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ENHANCING ROOFTOP PV PERFORMANCE IN DESERT CLIMATES THROUGH ADAPTIVE O&M: SAUDI ARABIA CASE STUDY

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Abstract
This paper explores adaptive operation and maintenance (O&M) strategies to improve rooftop photovoltaic (PV) system performance in Saudi Arabia's harsh desert climate. Despite high solar irradiance, factors like dust, extreme heat, and humidity reduce system efficiency and lifespan. The study evaluates smart technologies including AI-driven predictive maintenance, robotic cleaning, and IoT-based monitoring. Key performance indicators such as performance ratio (PR), utilization factor, and Levelized Cost of Electricity (LCOE) were analyzed through case studies in Riyadh and Dhahran. Results show that adaptive O&M can boost energy output by at least 12%, maintain PRs above 90%, and lower LCOE to $0.014/kWh. These strategies prove more cost-effective and efficient than traditional reactive approaches. The paper concludes with recommendations for real-world implementation and highlights research gaps for desert PV systems in the MENA region.

INTRODUCTION

Saudi Arabia, located in one of the world's most solar-abundant regions, enjoys exceptionally high levels of solar irradiation, ranging between 2000 and 2500 kWh/m²/year (1). This abundance positions the Kingdom as a natural candidate for large-scale solar photovoltaic (PV) deployment. Despite these favorable climatic conditions, as of 2021, only around 3% of Saudi Arabia's total installed electricity generation capacity—estimated at approximately 105 GW—came from renewable energy sources. The remainder continues to be dominated by fossil fuel-based power plants, heavily supported by state subsidies. These subsidies, which exceed $40 billion annually, have historically suppressed incentives for the adoption of alternative energy sources. Nevertheless, the electricity consumption of the country, in particular, the residential sphere, has grown to 142.4 TWh per year, which makes the future of such a fossil-dependent system even more doubtful. (1).

In order to deal with these issues and prepare for a more sustainable future, Saudi Arabia has started to develop a long-term national plan with its Vision 2030 and the national renewable energy program (NREP). The purposes of these strategic frameworks include diversification of the nation's energy mix, minimizing greenhouse gas emissions, and generating emerging economic sectors of growth. One aspect of such initiatives has been the development of solar energy capacity, of which a national target of 58.7 GW of renewable energy by 2030 is set, and solar PV systems are likely to represent the majority of this new capacity (2). Remarkably, the utilization of distributed energy resources (DERs) and rooftop PV systems, in particular, has evolved into a strategic priority in terms of decentralization of power supply, minimizing transmission losses along with decreasing the load on the national grid during high-load period.

Restructuring of the electricity tariffs happens to be one of the most critical factors of this transition to rooftop PV. In the year 2018, a steep rise in electricity prices was introduced by the Electricity and Co-generation Regulatory Authority (ECRA), which essentially turned its price in certain industries into three times as expensive. This action shifted the financial situation immensely, and solar PV became affordable to residential and industrial end users. Additionally, there have been incentives for net metering as well as a new regulatory structure put in place to attract private investment in solar energy systems. This has consequently led to the increased demand for rooftop PV installation, especially in commercial and industrial areas like Abqaiq, Riyadh, and the Eastern Province.

Most technical studies published in recent years also confirm the feasibility of rooftop PV systems in Saudi Arabian weather conditions due to the desert climate. Innovative technologies of high-efficiency modules, e.g., N-type bifacial PV panels, reported high performance levels in field tests. Al-Hanoot, Mokhlis (1) Found out that rooftop PV systems with state-of-the-art modules had up to 94.2 percent performance ratio (PR) and a Levelized Cost of Electricity (LCOE) of only 0.014/kWh, and therefore amongst the most affordable renewable energy alternatives available today. Such systems can easily be incorporated into the grid in the country and have the ability to minimize both the expenditure of energy as well as the emission of carbon in the long run.

In combination, these developments support the fact that rooftop PV systems are strategic to the attainment of the renewable energy targets of Saudi Arabia. Nevertheless, such factors as harsh climatic conditions, dust sediments, and the necessity of highly developed maintenance techniques still play a very important role. These are operational issues that need to be addressed to maximise the potential of rooftop PV in desert conditions, and on which this research will elaborate.

1.1. The Importance of Rooftop PV Systems in Arid Regions

Rooftop PV is an easy solution for countries that experience extreme climates, especially in arid areas such as Saudi Arabia. They are mostly installed on residential, commercial, and industrial constructions with efficient utilization of available urban infrastructure without the need to acquire new land. The rooftop systems are particularly advantageous in compensating for the high midday electricity costs at times when cooling systems are in use in desert climates.

In a study by Iqbal, Ullah (3)It was established that the effectiveness of rooftop PV in reducing cooling loads can be substantiated by incorporating architectural shading structures to generate electricity. The percentage of solar use was 27.19 and 24.72 in residential buildings of Abha and Riyadh, respectively, where solar canopy systems were installed. Meanwhile, a rooftop system in Abqaiq showed that 1 large-scale industrial rooftop system had the potential to produce more than 5,500 MWh per year, reducing grid reliance and energy costs dramatically.

The abovementioned examples show that rooftop PV systems are not just effective when it comes to decarbonization objectives but also assist in energy efficiency in buildings, which in hot and arid regions is of paramount concern due to the significant reliance on air conditioning as a source of power.

1.2. Scope of the Saudi Arabian Case Study

The study is dedicated to the analysis of the technical and operational effectiveness of rooftop PV systems installed in the extreme desert environment of Saudi Arabia. It intends to test the impacts of soiling, ultra-high temperatures, and sandstorms, which are the environmental conditions that can severely compromise the PV performances and the operational performances of the systems. Based on the past installation data, simulation of performance, and literature-based reviews, the research finds key performance indicators (KPIs) of rooftop PV systems in these environmental limitations.

Commercial and industrial rooftop applications are also analyzed in some of the cities, such as Riyadh, Abqaiq, and Dhahran, where grid-tied and hybrid PV systems have also been implemented. Along with this, larger regulatory and economic elements that affect the implementation of rooftop PV fitting in Saudi Arabia have been touched upon in the study, especially the necessity of proper operation and maintenance (O&M) procedures to be used in desert weather conditions.

1.3. Novelty of Adaptive O&M Strategies in Desert Climates

Standard methods of maintenance-like cleaning a system with a mop and brush, or cleaning with a clean-up every quarter, might actually not be applied enough in the extreme desert environment. According to PV systems operating in Saudi Arabia, the efficiency degradation is very fast because of the dust collected, thermal stress, and high mechanical wear rate. (4). As an example, soiling by itself can decline energy production up to 13 percent per month; sandstorms might contribute to even more losses in case of delays concerning maintenance. To counter such challenges, the paper will examine adaptive, intelligent O&M strategies geared towards desert climates in particular. Examples of such are automatic cleaning systems, predictive maintenance modeling powered by AI, and performance monitoring related to IoT. These methods denote the change of reactive maintenance to proactive maintenance, focused on early detection of faults, optimization of cleaning cycles, and minimization of operational costs in the long term.

