





The role of outdoor testing and robotic cleaning to reduce LCoE

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Amidst surging global adoption of photovoltaic (PV) plants in desert regions, dust accumulation poses a significant challenge to performance and reliability. Here, we explore the transformative potential of robotic cleaning systems, leveraging automation and advanced technologies to optimize maintenance practices, maximize energy production, and ensure the long-term sustainability of solar PV installation in harsh desert environments.

In recent years, the global adoption of utility-scale photovoltaic (PV) plants has surged, especially in desert climates, driven by abundant sunlight and expansive landscapes. However, the efficiency and reliability of these solar installations face significant challenges due to extreme desert environmental factors, with dust accumulation being the most notable obstacle impacting the performance and reliability of PV power plants.

Dust and sand accumulation on PV panels hinder sunlight transmission, diminishing energy output and efficiency. In addition, the abrasive nature of sand during a dust storm for instance can cause damage to the PV modules therefore reducing their performance and longevity. Conventional cleaning methods, such as manual washing or water-based systems, are labor-intensive, costly, and environmentally unsustainable, inadequately addressing the recurring nature of dust deposition in desert environments.



In response to these challenges, robotic cleaning systems have emerged as transformative solutions, heralding a paradigm shift in the operation and maintenance (O&M) of utility-scale PV plants. By leveraging automation, robotics streamline cleaning processes to remove dust while minimizing human intervention.

Equipped with advanced sensors, Artificial Intelligence algorithms, and precision mechanisms, autonomous cleaning systems navigate complex terrain, optimize cleaning patterns, and adapt to varying levels of dust accumulation. The utilization of such systems significantly maximizes energy production, enhances O&M practices in utility-scale PV plants, reduces downtime associated with manual cleaning, and maximizes revenue generation. This, in turn, enhances the bankability and credibility of investors in future power plants.

Furthermore, robotic cleaning systems offer a myriad of benefits beyond mere maintenance. By ensuring the optimal cleanliness of PV panels, these systems enhance light absorption and conversion efficiency, potentially increasing energy output by up to 15%. Moreover, they mitigate the risk of hotspots and module degradation, thereby prolonging the lifespan of PV panels and associated equipment.

Reliability is paramount in desert climates, where extreme temperatures, sandstorms, and abrasive dust particles pose significant operational risks. Robotic cleaning systems, engineered to withstand harsh environmental conditions while maintaining consistent performance, ensure the reliability and longevity of solar installations.

Real-outdoor data collected from testing these robotic systems enables improved reliability, defines an optimum cleaning frequency, and ensures their performance in desert climates. Their use of durable materials, rugged designs, and advanced sensing technologies fortify their resilience even in the harshest desert environments.

Looking ahead, world-class research in robotic cleaning continues to propel innovation and advancement in the field. Future developments may entail the integration of self-learning algorithms, predictive analytics, and renewable energy-powered solutions to further optimize cleaning efficiency, resource utilization, and adaptability to different PV system configurations.



Efforts are also underway to explore synergies between robotic cleaning and emerging technologies like the Internet of Things (IoT), blockchain, and edge computing, fostering interconnected ecosystems for smart energy management and grid integration.

A very important element linking all the above to maximize power plants yield and reduce operational costs is predicting the optimal timing for cleaning the PV panels, something especially key in desert climates where dust accumulation poses a significant threat to performance.

Various approaches and technologies can aid in forecasting and predicting the ideal moment for PV panel cleaning. Firstly, continuous monitoring of environmental factors like dust levels, humidity, temperature, wind speed and direction, and precipitation yields valuable insights into the buildup of dust and other pollutants on PV panels.

Secondly, dust sensors installed at plant sites measure dust deposition rates and trigger alerts when predefined thresholds are surpassed, signaling the necessity for cleaning.

Integrating weather forecasting models and real-time meteorological data also assists in anticipating forthcoming weather patterns, including dust storms and precipitation events, which impact the cleanliness of PV panels. Analyzing weather forecasts enables operators to schedule cleaning activities during periods of minimal wind and reduced dust activity, optimizing cleaning efficiency while mitigating the risk of dust redeposition.

