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Assessing Key Performance Indicators for Solar Energy Contracts in Building Applications

Nurul Ain Mohamed Idris[1], Mohd Hafizal Ishak[1,2]*, Azlina Md Yassin[1,2], Nurul Afiqah Ahmad[3] & Haidaliza Masram[1,2]

[1] *Department of Real Estate Management, Faculty of Technology Management & Business, Universiti Tun Hussien Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA*

[2] *Centre of Project, Property and Facilities Management Services (PRoFMs), Faculty of Technology Management & Business, Universiti Tun Hussien Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, MALAYSIA*

[3] *Department of Property Management Faculty of Built Environment (FBE), Kompleks Tahir Majid, Universiti Teknologi MARA, 40450 Shah Alam, Selangor Darul Ehsan, MALAYSIA*

*Corresponding Author: mhafizal@uthm.edu.my
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Abstract

Solar energy has emerged as one of the fastest-growing sources of renewable energy (RE) due to its low maintenance requirements and ease of installation. Despite extensive research conducted in countries such as Switzerland, China, and South America, there remains a limited number of studies focusing on solar panel performance and management within the Malaysian context. This study addresses a significant research gap by examining the Key Performance Indicators (KPIs) used in solar panel contracts, taking into account variations in seasonal conditions and operational management methods. The objectives of this research are twofold: (i) to determine the relevant KPIs for solar panel contracts, and (ii) to analyse suitable measurement tools based on these KPIs. A qualitative research approach was employed, involving face-to-face interviews with three industry experts. Data were analysed using thematic analysis. The findings identified ten sub-themes categorised under four critical success factors: Coating (type, efficiency, and durability, as well as coating replacement and surface cleaning), shading effect (site analysis and new obstructions), radiance energy (energy harvesting and dynamic panel systems), and fire safety (thermal limits and spark prevention). Additionally, three sub-themes emerged regarding performance measurement tools: process-oriented approaches, application-based monitoring, and limited integration of external tools. The study contributes to the development of a structured framework for KPI-based evaluation and monitoring of solar panel performance, particularly tailored for the Malaysian renewable energy sector.

1. Introduction

Solar panel energy has grown at the fastest rate in the current trend of increasing the amount of power generated through renewable energy (RE) due to its low maintenance costs and ease of installation. 60% of the newly installed RE capacity comprised the 140 GW increase in worldwide solar panel power capacity in 2021 (Jung et al., 2024). Renewable energy is a vital green industry in combating climate change and decarbonising the world economy. China's transformation from an industrial powerhouse to a leader in sustainable growth is exemplified by the expansion of its regional renewable energy sector, which offers important lessons for a sustainable future for all people (Nyangchak, 2024).

The widespread usage of solar panels is primarily due to the decision-making of real estate developers in Malaysia to invest in household projects that have built-in solar power. According to the Malaysian Investment Development Authority (MIDA, 2024), Teladan Setia Group Bhd is one example of a Malaysian developer that has equipped a township in Taman Bertam Heights (TBH) with solar panels. This trend is emerging among forward-thinking property developers, especially with the growing emphasis on sustainability and energy efficiency. The built-in solar panel enables each homeowner to save up to 75% on electricity costs. It is also important to note that the Green Building Index had a section on renewable energy and on-site energy capture. This encourages the use of renewable energy in government intervention in Malaysia (GBI, 2009).

For every kind of operation, a KPI is needed. Knowing methods to assess success is essential in every business. KPIs are measures used to monitor and evaluate the efficacy of various business processes. KPI may change your business's objectives about jobs, deadlines, and goals (Mosca, 2019). There are a few important KPIs to measure progress, analyse patterns over time, adjust, stay on track, and solve problems or tackle opportunities (Wishart, 2024).

Regular maintenance and operational procedures are essential for monitoring the functioning of solar panel installations. These actions are necessary for preserving the plant's lifetime safety, dependability, and power supply productivity and maximising return on investment.

Although the significance of operation and maintenance is increasingly acknowledged, many solar plant shareholders remain unfamiliar with the key concepts and procedures of this activity (Rediske, 2024). This occurs because they believe that operations and maintenance are limited to maintaining parts and monitoring the plant's status through the online tracking platforms provided by the equipment suppliers.