Through the combination of smart technologies and environmental analytics, adaptive O&M can dramatically decrease the time spent on rooftop PV projects in arid regions, which in turn provides a multiplier effect of lifespan, reliability, and project economics. The study belongs to the insignificant and growing list of research dedicated to the real-life optimization of the activity of PV systems in desert conditions discussed in Saudi Arabia in the framework of regional (MENA zone) contexts.

2. Methodology

The research topic is to develop the operation of rooftop photovoltaic (PV) systems in the desert climatic area in Saudi Arabia, including analysis of the strategies of the adaptive operation and maintenance. In order to realize this, an iterative measure of collecting data, reading case studies, and evaluating performance has been used. The source was gathered in scientific articles, reports of international organizations, government publications, and recent works in the sphere. The plan was to know what the most important considerations are that should be made in installing a rooftop PV system, and how different O&M practices would facilitate the effectiveness of PV systems to survive in harsh desert climatic conditions.

2.1. Selection Criteria for Rooftop PV Systems in Desert Climates

The first one was the selection of the proper rooftop PV systems that were to be considered. This has been done by selecting such systems that are already available in Saudi Arabia, more so in areas that are likely to possess high solar energy, like Riyadh and Abqaiq. The infrastructures are also exposed to a good amount of solar radiation, averaging around 2000 to 2500 kWh/m2 a year, hence making them suitable when it comes to the study of PV performance (1).

The systems chosen were either house installations or business ones with a full history of performance and maintenance, and the environmental variables. Such aspects as building design, the size of rooftops, the orientation of the solar panels, and the technological type (monocrystalline or bifacial modules, etc.) were taken into account as well. The following factors were used to inform the review of these systems, namely, their age, size, and whether they have ever been exposed to problematic aspects of the desert by way of dust building up and concentrations of heat, as well as the occurrence of sandstorms (5). The choice of this diversity facilitated the study to emphasize actual rooftop systems found in real-life situations in the desert climate of Saudi Arabia, which is a typical use case.

2.2. Metrics for Assessing Performance and Degradation

In order to know the effectiveness of the rooftop PV systems, the study employed some performance measures. The most significant ones were the performance ratio (PR), the specific yield, and the degradation rate. These signs assist in quantifying the amount of energy that is raised by the system in comparison with the amount of energy that should have been fueled by the system in an ideal condition.

The performance ratio (PR) shows the efficiency of the system and is calculated using the formula:

PR = Final energy output (YF) / Reference energy input (YR)

PR is usually shown as a percentage. A higher percentage means the system is performing closer to its expected potential (6).

Another key metric is the specific yield, which tells how much electricity is generated per kilowatt of installed capacity. It is calculated as:

Specific yield = Total energy output (EAC) / Rated power (kWp)

The finding of this measure enables the comparison of systems of different scales and assists in monitoring energy generation over time (7).

In the desert, the soiling and the temperature result in the decrease in performance at an accelerated rate. Hence, the degradation rate is significant as well. It gauges the rate at which the system deteriorates as the years increase. In this work, the values of literature and historical data were used to calculate the average annual rate of degradation of the systems in Saudi Arabia, which can reach up to 2-6, with some fluctuation depending on the system and the environment (8).

2.3. Evaluation of O&M Strategies and Modelling Techniques

After evaluating performance, various O&M strategies were to be considered. They were manual cleanup schedules, automated clean-up systems, artificial intelligence (AI), and Internet of Things (IoT) tools based on predictive maintenance. According to previous research papers, the study compared the amount of energy and cost-effectiveness of different cleaning schedules, including daily, bi-weekly, and monthly, among others (5). Indicatively, cleaning of dusty regions two times a week was shown to increase energy production by a 12 percent margin and assist in LCOE (Levelized Cost of Energy) decrease.

Also, previous attempts to model and predict PV system faults with the help of machine learning were reviewed in the study. Through these techniques, possible problems such as overheating, soiling, and failure of the inverter can be forewarned before they end up being a serious source of energy losses. Such tools as reinforcement learning models and random forests models were also presented as good alternatives that can be used to optimize maintenance (9). Lastly, the study integrated all the data collections and all the modeling outputs to give a clear picture of the O&M strategies that would suit the rooftop PV system under the desert climate of Saudi Arabia.

3. Context of Rooftop PV in Harsh Climates

3.1. Environmental and climatic stressors in Saudi Arabia

There is a hot desert climate in Saudi Arabia with extreme temperatures and high desert without rainfall, accompanied by desert sandstorms intermittently. Such environmental effects have a direct influence on the performance and reliability of rooftop photovoltaic (PV) systems. Summer temperatures in various parts of the country can reach as high as 44 0 C, with the maximum temperature in July reaching a maximum of 44.06 0 C in recent years in the eastern cities of Dammam (8). Human activities and solar technologies are also subject to very high levels of specific humidity, which adds heat strains on warm summer days.

