Driving Renewable Energy in Existing Buildings: A Paradigm Shift with Flexible Photovoltaic Panels and Intelligent Implementation

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Abstract

The Government of the Hong Kong Special Administrative Region aims for carbon neutrality by 2050, as outlined in Hong Kong's Climate Action Plan 2050. In support of this objective, the Electrical and Mechanical Services Department is at the forefront of integrating renewable energy technologies into existing government buildings. This paper explores strategies to enhance the installation of photovoltaic systems in structures with limited spare loading capacity while ensuring that operations remain undisturbed. Innovative solutions are introduced to expedite renewable energy installations and to manage effectively a rapidly growing network of energy generation assets. The approach harnesses the potential of lightweight PV technology, refines installation processes for widespread application, and integrates advanced management systems. The findings illustrate successful tactics for expanding renewable energy initiatives, offering valuable insights on the path to a sustainable energy future.

Keywords: Renewable Energy, Flexible Photovoltaic Panel, Innovative Smart Construction, Off-site Fabrication, Artificial Intelligence, Mass Deployment

1 INTRODUCTION

In response to the Paris Agreement, the Government of the Hong Kong's Special Administrative Region (HKSARG) has announced the Hong Kong Climate Action Plan 2050 (HKCAP2050), aiming to achieve carbon neutrality by mid-century. The HKCAP2050 highlights four key areas: net-zero electricity generation; energy saving and green buildings; green transport; and waste reduction [1].

Electrical and Mechanical Services Department (EMSD) has proactively integrated renewable energy technologies into existing government buildings. Considerations arise when implementing distributed solar harvesting systems in Hong Kong, a long-established and well-developed urban environment, such as the limited loading capacity of existing structures for conventional photovoltaic (PV) panels, and the need to maintain continuous services for users. To address these issues and expedite progress towards the 2050 target, we have initiated a series of projects that embrace the concept of mass deployment and smart operation.

The aim of this study is to investigate methods of applying renewable energy installations in buildings with limited structural load capacity while minimizing disruption to residents and users, and to enhance operation and maintenance effectiveness of Renewable Energy Installation by introducing Flexible PV Panels, Building Information Modeling (BIM), Design for Manufacture and Assembly (DfMA), Multi-trade integrated Mechanical, Electrical and Plumbing (MiMEP), the Government-Wide IoT Network (GWIN), and Artificial Intelligence (AI)-driven PV Management System with Energy Generation Prediction, Fault Detection and Diagnosis (FDD) and Predictive Maintenance features.

2 TECHOLOGY ADOPTED

2.1 Selection of Renewable Energy Technologies

Transitioning from the broader strategic goals outlined in the HKCAP2050, we delve into the specific technologies that enable the effective and optimized implementation of renewable energy solutions. In considering suitable PV installations for the building rooftops, it is necessary to select an appropriate technology through a comprehensive assessment. This assessment should encompass several factors: energy conversion efficiency, structural integration capacity, financial viability, installation logistics, and the potential for effective mass deployment. The options considered include conventional PV, flexible PV and walkable PV systems, the results of which are shown in Table 1.

Table 1. Comparison between Conventional PV Panel, Flexible PV Panel and Walkable PV Panel

	PV Modular Efficiency	Implication on Existing Structure	Installation Time	Cost
Conventional Monocrystalline PV Panel	✓✓✓	✓	✓✓	✓✓
Flexible Monocrystalline PV Panel	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Walkable PV Panel	✓✓	✓✓	✓✓	✓

Conventional monocrystalline PV panels (Figure 1 Left) are well-regarded for their high energy conversion efficiency and also carry a heavier weight, which, alongside additional wind load consideration, may challenge installations on buildings with limited structural reserve capacity. In contrast, walkable PV systems provide a multifunctional surface but entail higher financial costs and require an extended, disruptive installation process. Upon rigorous comparative analysis, flexible monocrystalline PV panels, which feature a similar energy conversion efficiency to conventional PV panels but are lighter in weight, emerge as the most suitable option for a pilot installation on a rooftop designed primarily for maintenance, with a limited spare structural capacity of 0.75kPa. Their installation is relatively straightforward, and they also offer the potential for mass deployment, further affirming their position as the preferred choice for this application.

