks and soiling [9]. In order to determine adapted and robust technologies of photovoltaic modules and help in the conception of photovoltaic modules, experimental platforms have been installed in desert environments to conduct studies under outdoor test conditions. Two examples of platforms with the outcomes that can be provided are presented hereafter.

Fig. 1. Sheikh Mohammed bin Rashid Al Maktoum Solar Park in Dubai.

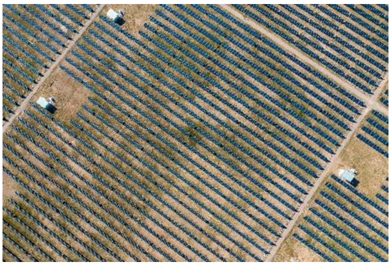

Fig. 2. Huanghe Hydropower Hainan Solar Park in China.

Fig. 3. Edwards and Sanborn Solar in California with a battery energy storage system.

Fig. 4. Oasis de Atacama in Chile, a solar plant and battery energy storage system.

The ATAMOS-TEC platform in Chile, located at the Plataforma Solar del Desierto de Atacama (PSDA), is dedicated to studying the aging and soiling of photovoltaic modules under extreme desert conditions. The platform combines outdoor characterization of photovoltaic modules with laboratory tests that simulate local environmental conditions, such as dust deposition, using indoor setups (Figure 5). In the Ph.D. work of Arbaretaz, analyses of deposited dust revealed a complex mineral composition (including gypsum, albite, muscovite, quartz, and halite), with larger particles showing signs of agglomeration likely due to dew drying [10]. The research demonstrated that bifacial modules experience up to 2% less soiling-related loss compared to monofacial modules, and that predictive models of soiling are more reliable during the hot season. Additionally, modules with Passivated Emitter and Rear Cell (PERC) and heterojunction cell technologies were found to be less sensitive to soiling. Short-term soiling rate predictions were significantly improved using recurrent neural network (RNN) models, highlighting the potential of AI for enhancing maintenance strategies.

The Green Energy Park platform in Morocco focuses on studying degradation mechanisms and solutions for photovoltaic modules exposed to desert conditions (Figure 6). In the study of Bouaichi et al., the investigations carried out on the platform enabled the identification of both visible defects, such as cracks, snail trails, delamination and discoloration, and invisible ones which were revealed through advanced imaging techniques like infrared thermography and electroluminescence, including hotspots, potential-induced degradation (PID) and microcracks [9]. Some degradation rates observed reached up to 2.7% per year – much higher than manufacturers' estimates – reducing the expected lifetime of these modules to about seven years, with severe consequences for the profitability of the plant. The main causes of these failures are high temperatures, thermal cycling, dust accumulation, intense UV exposure and humidity. The platform has developed recommendations at various levels to improve module reliability, including the use of multi-busbar cells and PERC or TOPCon technologies at the cell level, glass-glass encapsulation and anti-soiling coatings at the level of the module, and reinforced mounting systems and bypass diodes at the level of the system to mitigate mechanical and thermal stresses.

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Fig. 5. ATAMOS-TEC test platform in Chile in the Atacama Desert [10].

Fig. 6. Green Energy Park platform in Morocco with different technologies of photovoltaic modules [9].

4 Maintenance and examples of developed strategies

Desert environments exhibit high soiling rates that have a profound impact on the energy yield and the operations and maintenance of photovoltaic power plants. There are three main types of solar panel cleaning methods commonly used in desert environments, where dust and sand accumulation can significantly reduce energy output [3]. The first method is manual or mechanized cleaning using demineralized water to prevent mineral deposits from forming on the surfaces of the panels (Figures 7 and 8). This technique is effective, but can also be water-intensive. The second approach involves the use of cleaning robots, which are particularly suitable for large-scale solar power plants. These robots can operate autonomously, ensuring regular maintenance with reduced labor costs. However, vibrations caused by robotic cleaning of photovoltaic modules may degrade them (e.g., cell cracking, delamination). These vibrations are not currently a significant concern for degradation, but that as photovoltaic modules become larger and more flexible, vibration-induced stress could increase, especially since wind already causes greater deflection than cleaning robots. Thirdly, dry cleaning methods are also employed, using special brushes or compressed air.

In adding, Al-Housani et al. proposed several solutions to address soiling on photovoltaic panels in desert environments, including using anti-soiling coatings, implementing robotic dry cleaning systems, and optimizing cleaning schedules based on real-time monitoring of soiling rates and weather data [11]. Self-cleaning methods have been elaborated for photovoltaic panels to help maintain high energy efficiency, reduce maintenance costs, prevent surface damage, extend panel lifespan and support sustainable, low-energy operation. Syafiq et al. have reviewed advancements in self-cleaning methods for solar photovoltaic panels and highlight the interest of implementing superhydrophobic coatings inspired by the lotus effect—where rolling water droplets remove dust efficiently—as the most energy-efficient and surface-preserving solution among mechanical, electrostatic, and coating approaches to maintain the photovoltaic performance [12]. These solutions aim to reduce water consumption, minimize manual labor, and maintain photovoltaic efficiency, making them valuable especially in arid regions where water is scarce and conditions are harsh.

