Optimising Solar Energy: An Evaluation of IoT-Based Solar Panel Monitoring Systems

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Abstract. The integration of Internet of Things (IoT) technologies within the realm of renewable energy, notably solar power, has paved the way for the creation of intelligent and decentralised systems for enhanced monitoring and fault detection. In this review, we delve into the use of IoT-facilitated remote IV tracing mechanisms to identify and address faults within urban solar power installations. Concentrating on desert environments, where solar power is a cornerstone for sustainable growth, we consider the challenges introduced by dust deposition and its repercussions on solar energy output. We further elaborate on the integral role of IoT in spearheading smart monitoring systems that assess the efficiency of solar panels in dust-affected scenarios. This paper also provides a detailed assessment of a specific IoT-integrated solar monitoring framework designed for expansive and distributed solar provisions in smart cities.

1 Introduction

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Rapid urbanisation and population expansion in recent decades have presented a plethora of challenges, notably in the energy sector. This pressing need for dependable and long-term energy solutions has reignited and intensified the global discourse on renewable energy. Solar power, with its boundless potential, stands out as a preferred choice, particularly in distinct environments such as desert terrains that are privy to vast amounts of sunlight. These areas, while sun-rich, also introduce unique challenges for solar energy capture; one of the most significant being dust-induced contamination which can significantly reduce the efficiency of solar panels. In our modern era, where technological solutions are often sought for complex problems, the integration of Internet of Things (IoT) techniques offers a promising avenue. IoT, with its ability to connect, monitor, and analyse, can play a transformative role in enhancing solar panel efficiency and fault detection. Addressing these specific challenges, this review takes a comprehensive look at the utilisation of IoT-facilitated remote IV tracing mechanisms. It further examines their vital contribution to the ambitious vision of cultivating Smart Cities, thereby driving a sustainable and green urban evolution.

Table 1. Key insights and corroborative data from the research by MT Isla et al 2018 [1]

Finding	Supporting Evidence
CSP is a promising renewable energy technology that has the potential to generate electricity on a large scale.	The global installed capacity of CSP plants has been growing rapidly in recent years, and is expected to reach 60 GW by 2030.
The main drivers of CSP growth are the increasing demand for clean energy, government policies that support renewable energy, and the falling cost of solar modules.	The demand for clean energy is increasing due to concerns about climate change and air pollution. Governments around the world are also providing financial incentives for renewable energy projects. The cost of solar modules has fallen significantly in recent years, making CSP more affordable.
The main types of CSP plants are parabolic trough collectors, solar power towers, and linear Fresnel reflectors.	Parabolic trough collectors are the most common type of CSP plant. They use curved mirrors to focus sunlight onto a receiver tube, which then heats a fluid. Solar power towers use a field of mirrors to focus sunlight onto a central receiver tower, which then heats a fluid. Linear Fresnel reflectors use a series of long, flat mirrors to focus sunlight onto a receiver tube.
CSP plants can be integrated with thermal energy storage systems to provide dispatchable power, which makes them more attractive for baseload power generation.	Thermal energy storage systems store heat from CSP plants, which can then be used to generate electricity later. This makes CSP plants more flexible and able to provide power on demand.

CSP technology is still under development, but there has been significant progress in recent years.	The efficiency of CSP plants has been improving, and the cost of CSP plants has been falling. There has also been progress in developing new types of CSP plants, such as molten salt CSP plants.
The main challenges facing CSP technology are the high cost of mirrors and thermal energy storage, and the need to improve the efficiency of CSP plants.	The cost of mirrors and thermal energy storage is a major barrier to the widespread adoption of CSP technology. CSP plants also need to be more efficient in order to be cost-competitive with other forms of power generation.