Figure 1. Conventional PV Installation and Flexible PV Installation

The proposed installation at the rooftop of an existing office building (Figure 1 Right), comprising 10 flexible PV panels each with a power output of 430W_p and totaling 4,300W_p, would weigh approximately 3.25kg/m^2, well within the structural limits, and exhibit high modular efficiency of around 19.3%. Moreover, they offer a financially viable alternative by mitigating the need for costly structural reinforcements and simplifying installation complexity. With an expected product life of 25 years, these panels promise a cost-effective, high-performance solution suitable for buildings where structural modifications are impractical or undesirable.

2.2 Building Information Modelling, Design for Manufacture and Assembly and Multi-trade Integrated Mechanical, Electrical and Plumbing

BIM, DfMA and MiMEP not only streamline the integration of flexible PV panels but also play a crucial role in reducing on-site construction time, enhancing site safety, and minimizing material waste. By leveraging these methodologies, the deployment of flexible PV panels can be effectively scaled up, facilitating the widespread adoption of renewable energy solutions.

BIM is a digital process that creates and manages information on a construction project across its lifecycle, facilitating a detailed visualization of the building structure. Moreover, the collaborative environment fostered by BIM (Figure 2) helps to identify potential issues before they occur on-site, which can reduce the need for complex on-site coordination during the actual construction phase. This proactive approach can lead to a more streamlined building process, minimizing on-site coordination and enhancing overall project efficiency.

Figure 2. BIM for Flexible PV Installation Project

DfMA is a design approach that simplifies the manufacturing and assembly of products, thereby enhancing efficiency. When paired with MiMEP, which facilitates the offsite assembly of building services, these methodologies synergize to ensure that the production and installation of flexible PV panels are streamlined. This integration significantly reduces construction time and costs, thereby paving the way for scaling up the adoption of renewable energy on buildings globally.

3 STREAMLINED CONSTRUCTION OF THE PV INSTALLATION

3.1 Expedited On-Site Construction for Flexible PV

The on-site construction process for installing flexible PV systems is distinguished by its brevity, taking only 3 days. This rapid on-site assembly is in stark contrast to the 4 weeks required for other flexible PV installations that do not leverage advanced methodologies and is considerably more efficient than the conventional 2-3 months duration for standard PV installations.

This efficiency is the result of a streamlined workflow where the majority of the construction activities, such as the pre-assembly of flexible PV panels, as well as the comprehensive electrical system, which encompasses the inverter, isolation transformer, metering, and protective devices, are performed off-site. Employing DfMA and MiMEP not only expedites the process but also helps to minimize waste, as precise manufacturing and assembly lead to reduced material excess and resource use. The result is a highly reduced amount of on-site work, which not only speeds up the process but also minimizes interruptions to building occupants and local communities.

When the pre-assembled units arrive on-site, the installation is reduced to straightforward tasks like securing bolts and connecting wires, which can be executed quickly and with minimal noise, concluding the physical installation within the remarkable 3-day window.

3.2 Enhancing Installation Processes through BIM and DfMA Integration

The accelerated on-site construction timeline is largely attributable to the strategic use of BIM, DfMA and MiMEP. BIM technology is pivotal in creating a detailed digital twin of the project, which serves to proactively identify and resolve potential design and construction conflicts. This ensures that the design is thoroughly vetted and clash-free before any physical work begins.

In conjunction with BIM, DfMA and MiMEP principles guide the prefabrication process, allowing for the off-site construction of components in a controlled factory setting, which is then seamlessly executed on-site. This integration of BIM, DfMA and MiMEP streamlines the installation by allowing complex elements of the construction process to be planned, reviewed, and resolved prior to the arrival of materials on-site.

The culmination of these advanced planning and prefabrication techniques via BIM, DfMA and MiMEP is a construction process that is not only faster but also less invasive and disruptive, demonstrating a significant step forward in construction practices for renewable energy installations. The difference made by these methodologies is most evident in the minimized on-site construction duration, which benefits all project stakeholders, from the construction teams to the end-users.

4 REVIEW OF THE PV PANEL IMPLEMENTATION

4.1 Project Effectiveness Evaluation

The integration of flexible PV panels with BIM, DfMA and MiMEP has demonstrated significant effectiveness in establishing renewable energy systems within government venues and facilities. The effectiveness is particularly evident in the reduction of construction timeframes. Detailed planning and coordination through BIM, paired with the efficiency of DfMA and MiMEP's prefabrication process, have optimized the installation timeline, drastically reducing the period from inception to operation. The expedited process has minimized the interference with governmental operations and accelerated the transition to sustainable energy production.