A missing element that could combine all the research as a complete guideline for KPIs for future maintenance. Research by Arias Velásquez (2024) focused only on the maintenance of dust accumulation on the surface of solar panels. The researcher found that there is also a lack of studies in Malaysia. At the same time, research is abundant in other countries such as Switzerland, China, South America, and Indonesia. There is a significant gap in the previous study on KPIs, as technological advancements have occurred in the management of solar panel operations. This study aims to determine the KPI for building long-term contracts on solar panels in buildings and to assess the contract performance based on the KPI.

This study focuses on paying attention to the KPI that will be set to maximise the solar panel energy generated over a set period. Some of the KPIs mentioned in this research are the Coating on the solar panel, shading, irradiance, and fire safety in solar panels. Two objectives were set: to determine the KPI for building long-term contracts on solar panel installations and to assess suitable solar panel contract measurement tools based on this KPI. The scope of this study focuses on a residential and commercial building in Malaysia, which is especially limited to knowing the KPI, especially for buildings that have installed solar panels.

2. Literature Review

2.1 Introduction

This section reviews previous research on critical performance indicators for managing solar panels in buildings. KPIs are quantifiable indicators that show how much a company has allocated to fulfil strategic objectives to succeed. The elements contained in KPIs consist of strategic objectives, key indicators relevant to these strategic goals, the benchmark objectives, and the KPIs' time frame or period (Setiawan & Purba, 2020).

The objective of having KPIs is to connect the values of the vision and mission. KPI components include benchmark objectives, the time or period for which the KPIs are measured, strategic objectives, and critical indicators important to these strategic goals. Through organizational activities, KPIs are intended to establish a connection between the values of the vision and mission, organizational strategy, and organizational performance targets to meet expected performance targets

2.2 Coating on Solar Panel

Each solar panel will need regular cleaning or maintenance to ensure the panel can maximise the absorption of each cell in a photovoltaic cell. Suppose the solar panel is not well-maintained. In that case, it will cause a decrease in energy efficiency as the top of the solar panel will accumulate dust day by day, which will hinder energy absorption. Studies in Baghdad City, Iraq, examining dust deposition on solar panels in an in-field setting, found that after a day, solar panel energy production efficiency dropped by 6.24%, after a week by 11.8%, and after a month by 18.74% (Saidan et al., 2016). The investigation focused on the effects of breeze velocity, dust particle size, and dust substance on the rate of sand deposition. Most of these particles are made of clay, dust, pollen, smoke, and even animal faeces, especially bird faeces. (Zhang et al., 2023).

To optimise production while lowering maintenance costs, assessing the dust on solar panels and starting cleaning methods as soon as feasible is essential. The effect of accumulated dust on panels varies depending on the size of the dust particles and the prevailing weather conditions. The position, the characteristics of the dust, and the ambient temperature all affect the output power of the PV panels. Due to this restriction, research findings from one nation cannot be generalised to other countries (Khilar et al., 2022).

To ensure the solar panel absorbs the most energy, several methods can be employed to prevent efficiency reduction, such as regular cleaning and Coating. Coating as a material process of finding a definite answer is part of a preventative strategy (Arias Velásquez et al.,2024). Further research is needed to study the lifetime of these coatings. Typically, these items require the Coating to be reinforced every three to five years. (Arias Velásquez et al., 2024). One of the coatings being used is a solar panel coated with SiO2 nanoparticles, which are considered hydrophobic and can cause dirt particles on the solar panel surface to fall after rain.

The quantity of energy the device generates can be significantly reduced when the dust level on solar PV panels exceeds a certain threshold. Thus, cleaning operations can start as soon as the dust collected surpasses this limit. The best time of year to clean solar photovoltaic modules is during the off-season, as this avoids incurring additional expenses associated with regular cleaning. (Khilar et al., 2022).

2.3 Shading Effect

Shading in solar panels is the loss of electricity output that occurs when an obstruction blocks the panels from receiving direct sunlight. A variety of factors, like a physical obstruction, can cause shading. Physical obstruction is anything near the solar panel, such as trees, poles, buildings, dust, sand, bird droppings, or even the solar panel itself. Other than that, meteorological conditions, such as clouds and weather, have varied throughout the years. Shading effect analysis is essential, as the effect may not be immediately apparent. This involves a feasibility study, on-site survey, sun path diagrams, solar access and exposure calculations, shade maps, 3D modelling, and simulation software. This analysis is essential, as it will have a long-term effect on energy absorption if it is not good.