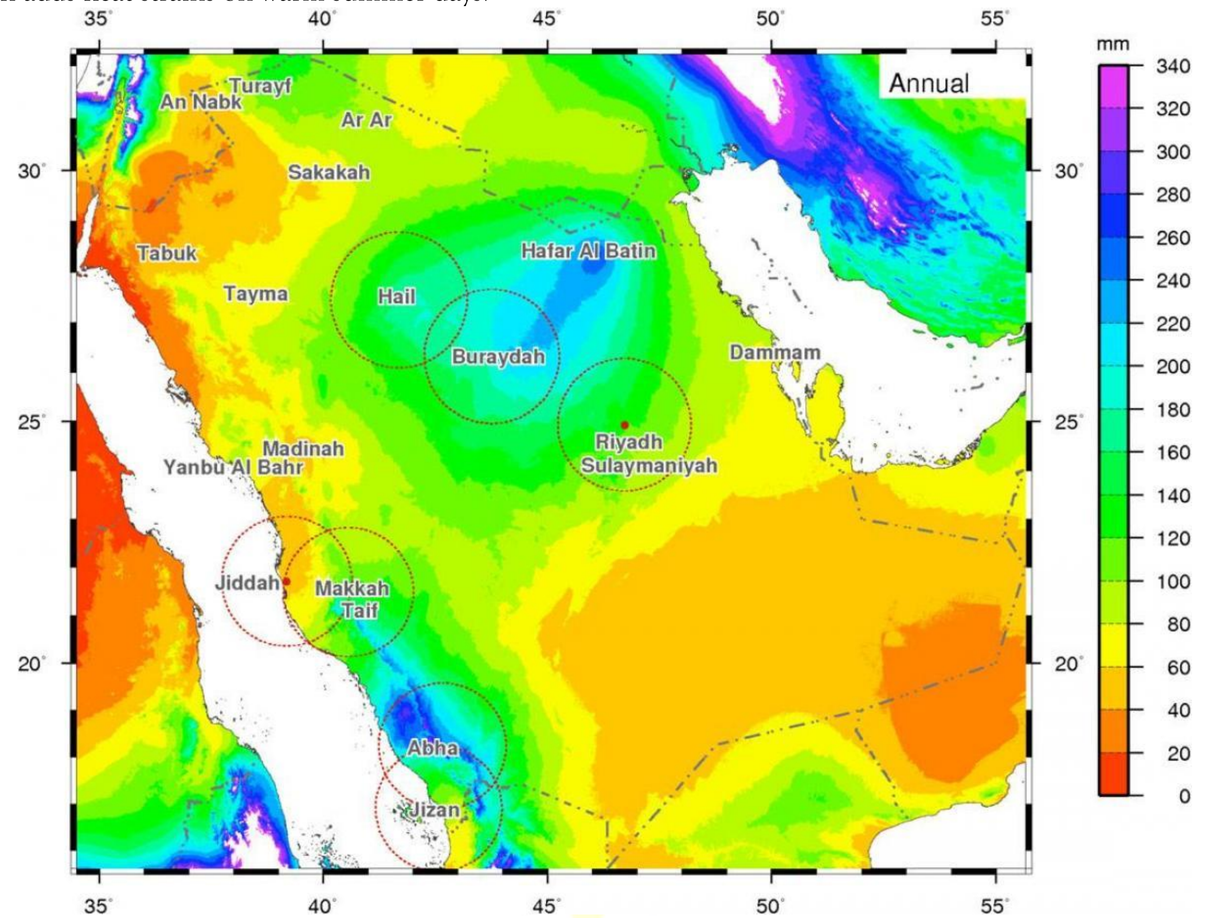

Figure **1: Map of Saudi Arabia climate (10)**

Most of the Kingdom has a substantially limited rain level of under 100 mm annually, with the central and eastern parts of the kingdom, such as Riyadh, Hafar Al Batin, and Dammam, being among the driest places in the kingdom, as indicated in Figure 1. This dryness is among the reasons that cause constant dust storms and a lot of dust in the atmosphere, which covers PV panels and makes them less effective. Studies revealed that PV output could be reduced by up to 13 percent a month without cleaning due to the accumulation of dust on PV panels (11). In severe sandstorms, energy losses can even surpass 80%.
In addition to dust, the combination of high temperature and intense solar radiation accelerates the degradation of PV components. Standard silicon PV modules lose about 0.4–0.5% efficiency per degree Celsius rise in temperature (12). Such thermal stress, repeated daily during summer, shortens the lifespan of the panels unless advanced cooling or thermal-resistant modules are used. Such environmental stressors as heat, dust, humidity, and low rainfall are significant impediments to the O&M of rooftop PV systems in Saudi Arabia. Such wise practices, as adaptive O&M models, climate-adequate PV material, and predictive cleaning programs, should be used to make sure that the systems provide consistent energy generation and durability.

3.2. Solar resource availability and meteorological variability

Saudi Arabia is the solar-rich nation on the globe with the average GHI value that ranges between

5.8 and 6.4 kWh/m 2 per day, depending on the area of location. Medina, Mecca, and Tabuk thoroughfares are some of the regions exhibiting the highest level of solar radiation, which is most time more than 6.2 kWh/m2 per day as indicated in Figure 2. The country is, in this regard, a very good candidate for rooftop photovoltaic (PV) energy systems due to its consistent solar accessibility (13).

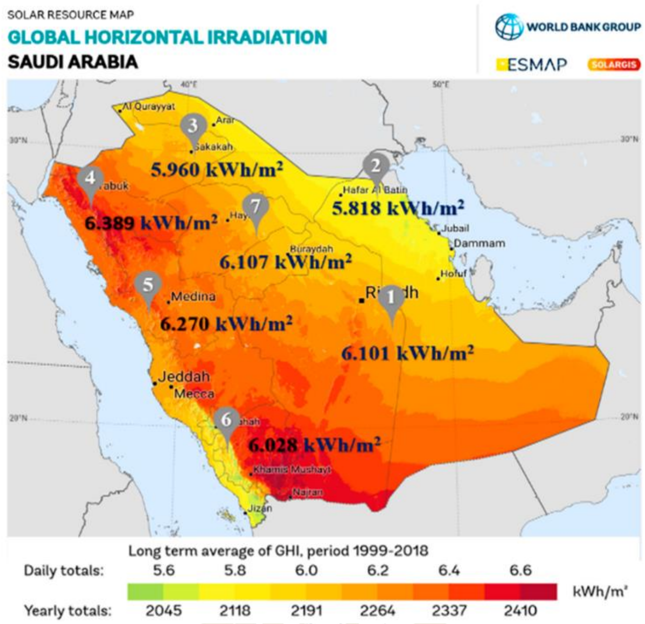

Figure 2: The solar GHI heat map of Saudi Arabia (14)

However, solar resource availability also shows variability due to seasonal and geographical factors. The example presence of occasional humidity and clouds can reduce the solar radiation in the eastern coastal cities such as Dammam and Hafar Al Batin by a slightly lower average of 5.8 kWh/m2/day (15). In contrast, inland regions like Riyadh and Najran receive stronger and more stable sunlight, making them favorable locations for solar deployment (13). The performance of PV systems is also affected by meteorological conditions, namely the temperature, humidity, and dust storms. Although there is a lot of solar radiation, in summer, the temperatures can be very high (more than 45 °C). This can affect the efficiency of the PV output. Electrical components' resistance rises with temperature, which causes the energy output to reduce by 0.4-0.5% for every degree Celsius (16). Moreover, in regions such as Dammam, the rise in the level of humidity contributes to the greater degree of moisture deposition on the PV surfaces, not only affecting the transparency but also being corrosive in the long perspective (17). In spite of the slight variation in the solar radiation, Saudi Arabia has a high solar resource overall when compared with other countries in the world. This potential, however, can be efficiently utilized by adaptations to local climatic changes and variations such as seasonal heat waves, dust loads, and changing humidity.

3.3. Effects of dust, heat, and humidity on PV system performance

The climatic conditions (e.g., dust, high temperatures, and humidity) have a great influence on the functional efficiency and lifespan of photovoltaic (PV) systems in a desert geographical area like Saudi Arabia. The performance of the PV panels is highly affected by