2 Challenges in solar power generation

Desert regions, such as those found in the Gulf Cooperation Council (GCC), offer favourable conditions for solar energy generation. However, dust-based soiling remains a significant challenge. Accumulation of dust particles on solar panels obstructs radiation absorption, leading to reduced energy output. Other factors, including shading, solar irradiance incidence angle, and weather conditions, can also influence solar power generation. These challenges necessitate innovative solutions to ensure stable and efficient energy production in smart cities[1][12]. The following table presents a comprehensive summary of various types of Photovoltaic (PV) cells and their corresponding efficiencies. Photovoltaic cells, which directly convert solar energy into electricity, play a pivotal role in harnessing the power of the sun for sustainable energy generation.

The table 2 categorizes PV cells into different generations, such as first-generation, second-generation, third-generation, and multi-junction devices, each employing distinct materials and technologies. The efficiency of each PV cell type is a key parameter that determines its performance and practical application. As the world seeks cleaner and more efficient energy sources, understanding the characteristics and efficiencies of different PV cell types is crucial for advancing solar energy technology and its integration into various sectors. The data provided in the table offers valuable insights into the progress made in solar cell development and provides a basis for informed decisions in renewable energy research and implementation[2][10].

2.1 Solar energy overview

2.1.1 The abundance of solarenergy

Solar energy, Mother Earth's generous gift to us, is vast and ubiquitous. Unlike certain non-renewable resources, sunlight is available in abundance, shining down on us each day. This makes it an indispensable asset in the world's search for cleaner, more sustainable energy sources. As we continue to face challenges like global warming and environmental degradation, turning to this inexhaustible resource offers hope for a greener future.

2.1.2 Harnessingsolar power

Solar energy, in its raw form, is incredibly versatile. Its energy can be harnessed and converted into usable electricity through two primary technologies: photovoltaic (PV) cells and Concentrated Solar Power (CSP). Each method offers its unique advantages, but both serve the critical purpose of tapping into this renewable source to cater to our power needs, thereby reducing our reliance on fossil fuels.

2.2 Photovoltaic (PV) cells overview

2.2.1 The principlebehind PV cells

Photovoltaic cells, often simply called PV cells, are marvels of modern science that have the innate ability to produce electric currents directly from sunlight. This happens due to a phenomenon known as the photovoltaic effect. When sunlight hits these cells, they absorb photons from it [3][14]. This energy then excites electrons, causing them to flow, thus generating electricity. It's a direct, clean, and efficient method of turning sunlight into power, eliminating the need for bulky machinery or harmful emissions.

2.2.2 The Evolution of PV Cells

Delving deeper into PV cells, we find an array of types, each distinct in its composition and method of operation. These cells have seen significant development over time, leading to their categorisation into three generations. The first generation consists of crystalline silicon cells. These were the pioneers, setting the stage for what was to come. Following them, the second-generation emerged, known as thin-film cells. These were leaner, more flexible, and offered a broader range of applications. Then came the third generation, which took the foundation laid by the second and enhanced it further, leading to even more efficient and adaptable thin-film cells. As technology continues to advance, these generations represent the milestones in our journey to perfect solar energy harnessing.

Solar photovoltaic (PV) technologies have experienced significant evolution over the years, both in terms of their construction materials and efficiency capabilities. Each generation of PV cells is characterised by specific materials and operational features that influence their performance and application[4][9]. The table 2 below offers a concise overview of the three primary generations of PV cells, highlighting their main components and efficiency metrics, followed by a comparative snapshot of efficiencies across various PV technologies.

Table 2. Summary of Photovoltaic (PV) Cell Types and Efficiencies[2]

PV Generations	Key Highlights and Specifications
First-Generation PV Cells	- Composed of crystalline silicon, encompassing both monocrystalline and polycrystalline varieties - Monocrystalline cells boast efficiencies nearing 25%, while their polycrystalline counterparts achieve around 20.4%