The continuous monitoring of PV system performance metrics, such as energy output, efficiency, and degradation rates, offers indirect indicators of cleaning needs. An unexpected drop in energy production or an uptick in system losses may signify dust accumulation, prompting the need for cleaning.

The use of historical data on dust deposition rates, weather patterns, and cleaning schedules helps identify trends that inform the development of predictive models for PV panel cleaning. Machine learning algorithms and data analytics techniques analyze historical data to forecast optimal cleaning times based on past performance and environmental conditions.

Finally, the use of satellite-based remote sensing technologies, such as satellite imagery and aerial surveys, furnish valuable insights into the dust accumulation across vast geographic areas. Analyzing satellite data aids operators in identifying areas with heavy dust accumulation, allowing for prioritized cleaning efforts and optimized resource allocation to minimize downtime.

In conclusion, forecasting the optimal time for cleaning PV panels demands a multifaceted approach that integrates environmental monitoring, weather forecasting, performance monitoring, historical data analysis, automated monitoring systems, and remote sensing technologies.

By leveraging these methodologies and technologies, operators can proactively manage dust accumulation,

optimize cleaning schedules, and enhance energy production and efficiency in utility-scale PV plants, ensuring their long-term sustainability and profitability in desert climates. As technology continues to evolve, ongoing research and development efforts are important to improve robotic cleaning systems' efficiency and ensure compatibility with emerging solar panel technologies.

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The Energy Center at the Qatar Environment and Energy Research Institute (QEERI) is at the forefront of addressing the challenges related to the operation and maintenance (O&M), performance, and reliability of utility-scale PV plants in desert climates.

QEERI, part of the Qatar Foundation's Hamad Bin Khalifa University, is committed to conducting cutting-edge research and developing innovative solutions to promote sustainable energy practices and address environmental challenges QEERI's multifaceted approach encompasses:

- **Research and Development:** Conducting extensive R&D endeavors focused on advancing technologies for solar energy production and management, QEERI collaborates on projects and partnerships to explore novel approaches enhancing the efficiency, reliability, and sustainability of utility-scale PV plants in desert climates.
- **Robotic Cleaning Technologies:** QEERI pioneers the development of robotic cleaning technologies tailored to the unique requirements of desert environments. Leveraging expertise in robotics, automation, and materials science, QEERI aims to design and deploy advanced cleaning systems capable of effectively removing dust and sand particles from PV panels while minimizing water consumption and environmental impact.
- **Sensor Networks and Monitoring Systems:** Utilizing sensor networks and monitoring systems, QEERI gathers real-time data on environmental conditions, energy production, and equipment performance in utility-scale PV plants. This enables predictive maintenance, early anomaly detection, and optimization of cleaning schedules to maximize energy yield and operational efficiency.
- **Climate Adaptation Strategies:** QEERI develops climate adaptation strategies to bolster the resilience of PV plants against extreme temperatures,

sandstorms, and abrasive dust particles. Through modeling, simulation, and field trials, QEERI assesses the impact of environmental factors on PV panel degradation, module efficiency, and overall system reliability, informing design guidelines and operational best practices for desert-based solar installations.

- **Knowledge Transfer and Capacity Building:** QEERI fosters knowledge transfer and capacity building through education, training, and outreach programs targeting industry professionals, policymakers, and the wider community. By disseminating research findings, best practices, and technological innovations, QEERI empowers stakeholders to make informed decisions, implement sustainable solutions, and drive positive change in the renewable energy sector.
- **Collaboration and Partnerships:** QEERI collaborates with local and international research institutions, government agencies, and industry partners to leverage complementary expertise, share resources, and accelerate the translation of research outcomes into tangible solutions. Through collaborative projects, joint initiatives, and technology transfer agreements, QEERI strengthens the innovation ecosystem and fosters synergies among stakeholders to address common challenges and achieve shared objectives in the solar energy domain.

In conclusion, QEERI plays a pivotal role in addressing the challenges confronting utility-scale PV plants in desert climates ensuring the optimal performance and longevity of solar PV systems through its research, innovation, collaboration, and knowledge dissemination efforts. Successful case studies have been demonstrated and published in the literature. By spearheading technological advancements, promoting sustainable practices, and building resilient infrastructure, QEERI contributes to the transition towards a more sustainable and energy-efficient future, not only in Qatar but also globally.