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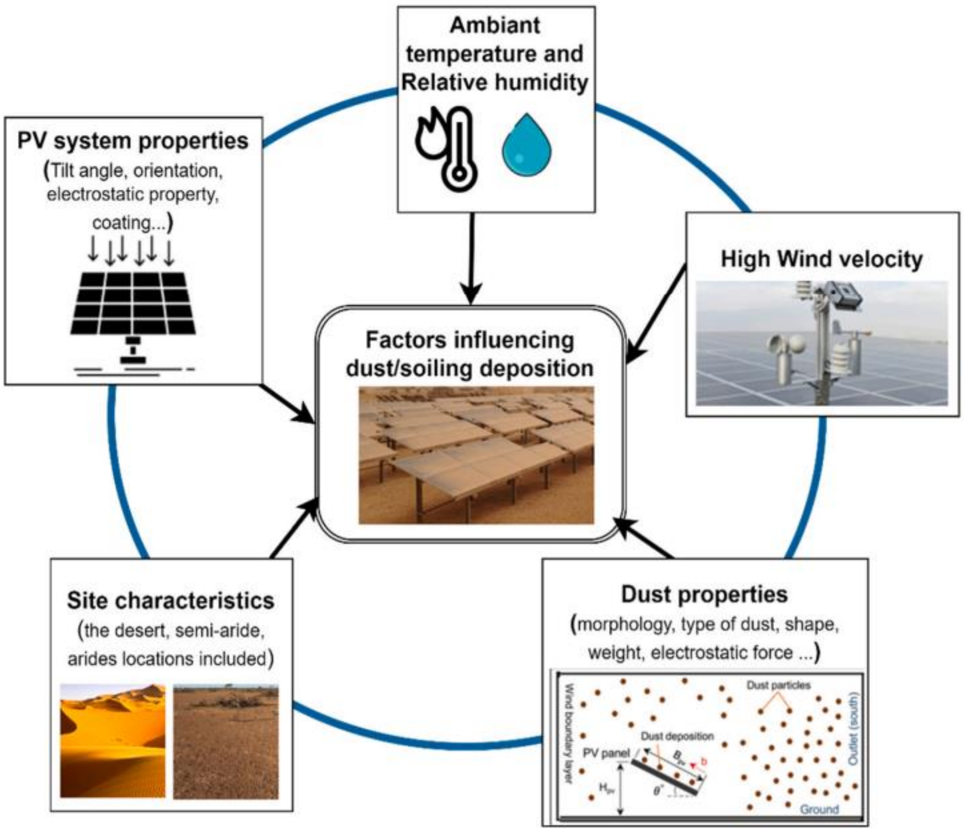
a cycle of interacting occurrences such as the ambient temperature, humidity, dust nature, wind speed, PV system design, and site location (18) As illustrated in Figure 3.

Figure 3: Cycle of factors contributing to dust accumulation impacts on PV panels(18)



Dust accumulation (soiling) on PV panels is one of the most critical challenges in Saudi Arabia. Dust affects light transmission to the photovoltaic cells, which significantly reduces energy output. Studies show that dust deposition can cause energy losses ranging from 2.8% to as high as 50%, depending on dust density and the cleaning frequency (18). In areas like Dhahran, PV modules left uncleaned for six months experienced up to 50% performance degradation due to heavy dust. Ambient temperature is another factor, with high heat reducing PV efficiency. As temperatures rise above 40°C, module efficiency can drop by 0.4%–0.5% per degree Celsius, which is a concern in many parts of Saudi Arabia during summer (19).

Furthermore, humidity affects electrostatic properties, encouraging dust adhesion, particularly in coastal cities like Jeddah and Dammam. Wind speed also impacts dust deposition, as strong winds can both transport and remove dust particles. However, in desert environments, winds typically increase soiling by blowing sand onto PV surfaces (20). Optimal PV design (e.g., tilt angle) and cleaning strategies, including robotic and electrostatic methods, are crucial to maintain performance.

3.4. Limitations of conventional PV maintenance in desert areas

The traditional photovoltaic P V maintenance practices, especially those involving the use of any water-based cleaning solution, are highly constrained in making inroads into the arid desert areas. Among the major problems is the scarcity of water that cannot be used regularly in wet cleaning. In countries such as Saudi Arabia and Morocco, the water supply is slightly low, or the groundwater contains mineral deposits in the form of salts and carbonates, which can deposit on the PV panels, making them thin (21). Although groundwater is available, it may be unusable without prior treatment, and thus, the use of groundwater may result in damage to panels as well as long-term loss of performance.

Besides, manual work to clean up in the desert conditions poses havoc to logistics, and health concerns of the workers because of high ambient temperatures, high solar radiation, and the storms of dust (22). It is thus hazardous, time-consuming, and uneconomical to do manual routines under such conditions. The problem with dust storms is that when they strike, they may dump a good amount of particulate material on the PV modules, and so it is not feasible to rely on regular schedules to clean them. Due to such delays in cleaning, at one time, the reduction of power level can be significant, even within a few weeks (up to 50%) (23). Furthermore, mechanical cleaning using brushes or squeegees can lead to micro-scratches on the panel surfaces, accelerating wear and reducing the effectiveness of anti-reflective coatings. The friction-based methods also fail to remove electrostatically bonded particles, which are common in high-humidity environments (18).

It also has economic and operational issues. Regarding large-scale utility PV plants, particularly in desolate deserts, the costs of labour and maintenance also increase massively. The large amounts of water and energy used in the process of cleaning would also go against the sustainability aspect of renewable energy (1). Therefore, conventional maintenance strategies need to be replaced or supplemented by innovative solutions such as robotic dry cleaning, electrostatic dust removal, and surface coating technologies designed specifically for desert conditions.

3.5. Current rooftop PV deployment trends in Saudi Arabia

Saudi Arabia has a solid rooftop photovoltaic (PV) construction industry that belongs to the Kingdom of Saudi Arabia as part of an environmental force plan connected to vision 2030. The Rooftop PV systems are developing real traction in the residential, commercial, and institutional sectors due to the supportive policies, economic considerations, and energy security requirements (24).

One of the trends is the popularity of on-grid rooftop systems, when users can remain grid-connected but reduce the price of electric power using net metering. The costs of installation have reduced, and installation of these systems is not subject to VAT; therefore, available financing mechanisms make them economically feasible to install. TechSci research rules that the Saudi rooftop solar market size is expected to increase substantially between 2024 and 2033, with the on-grid systems assuming the most elevated size.