According to studies, a single shaded cell in a solar energy system can drastically reduce its overall solar power production by 50–80% (Lee, 2022). Even if only a minimal amount of your solar array is in the shade, the effect on the performance of your whole Solar panel can have a considerable impact. It is essential to note the optimal location of the panel and avoid natural shadows during all seasons by adjusting the time of day throughout the year (Allw et al., 2022).

2.4 Irradiance

Solar panel electricity generation primarily relies on solar irradiance. To optimise output power, it is essential to orient the PV panel surface correctly with respect to the incoming solar rays (Vasilikos et al., 2024). Solar irradiance, measured in watts per square meter (W/m^2), quantifies the energy incident on a surface per unit area of solar radiation. This key performance indicator (KPI) reflects the number of hours a PV system operates at its nominal capacity.

The yield factor is determined by dividing the net alternating current (AC) energy generated by the system (measured annually, monthly, or daily) by the nominal power of the PV panel, as defined under standard test conditions—solar irradiance of 1 kW/m^2 and a cell temperature of 25°C (Rediske et al., 2024).

Regional comparisons of PV system performance reveal that variations in insolation have a significant impact on system size requirements. For instance, Iraq experiences an average annual solar irradiance of 5.5 kWh/m^2, compared to 3 kWh/m^2 in northern Germany. However, high insolation in the Middle East, where 52% of the radiation is in the infrared spectrum, poses challenges due to heating effects, which reduce PV efficiency (Allw et al., 2022).

Solar energy absorption differs across regions due to variations in sunlight intensity and duration throughout the year. In Bahrain, for example, the mean daily solar power ranges from 0.37 to 0.56 kW/m^2 for fixed panels and from 0.45 to 0.70 kW/m^2 for moving panels (Vasilikos et al., 2024).

The proposed system accounts for power stability constraints by considering factors such as availability, the state of charge of storage elements, and load demand. In conclusion, optimising a parameter to address environmental and operational factors can significantly enhance the performance of solar PV systems.

2.5 Fire Safety

Fire safety measures are crucial when installing photovoltaic (PV) systems, whether they are installed directly or indirectly. However, many designers and installers may not be fully aware of these practices, as most documentation lacks a dedicated section on fire safety management or clear warnings about fire risks. For instance, in California, a fire incident in 2009 damaged 1,826 PV modules. Similarly, Italy reported approximately 1,600 fire incidents out of 590,000 installed PV systems by 2016. In Japan, the government highlighted rooftop PV fire risks, documenting 172 fire-related incidents involving PV systems between 2008 and 2017. Fires in solar panels not only reduce energy generation but also cause toxic gas emissions, property damage, and, in severe cases, loss of life (Mohd et al., 2022).

An experiment was conducted to investigate the rate of temperature increase and the time required for solar panels to respond under varying conditions. The study involved testing opaque and transparent samples with different levels of transparency. Results showed that the opaque sample experienced the longest crack, measuring 115.31 meters, while the non-hollow transparent sample exhibited the largest glass fall-off area, at 8.76% (Dong et al., 2023). When exposed to fire, the unexposed surface experienced a high temperature rise, and glass cracking occurred earlier in larger fire scenarios.

Temperature and cracking onset times were measured using high-definition cameras and thermocouples (Dong et al., 2023). Advanced technologies, such as Artificial Intelligence (AI)—including AlexNet and VGG19—and machine vision algorithms are commonly employed to identify and classify PV faults. These segmentation algorithms achieve a detection accuracy of 91.7%, far exceeding what is possible with infrared or visible light cameras (Meribout et al., 2023). However, UAV-based ultraviolet fluorescence (UVF) monitoring faces challenges due to the need for a consistent distance between the UV lamp and PV modules for at least 0.1 seconds, which is critical to avoid image blurring and ensure a calibrated database is used.

Defects in photovoltaic cells can lead to hotspots caused by electron recombination, which damages the solar cells. These hotspots generate heat, creating a temperature disparity of over 50°C between functional and defective cells. According to the US NEC 690.5 regulation, PV systems exceeding 50 volts require ground fault protection during inspections to enhance safety (Meribout et al., 2023).

2.6 Plan Do Check Act

To achieve a good idea, model, innovation, or adaptation in a working industry, there should be continuous improvement or modification aimed at addressing specific issues. Constructing a workable action plan, including precise material for every criterion, is essential. The primary challenge is to develop action and assessment procedures tailored to the specific requirements, along with the corresponding standards, and to demonstrate the degree of evaluation for each assessed component of sustainability in FM (Graubner et al., 2016).