Second-Generation PV Cells	- Characterised by thin-film technology that offers cost advantages; the materials used include amorphous silicon (AS), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) cells. - Efficiency metrics vary with AS cells achieving about 10.1%, and CIGS cells leading the pack with up to 17.4%. - Notably, the use of CdTe cells is curtailed due to concerns over toxicity and the limited availability of tellurium.
Third-Generation PV Cells	- Designed with a dual focus on escalating efficiency and reducing costs, incorporating technologies like organic solar (OS) cells and dye-sensitized (DS) solar cells. - OS cell efficiencies hover around the 10% mark, whereas DS cells demonstrate solar-to-electric conversion efficiency slightly above 10%.
Efficiency Comparison Across PV Cells	A snapshot of efficiency benchmarks for different solar PV technologies reveals the following ranges: - Crystalline silicon (25.0-10.1%) - GaAs (28.3-18.4%) - CIGS (19.6-17.4%) - CdTe (16.7%) - Amorphous/nanocrystalline Si (10.1%) - Dye-sensitized (11.0-9.9%) - Organic thin film (10.0-4.2%) - Multi-junction devices standing at an impressive range of 34.1-11.7%.

3 Review and Discussions

3.1 Internet of Things (IoT) and Solar power plants

The IoT has transformed the idea of Smart Cities, wherein intelligent systems meld into diverse facets of urban living to amplify sustainability and living standards. Using IoT-fitted sensors, wireless networks, and data analytics tools, the foundation is laid for overseeing and handling various functions, like energy dispersion. Smart Cities utilise IoT to fine-tune energy usage, advance traffic control, uplift healthcare provisions and beyond. Pertaining to solar power installations, the IoT facilitates real-time oversight and issue identification, guaranteeing proficient energy production and allocation.

In a detailed investigation, Khoo et al. 2014 highlighted the paramount importance of both the orientation and tilt angle when it comes to the functioning of photovoltaic (PV) modules. These aspects, they noted, directly dictate the quantum of solar radiation that the modules capture. Through their research conducted in Singapore, they aimed to paint a comprehensive picture of the irradiance levels received by PV modules, especially when these modules are placed at a myriad of orientations and tilt angles. Three distinct sky models were employed in their study: Liu and Jordan, Klucher, and Perez et al. An interesting phase of their research involved juxtaposing the data from these models against real-world measurements taken from irradiance sensors. Of the three models, the Perez et al. model was identified as the most accurate, pointing towards the conclusion that, for Singapore's specific climatic nuances, modules oriented towards the east captured the lion's share of annual tilted irradiation. This observation was further fortified through a meticulous year-long monitoring exercise, revealing that systems with a 10° eastward tilt outshined other configurations in terms of energy yield[3].

In a pioneering effort, Shapsough et al. 2018 developed an innovative framework that hinged on the Internet of Things (IoT). This framework was meticulously designed to facilitate the real-time supervision and adept management of expansive solar PV systems. Nestled within the powerful trinity of IoT's communication paradigms, software capabilities, and hardware infrastructure, this ingenious system proffers stakeholders with the latitude to remotely regulate PV installations. Furthermore, it allows them to delve deep into the intricate interplay between various environmental parameters, such as ambient temperature and humidity, and their bearing on PV efficiency. A standout finding from their extensive exploration was the efficacy of MQTT (Message Queuing Telemetry Transport). Its performance metrics, particularly the minimal average network delay, underscored its potential as a formidable tool apt for applications in both the solar domain and broader smart grid ecosystems[4].

Tchuisseu et al. 2019 steered their research towards a pressing contemporary challenge: how to ensure unwavering grid stability amidst ever-escalating electricity consumption and the growing embrace of renewable energy sources. Their ingenious solution came in the form of dynamic demand control (DDC). With this model, electronic devices are imbued with the ability to autonomously recalibrate their functioning parameters based on the nuances of electric frequency. The culmination of their research introduced a groundbreaking communication-empowered DDC group coordination system. This innovative construct drastically curtailed both frequency variations and the backlog of pending tasks, offering a promising avenue for future grid management[5].