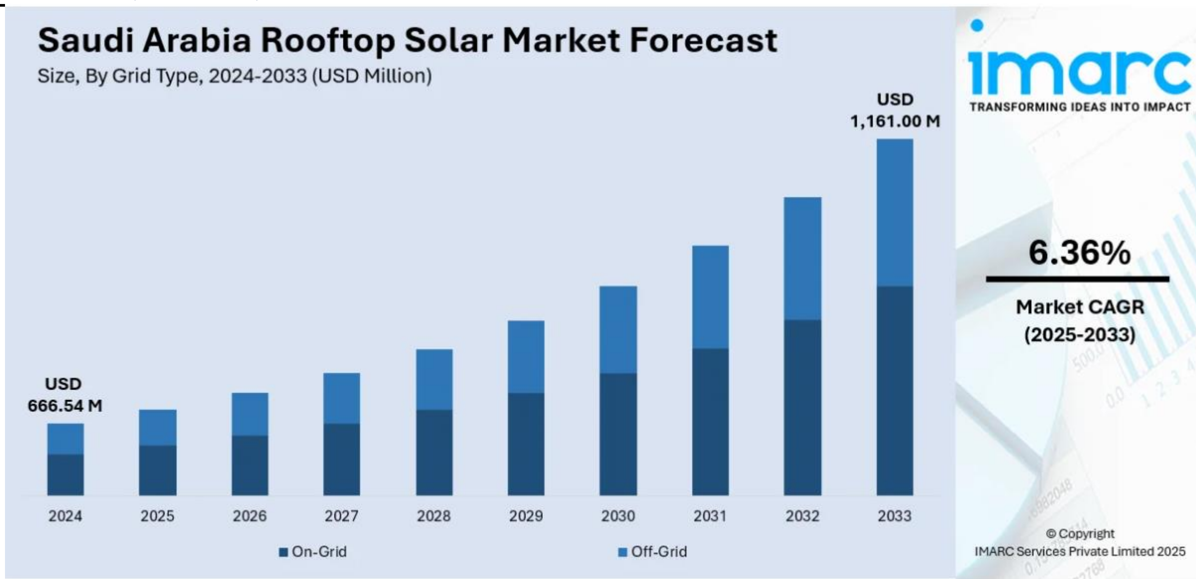


Figure 4: Saudi Arabia Rooftop Solar Market Forecast (USD Million), by Grid Type, 2024–2033 (25)

As seen in Figure 4, on-grid systems are projected to remain the dominant grid type due to their ease of integration with national infrastructure and cost-effectiveness. These installations are particularly attractive in urban areas, where buildings can reduce their utility bills by up to 43% with rooftop PV adoption (Al-Hanoot et al., 2024). Another notable trend is the rising contribution of residential and commercial sectors to the rooftop PV market. Schools, colleges, and government buildings have also started installing solar rooftops, building the consciousness and acceptance of the masses.

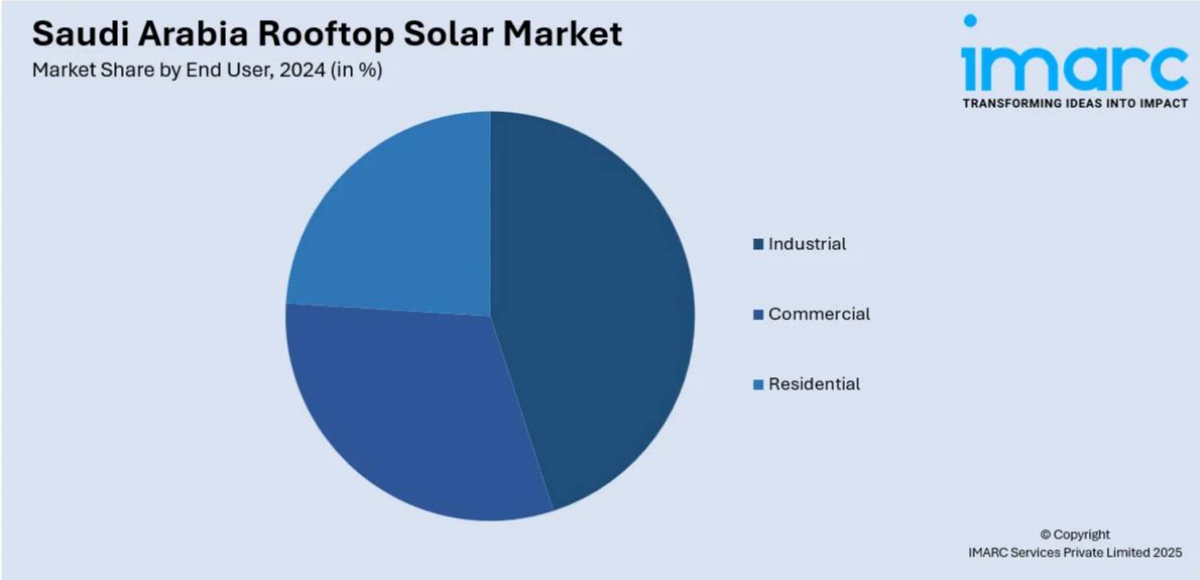


Figure 5: Saudi Arabia Rooftop Solar Market Share by End User, 2024 (%) (25)

Figure 5 indicates that the residential sector is the major solar rooftop user, followed by commercial users. This trend has been significantly triggered by increasing electricity rates, reasons of energy saving, and the convenience of setting up the system on the privately owned rooftops. In the meantime, business establishments enjoy affordable long-term operational expenditures and government incentive programs. Also, in the new forms of agriculture, rooftop PV is under consideration in hydroponics and aquaponics, where the energy is sustainable for water-intensive production of food (26). Such applications are growing in significance in areas where there is a water shortage and an increase in energy requirements in the agricultural sector. The Saudi Arabian trend of the rooftop PV deployment indicates a maturing market with markedly favorable policies, increased consumer interest, and a trend of increasing applications beyond the urban application by installing PV on rooftops.

3.6. Regulatory frameworks and incentives for rooftop PV systems

Besides, the Saudi Energy Efficiency Center (SEEC) and the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) contribute significantly to technical descriptions and recommendations about the safe integration of PV systems (27). A lack of VAT on PV modules and the availability of low-interest-rate loans on the part of state-affiliated banks have also accelerated the pace of adoption. Feed-in Tariff (FiT) and Net Energy Metering (NEM) policies have shown success throughout the world. FiTs played a key role in the early deployment of solar PV throughout Turkey and several European nations, and NEM policies, such as those in the United States, provide an incentive to install solar PV at the rooftop level (28). Relative to this, the regulating environment in Saudi Arabia is still developing, yet promising.

3.7. Opportunities for innovation in O&M practices

The nature of rooftop PV systems' operation and maintenance in the harsh desert environments, such as Saudi Arabia, creates a special challenge with regards to extreme heat, high intensity of dust, and water scarcity (29). Such challenges require the innovative nature of O&M strategies to maintain the maximum performance and years of service of systems. Another major advancement entails the invention of robotic and automated dry-cleaning processes that are growing in popularity because they are less water-consuming and cheaper in labor. These systems consist of brushes, blowers, or electrostatic systems that eliminate dust without damaging PV surfaces, being of special value in the areas affected by dust storms (18).

The next perspective is the use of the so-called self-cleaning and anti-soiling strata that eliminate the attachment of dust and combat the level of density of maintenance operations. These are either hydrophobic or photocatalytic coatings that are being modified specifically to work in an arid climate (30). Predictive maintenance is also possible with the use of advanced analytics of data and remote sensing technologies. Performance anomalies during shading, dust, or degradation of components can be tracked thanks to real-time monitoring sensors, IoT, and AI algorithms, and therefore maintenance can be carried out on condition and not routine cleaning cadres (31).

Also, combining thermal-resistant PV components and responsive cooling devices can increase the efficiency of systems working in hot areas, which otherwise suffer the loss of thermal energy that negatively affects PV outcomes (19). Lastly, the new mobile models of O&M services that are specific to small rooftop owners in residential places offer an avenue of scalable and affordable technical support access, especially in hard-to-reach areas or areas that have not been served well. Public-private partnerships have a potential key role to play in broadening those services and encouraging entrepreneurship to undertake local maintenance on solar.