The quality of project delivery has likewise seen notable improvements. The foresight in error detection and optimization afforded by BIM, in conjunction with the precision of DfMA and MiMEP's factory-based quality control, have culminated in installations that adhere to the highest quality standards. The project has further exhibited effectiveness in safety management through the transition of much construction activity off-site, reducing on-site hazards, and utilizing BIM to simulate installation processes for better preparedness.

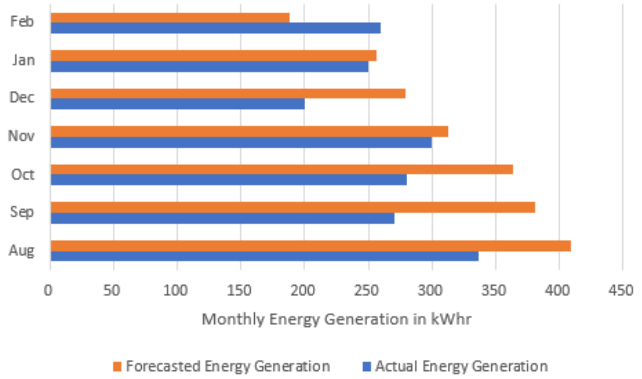

Figure 3. Energy Generation Analysis

Regarding the energy generation analysis, the predicted total energy generated by the flexible PV panels for the period from August 2023 to February 2024 was approximately 2,189 kWh, while the actual energy generated was about 1,900 kWh, corresponding to 86.6% of the predicted figure (Figure 3). Several factors may have contributed to this difference, including the frequency of inspection and maintenance, accumulation of dirt or debris on the panels, the environmental conditions and variations in solar irradiance. The performance of these flexible PV panels is consistent with that of other conventional monocrystalline PV installations, indicating that the overall performance of the flexible PV panels is within acceptable limits.

Moreover, this project has been instrumental in the development of a standardized flexible PV module and a modular electrical panel, which are poised to be integral components in the upcoming mass deployment. The standardization efforts will ensure consistent quality and compatibility across various installations, further contributing to the ease and speed of future projects.

4.2 Endurance of PV Systems in Severe Weather Conditions

The durability of the PV system was distinctly illustrated when it withstood the harsh conditions brought by Typhoon Saola, which led the Hong Kong Observatory to issue Hurricane Signal No. 10, as winds reached a maximum hourly mean speed of 130 to 153 km/h. Installed just nine months prior, the system maintained its structural integrity and showcased remarkable resilience in the face of this extreme weather event. A week thereafter, the installation braved record-breaking rainfall, and the black rainstorm warning was in force for more than 16 hours, with rainfall intensity reaching 158.1 millimeters within a single hour. Following the onslaught of both the typhoon and the torrential downpour, the system continued to function without interruption, proving its ability to withstand severe weather events and maintain stability.

4.3 Lessons for Future Implementations

The successful deployment of the PV system provides a compelling case for its widespread adoption, especially in structures where additional structural load capacity is at a premium. Its resilience in extreme weather, coupled with benefits such as reduced construction time, improved quality, and increased safety, makes it an attractive option for mass deployment.

Careful consideration of the roof's drainage design, specifically the lay to fall direction, is essential to prevent water accumulation and ensure the longevity of the system. Also, during very hot weather, minimal deformation was observed in the stainless-steel backing panel, but this did not impair the system's operation, which continued to function effectively. Moving forward, enhancements will be made to the stainless-steel panel design, strengthening its resilience to high temperatures and securing the system's performance and durability for the long term. After these enhancements are implemented, we will initiate the second stage of our series of projects, which entails a small-scale mass deployment.

5 REMOTE PV MANAGEMENT SYSTEM

5.1 System Architecture

The remote PV management system is a strategic response to the increasing number of PV installations and the widespread distribution of government venues, which includes sites in areas with limited accessibility. This distribution presents complexities for continuous individual on-site monitoring of PV systems, necessitating a more streamlined approach to enhance efficiency and optimize resource allocation. Central to this architecture is the deployment of a local renewable energy monitoring system at each venue. Through integration with the GWIN, the system is configured to collect critical real-time data, including DC/AC current and voltage, along with environmental factors such as temperature and solar irradiance. This facilitates comprehensive analysis and supervision of energy generation.