Diaz et al. 2007 embarked on an insightful journey into the realm of stand-alone PV systems, placing a pronounced emphasis on the concept of 'dependability'. Their research contended that integrating dependability frameworks into PV system design and management could notably enhance the system's holistic performance. A series of challenges, especially those posed by system failures and the ongoing demands of maintenance, were brought to the fore. Diaz and his team underscored the profound importance of the quality of PV components, the consistent availability of spare parts, and a robust arsenal of maintenance resources. The research resonated with a clarion call for unwavering quality assurance in sprawling PV projects, spotlighting the need for data-backed insights to ensure the long-term health of these energy ecosystems[6].

Collins et al. 2009 delved deep into the intricacies of photovoltaic systems, championing the cause of reliability and availability as non-negotiable metrics for ensuring their cost-effective design and streamlined operation. Their methodological approach was exhaustive, involving a meticulous amalgamation of system failure data, repair chronicles, and the crafting of a comprehensive Reliability Block Diagram (RBD) for PV setups. With the 4.6 MWdc photovoltaic installation in Arizona as their study's canvas, they unravelled insights about its near-sterling reliability and availability indices, laying down a roadmap for similar future ventures[7].

Taking the discourse on PV system performance a notch higher, a study on grid-connected solar-PV systems championed the analytical prowess of Reliability, availability, and maintainability (RAM). This study, rooted in the vast and varied nuances of RAM analytics, shifted its lens from the microscopic details of sub-assemblies right up to the overarching system. A rich tapestry of data, gleaned from global databases detailing the myriad trajectories of sub-assembly failures and repairs, became the backbone of this research. One of the pivotal takeaways was that a vigilant and strategic monitoring regimen, especially of pivotal sub-assemblies, could dramatically elevate a PV system's operational performance, ensuring both heightened efficiency and optimised expenditure on maintenance[8].

4 Conclusion and Future Directions

IoT Revolutionizes Solar Energy Management: The integration of Internet of Things (IoT) technologies into solar power plants enables real-time monitoring, fault detection, and management. This enhances the efficiency and reliability of energy generation and distribution, making solar power a more viable and attractive option for sustainable urbanization.

Dust-based Soiling Challenge: Dust-based soiling remains a significant challenge in solar power generation, particularly in desert regions. Accumulation of dust particles on solar panels obstructs radiation absorption, leading to reduced energy output. Addressing this challenge is crucial for maximizing solar energy yield in such environments.

Smart Cities and Sustainable Urbanization: The application of IoT-based remote IV tracing systems contributes to the development of Smart Cities and supports sustainable urbanization. By enabling efficient monitoring and fault detection in solar power facilities, IoT technology aids in optimizing energy production and consumption in urban areas.

Photovoltaic Cell Efficiency and Types: Different generations of photovoltaic (PV) cells, including first-generation (crystalline silicon), second-generation (thin-film), and third-generation (improved thin-film) cells, offer varying levels of efficiency. Understanding the characteristics and efficiencies of these PV cell types is crucial for advancing solar energy technology and its integration into diverse sectors.

Optimizing PV System Performance: Research findings by Khoo et al. (2014) highlight the importance of optimizing the orientation and tilt angle of PV modules to maximize energy generation. IoT-enabled systems can help achieve this optimization and improve overall PV system performance.

Reliability and Maintenance: Ensuring the reliability and maintenance of solar PV systems is essential for long-term performance. Studies emphasize the importance of using quality components, monitoring critical subassemblies, and conducting RAM analysis to identify and address potential failures. Improving reliability and maintenance practices contributes to stable energy production.

In summary, the integration of IoT technology in solar power plants, particularly in desert regions, has the potential to address challenges like dust-based soiling, enhance energy generation efficiency, and support the development of Smart Cities for sustainable urbanization. Additionally, understanding PV cell types and their efficiencies, optimizing PV system orientation, and implementing effective reliability and maintenance strategies are crucial for advancing solar energy technology and ensuring its long-term success.

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