The task force selected a consistent structural approach based on the dependable plan-do-check-act (PDCA) model, which is widely recognised in the worldwide standards for quality management systems (ISO 9001, 2008), while examining the problem of necessary procedures.

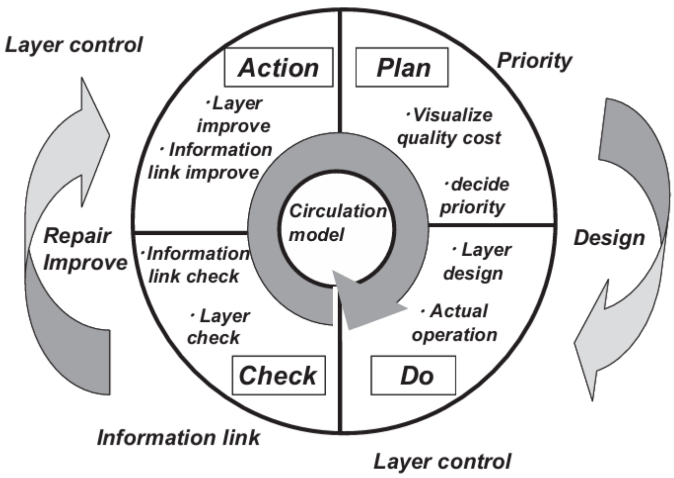

Fig. 1 *Plan-Do-Check-Act Cycle (Source: ISO 9001, 2008)*

By following the model, the first step is to find a suitable location to install a solar panel where it can obtain optimal exposure to sunlight and absorb the highest total solar irradiation possible simultaneously. Plan any improvement, such as adjusting the panel by tilting it after exposure to the sun. During the "Do" phase of the PDCA cycle, the layer design is executed, and the activities are carried out. Additionally, we can obtain crucial information about the layer, which means it needs to implement changes based on the plan being made (Fumio B. & Hiroyuki Y., 2012).

Then, check and note the total irradiance collected, and compare the exposure before and after to see if it yields a better result. The effect of the changes being made is the important part. Based on these changes, the team should take appropriate action. If the measures taken have yielded a positive result, they should be recorded for future reference in a manual. If the solar panels were not generating enough power, repositioning them would result in more efficient exposure to sunlight, thereby enhancing irradiance and energy output. This

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will be revealed through the PDCA process, as continuous action will be taken. The Phases plan Do Check Act is associated with "Improvement or repair"(Fumio B & Hiroyuki Y, 2012).

2.7 Balance Scorecard

Maintenance is a key component in maintaining an asset at a high standard for an extended period. At the same time, it could also increase profitability and reduce production costs. To achieve the standard, a few authors recommended the Balanced Scorecard as a specific maintenance strategy system, especially for those who need to monitor a continuous process (Biasotto et al., 2010). It is suitable for use in the solar panel maintenance process, which requires constant supervision.