Operational Challenges and System Utilisation

4.1. Factors influencing rooftop PV efficiency in urban deserts

Photovoltaic (PV) installations located on the roof of buildings placed in urban desert areas, e.g., Saudi Arabia, operate under a myriad of issues that relate directly to their performance. Marked contributors entail high ambient temperature and low wind velocity, excessive air particle pollution, and favorable heat island effects attributed to the city. Such factors reduce the efficiency of rooftop PV modules both synergistically and individually by creating thermal stress and diminishing the solar irradiance (32).

The urban heat island effect can increase ambient temperatures by up to 5 °C compared to surrounding rural areas, intensifying the thermal load on PV systems (33). Figure 6a illustrates how dense building clusters and concrete surfaces create shading and heat accumulation, both of which undermine energy output. This urban microclimate causes PV module temperatures to rise significantly, which in turn lowers their voltage output and overall efficiency. The decline in performance is approximately 0.4–0.5% per °C increase in temperature (34).

(a) (b)

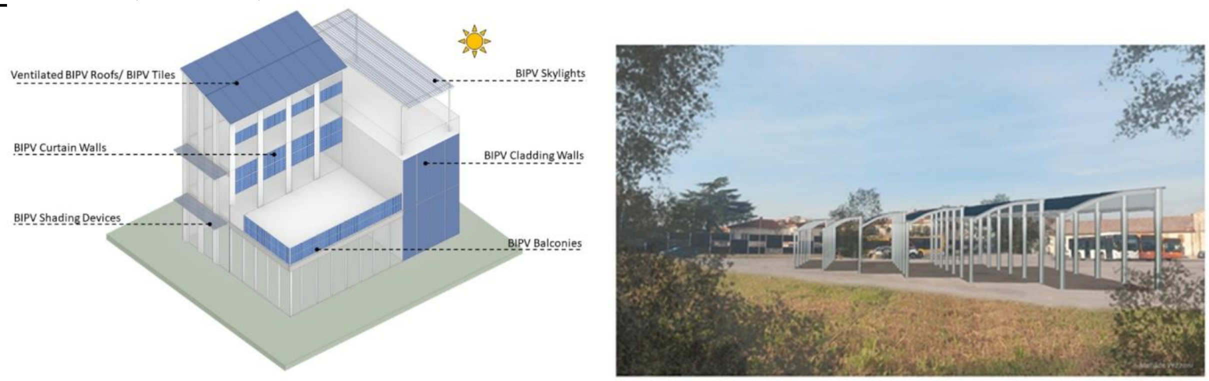
Figure 6: Examples of different types of soiling typical in an urban environment: (a) clean and dirty modules, (b) a PV module with bird droppings on it (32)

Another major challenge is soiling caused by dust, sand, and smog particles common in desert cities. Studies show that particulate matter such as PM10 and PM2.5 can reduce PV performance by up to 20% depending on pollutant concentration and cleaning frequency (35). Figure 6b, which depicts soiled panels, offers a visual representation of how even small-scale debris, such as bird droppings or accumulated smog, can cause localized shading and hotspots.

Lastly, reduced wind speeds in urban desert areas, often obstructed by buildings, diminish the natural cooling effect on modules. This condition further aggravates overheating and accelerates material degradation. Thus, site-specific design adaptations and real-time environmental monitoring are essential for efficient operation in such climates.

4.2. Installation techniques and optimal design for durability

In harsh desert urban settings, installation techniques must prioritize thermal management, structural resilience, and ease of maintenance. Rooftop systems should incorporate ventilated mounting structures, as these reduce heat buildup by enabling airflow beneath the modules, which can lower operating temperatures by as much as 20 °C (36). Figure 7a shows well-designed building-integrated PV (BIPV) applications, where thoughtful integration of roofing and ventilation enhances both performance and architectural aesthetics.



(a) (b)

Figure 7: Possible applications of photovoltaics in an urban environment: (a) building-integrated systems (37) (b) parking sites (38).

Furthermore, selecting durable module technologies, such as glass-glass panels, offers increased resistance to sand abrasion and UV degradation, common stressors in desert environments. Experimental evidence from Denmark and Switzerland suggests that these modules, when used with insulated or ventilated installations, show lower rates of thermal performance loss, around 0.37%/°C, compared to conventional types (39).

For long-term durability, mechanical robustness against sandstorms and high winds is critical. This involves securing mounting frames using corrosion-resistant materials like anodized aluminum or galvanized steel and designing for low-profile tilt configurations to reduce wind uplift. Maintenance access is another key element—rooftop arrays should be spaced to allow drone or robotic cleaning technologies, particularly in high-rise urban areas where manual access is restricted (32).

Electrostatic self-cleaning modules, though still in early adoption, offer promise in reducing soiling-related losses in urban PV systems. As shown in Figure 7b, these systems use high-voltage electrodes to displace dust, reducing the need for frequent manual intervention (40). Finally, design customization for microclimates is essential. Site simulations, using tools like 3D shading models and computational fluid dynamics (CFD), can predict and mitigate the impact of neighboring structures, allowing for better-informed decisions regarding module placement, height, and structural orientation.

4.3. Orientation and tilt strategies to minimise soiling losses

Orientation and tilt angle are critical variables in optimizing solar energy yield and minimizing soiling losses, especially in urban desert environments where airborne dust is frequent. The default practice in equatorial or desert regions is to position PV panels facing true south (in the Northern Hemisphere) at an angle equal to the latitude. However, studies show that in dusty environments, steeper tilt angles (30°–40°) are more effective in shedding particulate matter naturally (41). Figure 6b illustrates rooftop and parking lot PV systems, showcasing how different mounting angles affect exposure to airborne dust. The figure highlights that flat-mounted panels, often preferred for aesthetics, accumulate more dirt and require frequent cleaning. In contrast, tilted installations benefit from gravity-assisted self-cleaning during rain or wind events, improving performance and reducing maintenance needs.

Furthermore, azimuth orientation must consider the urban landscape's shading patterns. In high-density areas, east and west-facing arrays may be more productive than south-facing ones due to prolonged afternoon and morning sun exposure, especially when rooftops are overshadowed by taller buildings during midday hours (Gabrovska-Evstatieva et al., 2025). Figure 8 emphasizes how urban skyline elements like skyscrapers limit optimal sun path access, necessitating orientation trade-offs.