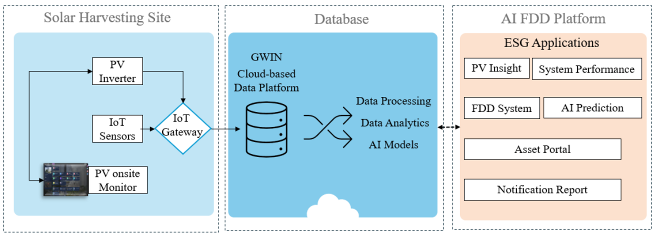

Figure 4. System Architecture

The architecture as shown in Figure 4 further incorporates advanced AI models that process this data to provide detailed monitoring and predictive forecasting of energy generation, system health assessments, and proactive fault detection and diagnosis. By adopting this strategy, the maintenance efficiency is significantly improved, and the reliability and effectiveness of the renewable energy systems are ensured, leading to a cohesive and sustainable energy management approach.

5.2 Remote Monitoring by Government Wireless IoT Network

In the modern era, data security is a critical component of modern infrastructure, especially in the context of smart applications. With this in mind, the EMSD is constructing a government-operated network of wireless sensors deployed throughout Hong Kong. This network is designed to support a variety of smart applications, improving the efficiency and responsiveness of public services.

GWIN eschews traditional 4G connections for a low-power, secure Long Range (LoRa) network, reducing installation complexity and energy consumption while enhancing data security by avoiding third-party networks. This allows for efficient, real-time remote monitoring of PV systems across Hong Kong, optimizing maintenance and ensuring data integrity.

5.3 AI-powered Remoted PV Management System

The Remote PV Management System (Figure 5), enhanced by the deployment of AI, has revolutionized the way energy management, system health analysis, and FDD are approached. The Summary Page offers a dashboard that not only showcases key metrics such as instantaneous energy generation and solar irradiation, but also the overall condition index of the PV installation. This index is a composite measure derived from three critical sub-indices: System Performance Index, System Stability Index, and System Degradation Index.

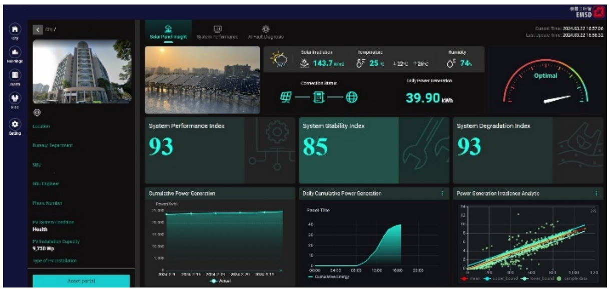

Figure 5. AI-enabled Remote PV Monitoring System

The System Performance Index is an important indicator of a PV system's operational health, reflecting the performance by comparing actual energy generation to what would be expected. This comparison incorporates a normalization process that adjusts over time, accounting for a variety of losses, such as those due to temperature variances, DC to AC energy conversion losses, wiring losses, and environmental conditions that are difficult to replicate in simulations because they are location-specific. A high System Performance Index signifies that the PV panels are in prime condition, while a significant drop may indicate potential issues, like soiling, shading, the presence of hotspots, or junction box faults, necessitating maintenance or cleaning to restore the system's original performance levels.

The System Stability Index serves as a measure of the PV system's reliability, reflecting the frequency and severity of system faults through its value. A lower index value indicates a greater occurrence of issues, prompting a closer examination and the potential need for maintenance actions. This index assists maintenance teams in focusing their attention on which is most needed and in preparing for significant repairs or replacements that may be forthcoming.

The System Degradation Index is a tool for assessing the long-term health of the PV system by comparing its actual degradation with the degradation rates claimed by the manufacturer. This comparison is essential to determine whether the system's aging process aligns with or deviates from the expected. Maintenance teams rely on this index to strategically schedule any extensive refurbishment that the system may require, facilitating timely interventions to uphold the system's performance and extend its operational lifespan.

5.4 AI Application in Energy Generation Prediction

Energy generation stands as the key performance index for all PV installations. Determining the health and efficiency of these systems typically involves comparing forecasted energy generation values with actual power generation data. Embedding a prediction feature for energy generation within the monitoring system enables the analysis of this gap. It's crucial to recognize that in energy generation prediction, the prevalent issue is the gap between forecasted and actual outputs, often exceeding 10%. This gap can be attributed to factors such as wiring losses, fluctuating weather conditions, and environmental variables, as previously mentioned, which pose challenges to simulation accuracy. For instance, in the case of a pilot flexible installation, this discrepancy was as high as 13.4% right from the beginning. Such variances can mistakenly indicate underperformance, leading maintenance teams to consider unnecessary cleaning or immediate corrective actions. Therefore, developing a more precise prediction methodology is essential to narrow this gap and ensure that maintenance decisions are based on reliable and accurate information.