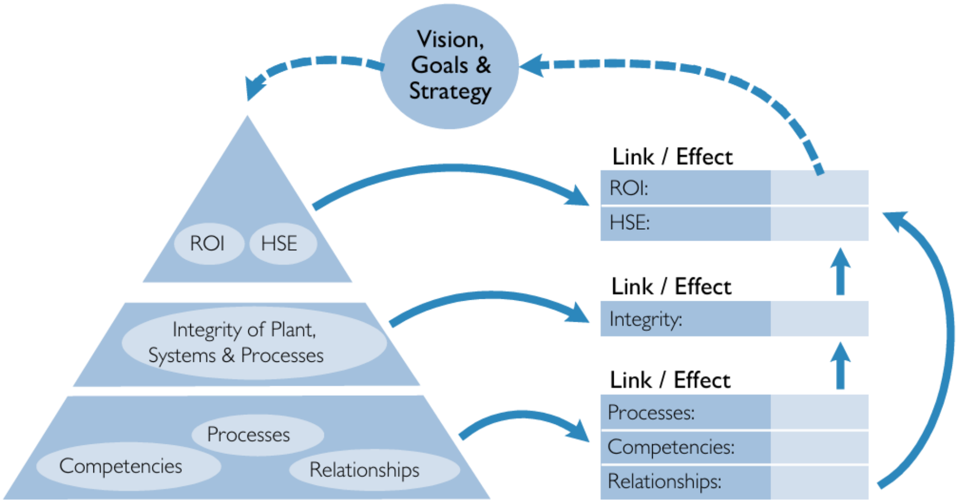

Fig. 2 *Balance Scorecard (Source: Biasotto et al., 2010)*

Figure 2 illustrates a Maintenance Balance Scorecard, which aligns operations and maintenance with corporate goals, vision, and strategy. Competencies, Processes, and Relationships are the fundamental components at the pyramid's base required for solid operational and maintenance performance. The Integrity of Plants, Systems, and Processes is the subject of the next level, which implies that training objectives depend on maintaining operational reliability. The organisation's high-level goals, ROI (Return on Investment), and HSE (Health, Safety, and Environment) are mentioned at the top of the pyramid, as the elements below the pyramid directly influence them through implied processes and competencies. According to (Biasotto et al., 2010), by connecting long-term goals, performance indicators, their targets, and action plans, the strategy is transformed into something more concrete and functional using the BSC. Higher returns and improved safety performance are the outcomes of enhanced system integrity.

2.8 Conceptual Framework

From the past literature review, the researcher found that four main elements influence the Key performance indicators of solar panel contracts for residential and commercial buildings. These elements were essential to ensure that the constructed contract covers all key aspects. The elements highlighted are the shading effect, the Coating on the solar panel, the amount of radiant energy, and fire safety. A conceptual framework, as illustrated in Figure 3, was developed based on the elements identified in previous studies.

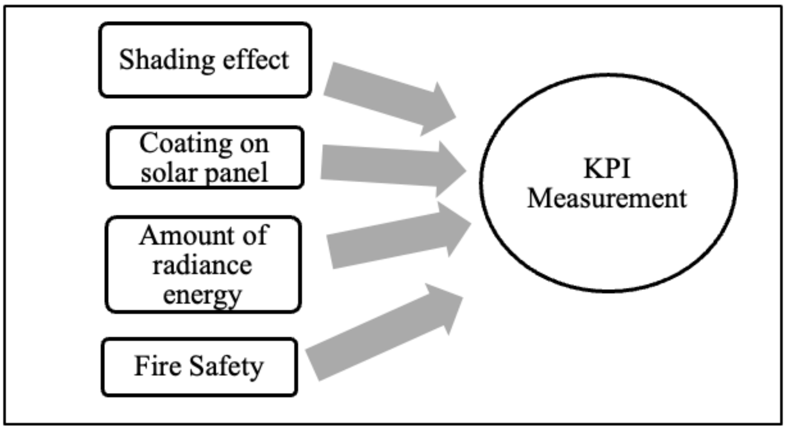

Fig. 3 *Conceptual Framework*

The Literature metrics in Table 1 provide a structured approach to evaluate and optimise solar panel performance in residential and commercial buildings. It focuses on four primary objectives: energy maximisation, mitigation of the shading effect, irradiance optimisation, and enhancement of fire safety. Each objective is linked to Critical Success Factors (CSFs) such as coating types, shading analysis, irradiance levels, and fire detection systems, with corresponding Key Performance Indicators (KPIs) to monitor effectiveness. Details of Key performance indicators (KPIs), such as SiO2 nanoparticles for Coating, feasibility studies for shading, irradiance readings, and thermocouples for safety, are used to ensure that performance standards are met. Responsibilities for these tasks are divided among contractors, suppliers, and installation teams to ensure effective implementation and continuous improvement.

Table 1 *Key Performance Indicators (KPIs)*

Critical Success Factor (CSF)	Key Performance Indicator (KPI)	Detail of Key performance indicator (KPI)	Description	Responsibilities
Coating on solar panel	Types of Coating Frequency of changing the Coating Frequency of cleaning the surface	SiO2 nanoparticles Reinforced new Coating every three to five years Cleaning operations can start as soon as the amount of dust collected surpasses the threshold of dust accumulated on the surface.	To ensure the solar panel absorbs the most energy without any obstacles from dust accumulating on the solar panel.	O&M contractors
Shading effect	Method that implemented	Shading effect analysis Feasibility study on-site surveys	Avoiding loss of electricity output that occurs when an obstruction blocks the panels from receiving direct sunlight	Supplier and installation team
Amount of radiance energy	Irradiance energy	Irradiance: 1 kW/m2 Cell Temperature: 25 ^{o}C Bahrain: Fixed panel (0.37- 0.56 kW/m2) Moving panel (0.45 –	Total energy absorbed on the surface per second per unit of a prospect area	O&M contractors

		0.70 kW/m2) Iraq : 5.5kWh/m2 German-Berman : 3 KWh/m2		
Fire safety	Temperature limit Device detector system	Defective one of more than 50 ◦C. Thermocouples UV-based grounded system (could monitor up to 91.7%) Infra-red (IR) cameras	To measure temperature and cracking start time on the exposed surface	Fire safety management

3. Research Methodology

This research had a three-stage methodology. The first stage is about the research background. Stage two focuses on determining KPIs for building long-term contracts for solar panel installations, and the third stage focuses on assessing suitable solar panel contract measurement tools based on these KPIs.