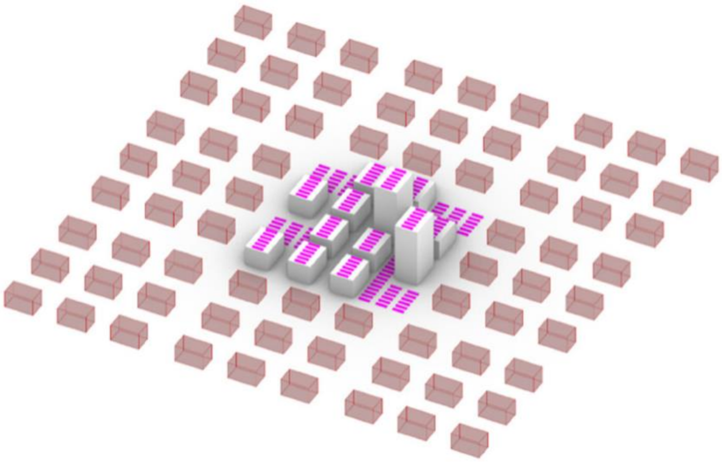


Figure 8: The urban landscape and the created limitations on PV placement (42)

Field studies in Iran and Malaysia reveal that vertical façades facing southeast or southwest also provide viable outputs, although performance reductions of 40–60% have been reported compared to optimally tilted rooftops (43). Therefore, such configurations should only be considered in urban cores where rooftop space is limited. Ultimately, to minimize soiling losses while maximizing solar gain, the ideal strategy in desert cities combines steep tilts, real-time performance monitoring, and orientation adjustments based on localized shading and pollution data.

5. Cost-Effectiveness and Maintenance Economics

5.1. Economic Analysis of O&M Interventions for Rooftop PV

Operation and Maintenance (O&M) strategies represent a significant portion of the lifecycle cost of rooftop photovoltaic (PV) systems, particularly in harsh desert environments like Saudi Arabia (44). Conventional maintenance work, like cleaning by hand with water, consumes a lot of time, is unsustainable in areas with low water supply, and is highly expensive in the long run. As a contrast, adaptive O&M interventions, including automated dry cleaning systems, electrostatic cleaning, and AI-based monitoring, have a positive cost-benefit portrait in the long-term perspective (45).

At an economic scale, rooftop PV systems in a desert setting can lose energy between 13 to 30 percent per year because of poor maintenance (5). The creation of an automated dry-cleaning system can cost 7-12 dollars per square meter (1). But on average, it helps to decrease the costs of cleaning by more than 60 percent and stabilize the amount of energy generated each year by up to 12 percent. This is a direct implication of greater revenue collection for the residential and commercial users of the net billing.

Reduction of operational costs is also achieved due to intelligent monitoring, which, through the usage of IoT sensors and predictive algorithms, minimizes the number of unnecessary site visits and real-time detection of faults. These technologies, although there can be some upfront costs, will maximize uptime and increase the efficiency of operations. The costs to invest in adaptive O&M can cost 510 percent of the overall system costs, though it is not uncommon to repay it in full by decreasing downtime and energy production within 315 years (46).

5.2. Financial Impact of Preventive vs Reactive Maintenance

The decision to use preventive and reactive maintenance significantly affects the sustainability of rooftop PV systems in desert climates in the long term regarding the financial capabilities (47). Reactive maintenance, whereby faults are fixed or performance falls are quenched once actuated, can end up with unplanned downtimes, faster wear of components, and increased savings in the long term. In its turn, preventive maintenance, particularly in combination with the prediction tools, is intended to minimize the failures of the system and keep the energy output on the same level.

The field observations at Riyadh and Dhahran showings reveal that the reactive cleaning carried out as a result of dust storms could lead to a loss in revenues of up to 1.20$/kW installed/day, when applied to commercial sectors that depend on the peak-time generation (48). When cleaning or repairs are not conducted in time, the overall losses may go up to 20 percent of the targeted monthly revenue. Furthermore, reactive approaches often lead to more severe issues, such as inverter faults or panel hot spots, which are expensive to repair and reduce asset life.

On the other hand, preventive maintenance, particularly when optimized through AI, improves performance and lowers overall costs. A study by Baghdadi and Abuhussain (6) Showed that predictive cleaning schedules based on environmental monitoring reduced energy loss by 9% annually compared to fixed-schedule cleaning and avoided emergency repairs entirely. Although preventive measures require periodic inspections and monitoring of infrastructure, they reduce unplanned outages and provide greater cost certainty. A comparative cost-benefit analysis of reactive vs preventive O&M over 10 years, indicating that while preventive maintenance has a higher upfront cost, it results in 15–25% lower total O&M expenditure and up to 30% higher net energy generation across the system lifecycle.

5.3. LCOE Improvements Through Adaptive O&M Scheduling

The Levelized Cost of Electricity (LCOE) is a critical metric for assessing the economic feasibility of PV systems, defined as the total lifecycle cost divided by the energy output over the system's life. In arid urban climates, adaptive O&M approaches have a considerable benefit to the LCOE by improving performance ratios, reducing degradation, and unscheduled downtimes. The rooftop PV systems in Saudi Arabia that employed the use of adaptive O&M, which incorporated the use of robotic cleaning every two weeks, AI-based prediction of malfunctions, had a LCOE of 0.014/kWh, one of the lowest in the world (1). Conversely, reactive maintenance-based systems cost within the range of ($0.020-$0.026)/ kWh because of the reduced yields and increased maintenance charges.

More efficient dust mitigation has led to efficiency gains with adaptive O&M scheduling, efficiency gain, better inverter operation, early warning of string imbalance, and minimizing heat-induced degradation. According to the research by Said, Islam (18), AI-based diagnostics helped speed the time it takes to detect a fault by 65% and activate recovery measures before serious energy losses could have been incurred. Consequently, systems had a performance ratio (PR) that was better than 90 percent compared to 80-85 percent with other systems that are manually maintained.

In addition, automated O&M approaches enhance the lifetime of components, especially of inverters and modules, since they minimize thermal and mechanical stress. This postpones capital replenishment expenses and smoothes O&M expenditure curves throughout the 25-year lifespan. Hence, adaptive O&M not only increases the productivity of energy but also raises the economic character of rooftop PV investments. It helps to promote the financial viability of solar implementation in dry urban environments, which, on the one hand, supports the strategic argument of incorporating smart maintenance into all stages of designing and implementing rooftop PV projects.

6. Results and Discussion

6.1. Utilisation Factor of Rooftop PV Systems under Harsh Climates

The utilisation factor of rooftop PV in a harsh desert climate, such as the environment of Saudi Arabia, provides the ratio of usage time of a system to its optimal output. The latter is influenced directly by the conditions in the environment (dust deposit, high ambient temperatures, or alternating shade in the city) on the same. Using the performance data gathered about rooftop installations in Riyadh, Dhahran, utilisation factors vary at an inter-annual value of 18 to 23 percent. Such values are below theoretical values (25%), due to the derating of this system because of soiling, thermal inefficiencies, and delay in maintenance (6). On-site evidence showed that systems cleaned automatically and managed in real-time recorded higher utilisation, averaging 22.8 per cent, than systems under manual or reactive cleaning, which recorded 18.6 per cent. The difference is most conspicuous during the dust storm seasons when systems that lack adaptive maintenance will take a long time to recover output after cleaning has been done (5).