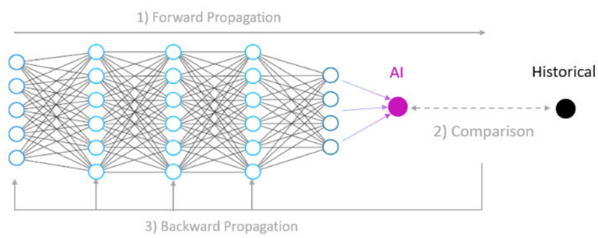

Figure 6. AI Algorism for Energy Generation Prediction (Neural Network)

To enhance energy generation prediction, a Neural Network (Figure 6), a sophisticated type of Artificial Neural Network with multiple hidden layers, is utilized. These layers enable the network to hierarchically learn data features and discern complex patterns necessary for accurate forecasting. The methodical approach begins with gathering historical data from solar harvesting systems, followed by rigorous preprocessing to clean and normalize the dataset. Subsequently, a Neural Network architecture is designed, calibrated in hidden layers and nodes. Training involves feeding this data into the network, allowing it to learn by adjusting weights and biases. After training, the model's performance is evaluated on a separate test dataset to ensure robustness. Finally, the trained network is utilized to predict power generation for new data, aiming for high precision in real-world application.

With the aid of this AI-powered prediction tool, the gap between actual and predicted energy generation has been significantly reduced to within a 5% margin. This improvement is substantial as it allows for a clearer distinction of normal system performance variations from those caused by soiling, thereby enabling more accurate and effective maintenance decision-making.

5.5 AI Application in System Health Analysis and FDD

Developing a system health analysis and FDD platform for PV panels begins with understanding common issues like soiling, shading, hotspots, and junction box faults. These issues can be identified by the rate of change of energy loss and the level of energy loss they cause. For example, energy loss due to soiling can reach up to 25%, shading can account for losses up to 10%, [3] and a hot-spotted PV string can lead to a loss as high as 26.3% [4]. Notably, the rate of energy loss is relatively slow for soiling, which allows for distinct pattern recognition over time.

A Supervised Learning Model is selected for its proficiency with labeled data, which is especially valuable in scenarios where the rate of change of energy loss is gradual and can be tracked against known issues. The process entails data labeling with historical maintenance outcomes, which involves marking data with the identified issue, such as the specific type of soiling or shading observed. This detailed labeling provides a rich dataset that enables the chosen algorithms, such as Random Forest and Decision Tree (Figure 7), which are selected for their effectiveness, to learn and discern the subtle nuances of system health issues.

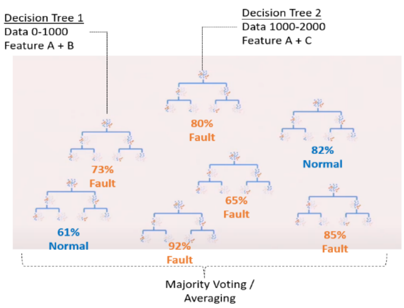

Figure 7. AI Algorism for Predictive Maintenance (Random Forest)

Through this training, the algorithms develop the ability to accurately identify and predict potential failures from the subtlest of data trends. Once the model's predictive accuracy is validated and refined, it is deployed for predictive maintenance operations. It analyzes new data inputs, such as real-time GWIN readings, to proactively detect signs of impending issues. This predictive capability facilitates the scheduling of maintenance before failures occur, effectively reducing downtime and maintenance costs, and ensuring the sustained high performance of PV installations.

6 CONCLUSION AND WAY FORWARD

To conclude, the pilot project in this series has successfully demonstrated the integration of Flexible PV Panels, BIM, DfMA, MiMEP, GWIN, and an AI-driven PV monitoring system in buildings with limited structural capacity. The resilience of these installations against extreme weather, coupled with a rapid three-day installation, highlights a significant reduction in disruption and a path for mass deployment. The AI-driven system is particularly noteworthy for its role in future scalability, providing continuous monitoring and predictive maintenance insights that inform timely refurbishment and upgrading plans. This ensures long-term efficiency and performance of solar energy systems, streamlining the transition to renewable energy.

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