Stage 1 focuses on the research background, research question, research objective, research scope, and methodology. All these elements need to be identified to obtain results for stages 2 and 3.

The second stage focuses on determining KPIs for building long-term contracts on solar panels, which involve three key elements: a coating, shading effect, irradiance, and fire safety. This stage will include data collection and analysis to ensure that the first objective is achieved. The output for stage 2 is to access suitable solar panel contract measurement tools based on the KPI, which has two elements: either the Balance Scorecard or the PDCA method.

Data collection was conducted through interviews with three respondents, all of whom are experts in solar panels. A qualitative approach, utilising a questionnaire, was employed to gather information about the KPI for establishing long-term contracts for solar panel installations. This questionnaire was designed and administered through face-to-face interviews with the respondents. This questionnaire was divided into three parts as follows: Part A covered the demographics of the respondents, Part B addressed the KPIs for building long-term contracts on solar panel installations, and Part C outlined suitable solar panel contract measurement tools based on the KPIs.

The research method used in this study was a semi-structured interview. This is because the semi-structured interview angles are two ways of communication between the interviewer and the respondent. The population taken for this study are taken from. The sample of this study will comprise three experts from three different companies, each providing different insights into the KPIs in solar panels. Thematic analysis is a qualitative research method used to identify, analyse, and interpret patterns or themes within data. It involves organising data into meaningful categories that represent key ideas or concepts related to the research question. This approach is commonly used to understand people's experiences, perceptions, or behaviours.

Stage 3 focuses on accessing suitable solar panel contract measurement tools based on the KPI. This is to identify which of these two tools is being used in the industry, specifically, whether they utilise the Balanced Scorecard or the PDCA method. Stage three can only be determined by analysing the outcome of objective one. The research objectives can be effectively examined by utilising the appropriate methodology, leading to accurate and precise results. Therefore, the research objective can be achieved. The overall methodology flow is shown in Table 2.

Table 2 *Overall research methodology*

Objective	Method	Variables	Tools
To determine KPI for building long-term contracts on building solar panels	Qualitative: Interview with three experts.	KPI solar panel contract	Thematic analysis
to access the suitable solar panel contract measurement tools based on the KPI		Contract measurement tools	

4. Results and Discussion

The performance and reliability of solar panels depend on key factors such as Coating, shading, radiance energy, and fire safety. Figure 3 shows that Coating enhances efficiency and durability, reduces maintenance needs, and ensures longevity; however, its effectiveness depends on the type of Coating and the manufacturer's support. Proper site analysis and addressing shading effects, including new obstructions and environmental adaptation, are crucial for optimal energy harvesting and system placement. Radiance energy management involves selecting dynamic or fixed panel systems and strategically positioning panels to maximise energy collection. Lastly, fire safety is critical, requiring strict attention to thermal limits, temperature control, and the prevention of workmanship errors, such as sparks, to ensure long-term operational safety.

Fig. 4 *Mapping Thematic analysis of Key performance indicators obtained from the interview*

In this study, three respondents from three different organisations were interviewed and provided the best responses to meet the objectives of this study. Each interviewer held unique positions and possessed relevant experience, qualifying them as suitable respondents, as shown in Table 3.

Table 3 *Demographic Respondent*

Respondent	Position	Period of service	Company	Company Field
R1	Chief Operating Officer	3 Years	Solar Voltech	Rooftop Solar (residential/ commercial)
R2	Operation Engineer	3 Years	Greenviro Solution Sdn. Bhd.	Solar Farm.
R3	Project engineer	2 Years	Verdant Solar	Rooftop Solar (residential/ commercial/ industrial)

4.1 Achieving Objective One

a. Coating

The efficiency and maintenance of solar panels are heavily influenced by the type of Coating, which depends on the manufacturer's specifications and the availability of materials such as titanium oxide, zinc oxide, or silicon oxide. While some solar farms operate without coatings, others rely on coatings to enhance durability, transparency, and radiance absorption, contributing to long-lasting efficiency of up to 90% over 25 years. Coating longevity often spans 25-30 years, minimising the need for frequent replacement, and manufacturers typically provide extensive warranties to address defects. Regular surface cleaning varies by location, with solar farms requiring more frequent cleaning due to their exposure to dirt. At the same time, rooftop installations or panels in non-industrial areas may only need maintenance once every one to two years. Ultimately, proper coating application, maintenance, and manufacturer support ensure optimal performance and sustainability for solar panel systems. The summary of findings from the interview regarding the KPI for Coating is presented in **Table 4**.