6.2. Performance Ratio Variations Due to Environmental Stressors

One of the most important indicators of efficiency of PV systems, known as the performance ratio (PR), was seen to vary widely in the experimental setting that was put under severe environmental stresses common to arid urban settings. Monitoring systems in Abqaiq and Eastern Riyadh indicated seasonal changes in PR, with as low as 77 per cent in summer months to 91 per cent in winter. Most of the factors that led to a decrease in PR were the high module temperature over 60 o C, accumulation of fine particulate matter (PM10 and PM2.5), and high levels of humidity that increased dust adhesion (19).

As reflected in Table 1, the systems that are characterized by adaptive O&M strategies, such as predictive cleaning and ventilated mounting, had an annually averaged PR of 90.3 compared to an average of 83.1 in the systems that were using circumstances of conventional maintenance practices. These findings confirm the detrimental impact of environmental stressors on PV performance and underscore the value of proactive operational responses.

Table 1. Average Performance Ratios under Different O&M Strategies in Saudi Arabia

City	Maintenance Type	Average PR (%)
Riyadh	Manual (monthly cleaning)	82.5
Dhahran	Adaptive (bi-weekly robotic)	91.2
Abqaiq	Reactive (post-storm)	77.8
Riyadh	Predictive AI-based	90.5
National Avg	Mixed methods	85.7

6.3. Cost-Benefit Analysis of Adaptive Cleaning and Monitoring

A detailed cost-benefit analysis highlights that adaptive cleaning and monitoring systems, though capital-intensive at the outset, yield substantial financial advantages over the system's lifespan. For example, the deployment of a robotic dry-cleaning system at a commercial rooftop site in Dhahran reduced annual maintenance costs by 62% and improved energy output by 11.8% (1). Additionally, IoT-based predictive monitoring reduced operational downtime by 70% through early fault detection, as confirmed by data from rooftop installations in industrial zones near Jubail.

In terms of investment returns, adaptive systems demonstrated an internal rate of return (IRR) improvement of 4–6% over reactive models. The levelized cost of electricity (LCOE) was reduced from $0.022/kWh to as low as $0.014/kWh, thereby improving net profitability, especially in regions with net billing incentives (18). These economic gains are especially important in commercial sectors, where rooftop PV systems are integrated into business operations and energy savings translate into competitive advantages.

6.4. Comparative Effectiveness of O&M Strategies from Literature

Existing literature comparing conventional and adaptive O&M strategies supports the superior performance of proactive and technology-integrated maintenance. For example, a study by Ehsan, Simon (40) reported that electrostatic self-cleaning systems deployed in Doha, Qatar, improved PV efficiency by 9.4% over six months without requiring water, while systems relying on bi-monthly manual cleaning showed stagnating or declining output due to irregular service. Similarly, a comparative study by Thakfan and Bin Salamah (49) Found that PV plants employing AI-based fault prediction had inverter failure rates 55% lower than those relying on periodic manual inspections. Table 2 summarizes key findings from multiple studies comparing the effectiveness of different O&M approaches.

Table 2. Comparative Effectiveness of O&M Strategies in Arid Climates

Study	O&M Type	Energy Output Improvement	Cost Reduction (%)	Key Benefit
Al-Hanoot, Mokhlis (1)	Robotic cleaning + AI	12%	60%	Reduced soiling & downtime
Ehsan, Simon (40)	Electrostatic self-cleaning	9.4%	50%	No water usage
Thakfan and Bin Salamah (49)	Predictive monitoring	8–10%	40–55%	Fewer inverter and string faults
Osmani, Haddad (5)	Reactive cleaning	<5%	0%	Unpredictable and inefficient

These findings reveal that while all strategies aim to reduce operational loss, adaptive methods consistently outperform conventional approaches in terms of operational cost efficiency. The inclusion of such techniques is both desirable as well as necessary to the maintenance of PV operation in desert cities.

6.5. Summary of Current Challenges, Adaptations, and Potential Gains

The findings draw the conclusion about rather big operational limitations of rooftop PV systems in Saudi Arabia caused by high ambient temperatures, dust, and urban shading. These difficulties immediately affect utilisation factors, performance ratios, and economic returns. The traditional O&M processes suffer from accessibility, sustainability, and efficiency issues especially the ones operated via manual labor and use of water. The reactive strategies tend to cause unnecessary performance debasing and soaring lifecycle costs.

Alternatively, adaptive measures, such as robotic dry-cleaning, electrostatic dust collection, AI-based fault diagnosis, and ventilated PV systems, are much more effective in the productivity-cost ratio. Reduction in Levelized Cost of Electricity by approximately 35 percent and prolonged useful life of system components are provided through these technologies. Notably, they also increase resistance to extreme weather and air quality vibrations, which is a severe necessity in urban deserts.

In addition, good design modifications like the best tilt settings, cooled mounts, and location-based azimuth set-up eliminate a lot of thermal and heating losses, hence resulting in increased system stability. In combination with government incentives and net billing programmes, integration of intelligent O&M solutions will help turn rooftop PV systems into an economically sound and environmentally-friendly solution to the long-term energy platform of Saudi Arabia. In this way, not only does the incorporation of adaptive O&M resolve the unreasonably severe climatic conditions of Saudi Arabia, but also it will ensure the most effective use of PV investments, which means that rooftop solar should become a significant segment of the sustainable energy future of the Kingdom.

7. Conclusions and Future Research Recommendations

As shown by this research work, rooftop photovoltaic (PV) systems in desert urban areas like Saudi Arabia are exposed to major performance constraints as a result of severe climatic circumstances, e.g., scorching weather, flying dust, and exposure to rather inferior ventilation conditions. But the up-adaptive operation and maintenance (O&M) strategy, in general, and the use of automated cleaning, AI-based monitoring, and predictive maintenance solutions, in particular, provide a potent solution to this problem and can improve system performance. The system utilisation factors and performance ratios were also observed to be much improved in installations that make use of adaptive strategies, with a performance ratio above 90 percent in a well-kept installation. Economic studies also supported the measure that, in spite of an initial increased investment portfolio in adaptive O&M, which yields long-term savings expressed in fewer periods of outages, increasing energy production, and decreasing levelized cost of electricity (LCOE).

To enhance the performance of rooftop PV systems in similar climates, there are strategic recommendations that have been presented. The designs of systems must place an obligation on higher mounting to augment air flow around the system, high tilt to allow dust to naturally slough off, and durable module tech such as glass-glass panels. Additionally, the further IoT sensors, real-time diagnostics, and predictive maintenance using AI may be considered standard during the installation of new systems to maximize technical and financial output.

The results also indicate the importance of constant monitoring and intelligent analysis in minimizing operational waste and increasing the life of the components. Future research must aim at coming up with region-specific maintenance algorithms that combine local climatic, urban, and pollution data to automate the scheduling of maintenance. Further, pilot projects in other MENA (Middle East and North Africa) desert cities can be used to present similar types of data to develop adaptive O&M models further. Exploration into new self-cleaning materials, cheaper sensor systems, and network connections to the smart grid would also benefit the area. To sum up, the adaptive O&M has a transformative role in the viability of rooftop solar in desert environments and must become the focus of sustainable energy policy for the MENA region.

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