The maintenance of photovoltaic plants in desert environments involves several other essential tasks to ensure optimal performance and long-term reliability. These operations include regular maintenance of inverters, such as cleaning filters, checking ventilation systems, inspecting electrical connections, and replacing worn-out components like capacitors and fans. The structural integrity of the installation is verified through the tightening of bolts and screws and inspection of the support structures for signs of corrosion, especially in areas exposed to saline environments as well. The maintenance of cables and connectors consists of checking UV protection on cable sheaths, ensuring the integrity of connections and junction boxes to prevent short circuits. Lastly, monitoring of meteorological conditions and performance data is conducive to anticipate failures and adjust operations accordingly, with periodic analysis of production data to detect anomalies and optimize plant management. Operational temperatures of both panels and inverters are monitored to identify abnormal heating patterns that could signal component failure or inefficient performance.

With regard to diagnosis purposes, visual inspection associated with detection techniques such as infrared thermography, electroluminescence, ultraviolet fluorescence, and current-voltage and power-voltage characterization can play a key role in the diagnosis for the maintenance of photovoltaic plants, particularly in harsh environments like deserts [9]. These types of inspection allow for the detection of hotspots, snail trails, and mechanical and thermal stress areas that can indicate underlying faults. The studies of Daher et al. and of Ramirez et al. both demonstrate the effectiveness of using Convolutional Neural Networks (CNN) for automated fault detection in photovoltaic modules through infrared thermography, enabling the identification and classification of various anomalies with high accuracy and minimal manual intervention [13]. More, a novel technique based on apparent emissivity measurements using long-wave infrared (LWIR) cameras is also being developed to detect surface erosion on the glass layer of photovoltaic modules [14].

Besides, aerial inspection methods for photovoltaic plants increasingly rely on unmanned aerial vehicles (UAVs) equipped with a variety of sensors, each offering specific advantages for fault detection [15]. Aerial infrared thermography (aIRT) is one of the most established techniques, enabling the detection of thermal anomalies such as hot spots, disconnected substrings, or faulty junction boxes across large installations in a fast and non-invasive manner (Figure 9). Red, Green, Blue (RGB) visual imaging, often combined with aIRT, allows for the detection of surface defects like glass cracks and soiling from dust or bird droppings, introducing AI-based detection models. Moreover, aerial electroluminescence (aEL) imaging is an emerging method that uses near-infrared (NIR) cameras to capture luminescent emissions from photovoltaic cells under reverse bias, revealing microcracks and shunted regions that are often invisible to thermal inspection, although this technique is technically demanding. Digital aerial photogrammetry further complements these approaches by generating georeferenced orthomosaics that simplify the localization of the defects and support the development of automated fault detection pipelines. Additionally, inspection path optimization using algorithms like Particle Swarm Optimization and Genetic Algorithms contributes to reducing time, energy consumption, and data redundancy while ensuring complete coverage of the plant. Together, these methods and advancements enable faster, more accurate, and scalable photovoltaic inspection strategies. Each method thus offers complementary advantages: thermography provides rapid and efficient thermal analysis, RGB imaging supports visual diagnosis, photogrammetry permits precise mapping, and aerial electroluminescence reveals defects that are otherwise invisible. The integration of artificial intelligence and the optimization of flight missions will help automate and enhance the reliability of the entire inspection process.

Fig. 7. Manual cleaning of photovoltaic modules.

Fig. 8. Mechanized cleaning of photovoltaic modules.

Fig. 9. Thermal inspection of a photovoltaic plant.

5 Conclusion

Desert environments offer exceptional solar resources for large-scale photovoltaic power generation, but also present harsh conditions that accelerate the degradation of the photovoltaic modules and complicate the maintenance operations. This paper has highlighted both the opportunities and challenges associated with deploying photovoltaic systems in arid regions. Through a review of major international projects, it was shown that diverse design approaches are being implemented to increase the renewable energy production, namely by integrating storage solutions. Field studies conducted on dedicated experimental platforms enable the achievement of valuable insights into the dominant degradation mechanisms affecting photovoltaic modules in desert climates. These results inform technological choices for materials and module design. Furthermore, the development of effective maintenance strategies – ranging from robotic and self-cleaning systems to AI-based fault detection and aerial diagnostics – emerges as essential for ensuring long-term reliability and high performance of the photovoltaic plant. Future research should continue to address the trade-offs between cost, durability and efficiency in desert applications, with a particular focus on optimizing predictive maintenance and resilience to environmental stressors.

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