Table 4 *Sub-theme generated for Coating*

Sub theme	Small sub-theme	Description
Type coating	Manufacturer dependency Types of Coating No coating in certain cases	R1: " actually for coating we only depend on what have been provided by the manufacturing we do have a few types such as reflective coating, water repellent and also soil coating" R2: "actually for our solar farm that we are managing right now we did not apply any coating on the solar panel at our site right now." R3: ". There is a few types that are mainly used for Coating such as titanium oxide(Tio2), zinc oxide (ZnO) and there is also coating like silicon oxide(SiO2). It will depend on several factor on choosing which is the most suitable and relate to what the manufacturer want to achieve for their production. ."
Efficiency and durability	Quality of solar panel Role of Coating in efficiency	R1: "....the efficiency are based on the solar panel itself and not only on the Coating. It's about the solar panel manufacturing itself. Nowadays there is solar panel that can go up 90% efficiency for 25years with consistently." R3: "Each coating will have the characteristic itself such as durability, transparency, and increased radiance absorption."
Change Coating	Coating longevity and replacement Low Maintenance Requirements Warranty and Manufacturer Support	R1: "The manufacturer will give warranty up to 25 years; therefore, if there is any detected defect or damage which leads to a drop in efficiency, we will request to change one to one." R3: "Basically, once they apply the Coating, it will last for 25-30 years. Therefore, we does not need to recoat every 3 to 4 years."
Surface cleaning	Standard Maintenance Intervals Adaptability to Dust Accumulation Frequency Based on Location and Exposure	R1: "basically for cleaning we do once a year for roof top, but we operate for solar farm it might need cleaning more frequent as there are expose to dirt." R2: "we usually do for everything every 6 month. But we will also defence on the dust accumulation too. If we still think the performance is still okay then, the cleaning we be delay at 7or 8 month later. But it will always be 2 time per year for cleaning" R3: "maybe if it is located in an industrial area, it will conducted once a year. For non-industrial it is once every two years. For now, maintenance we will do once for every two year."

b. Shading Effect

Site analysis for solar panel installation often involves using PVSyst software and conducting site visits to ensure optimal planning. Addressing new obstructions, such as buildings or trees, may require relocation, trimming, or selecting open areas free from environmental barriers to maximise radiation exposure. This careful approach ensures excellent site selection and adaptation for sustainable and efficient solar energy generation. The summary of findings from the interview regarding the KPI for shading effect is presented in **Table 5.**

Table 5 *Sub-theme generated for Shading Effect*

Sub theme	Small sub-theme	Description
Site analysis	PVSyst application Site visit	R1: "we do use PVSyst software. " R2: "usually we use Pvsyst" R3: "first stage we will conduct a site visit."
New obstruction	Relocation Excellent site selection Environmental adaptation	R1: "we will try to relocate it to get the maximum radiation" R2: "usually, solar farm will be built in an open area. This means that the surrounding area will not have building or any hills nearby." R3: "If there is no other alternative, we will resort to we will trim the tree or do a relocation on the tree.

c. Radiance energy

Energy harvesting from solar panels in Malaysia averages 3.2 to 4 hours per day, which is sufficient given the local weather conditions. Fixed panel systems are preferred, particularly for residential setups, as they are designed to capture maximum sunlight by covering east and west orientations without requiring movement. This fixed design ensures stability, efficiency, and optimal energy collection tailored to the region's climate. The summary of findings from the interview regarding the KPI for radiance energy is presented in **Table 6** of the appendices.

Table 6 *Sub-theme generated for Radiance Energy*

Sub theme	Small sub-theme	Description
Energy Harvesting	Energy collection variability	R1: "The full a solar panel can go easily are up to 4hour per day. And it is good enough for the weather in Malaysia" R2: "Usually we will take 4 hours average as a calculation." R3: " In Malaysia the average time it can capture is around 3.2-3.6 hour per day."
Dynamic panel system	Fixed system Panel placement Position	R1: "Fixed panel are better to cater with Malaysia weather." R2: ". It will not move atoll, the structure of our panel do cover both East and West. It is place and design to be arrange as a roof, therefor it could capture to its maximum." R3: "for residential we only focus on fixed panel, they will not move. once we instal, it will fixed there."

d. Fire Safety

Solar panels operate efficiently within a temperature range of -40°C to 85°C; however, exceeding these limits can lead to reduced performance, damage, or even fire risks due to prolonged exposure. Workmanship errors, such as faulty connections, incorrect wire specifications, or design flaws, are common causes of sparks and short

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circuits, with pests occasionally contributing to these issues. Maintaining proper installation practices and adhering to thermal limits is crucial for ensuring the safety and long-term functionality of solar panels. The summary of findings from the interview regarding the KPI for fire safety is presented in **Table 7.**

Table 7 *Sub-theme generated for Fire Safety*

Sub theme	Small sub-theme	Description
Thermal limits	Thermal impact on performance	R1: "Once it reach its limit, the efficiency will starts to drop"
	Temperature limitation	R2: "for a solar panel to be operate with efficiency, the temperature should be in between -40o until 85 o Celcius. The temperature will lead to damages. The operation will also stop once it reaches its limit."
		R3: "the minimum it can go is -40 degree and the maximum is 85. So that's why when it being expose continuously it will became short and starts a fire."
Spark causes	Workmanship error	R1: "For me its related to the workmanship during the installation. Its either the faulty way the connection being made, the wrong specification of wire used or misdeed action during the design process"
	Pest issues	R2: "the short circuit issues usually happens might be from pest."
	Rare case	R3: "Be it is quite difficult to reach 85. And it is still in the normal temperature.

4.2 Achieving Objective Two

Performance monitoring in solar panel systems often follows a process-oriented approach, such as the PDCA method, although the term itself may not be explicitly used. Application-based tools are preferred for daily monitoring and operational improvements, whereas external methods, such as the Balanced Scorecard, are less commonly implemented due to unfamiliarity and limited relevance. This approach emphasises practicality and adaptability to internal processes for efficient performance management. The summary of findings from the interviews regarding performance tools in solar panel management is presented in **Table 8**.

Performance monitoring in solar panel systems often follows a process-oriented approach, such as the PDCA method, although the term itself may not be explicitly used. Application-based tools are preferred for daily monitoring and operational improvements, whereas external methods, such as the Balanced Scorecard, are less commonly implemented due to unfamiliarity and limited relevance. This approach emphasises practicality and adaptability to internal processes for efficient performance management.

Table 8 *Sub-theme generated from performance tools in solar panel management*

Theme	Sub theme	Description
Performance tools	Process-Oriented Approach	R1: "basically it is the same as PDCA. But we don't use the term PDCA. We do practice this on daily basis."
	Application-Based Monitoring	
	Limited Use of External Tools	R2: "For now we did not apply Balance scorecard method, we are still not using it as we are not familiar with it yet."
		R3: "Balance scorecard we will not use as it is related to external. There for we do use apps."

5. Conclusion

This research has determined the KPI and has access to suitable solar panel contract measurement tools based on the KPI for building long-term contracts on residential and commercial solar panels. Based on the research, the researcher can identify the best elements that the supplier in Malaysia uses, as determined through interviews conducted with three solar panel suppliers. The KPIs are being adjusted to account for climate change, which is particularly relevant for Malaysia, located on the equator line and with long hours of sun exposure. The study's outcome has identified four themes: Coating, shading effect, radiance, and fire safety, along with 10 smaller sub-themes. This research can benefit the public and government sectors in building more structural contracts. Finding the best supplier will be easier for the property manager, as it will provide more detailed elements, and there will be no missing elements in the contract.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** Nurul Ain Mohamed Idris, Mohd Hafizal Ishak*;* ***data collection:*** Nurul Ain Mohamed Idris,*;* ***analysis and interpretation of results:*** Nurul Ain Mohamed Idris, Mohd Hafizal Ishak*;* ***draft manuscript preparation:*** Nurul Ain Mohamed Idris, Mohd Hafizal Ishak, Azlina MD Yassin, Nurul Afiqah Ahmad**,** Haidaliza Masram*. All authors reviewed the results and approved the final version of the manuscript.*

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