

Enhancing Construction Site Efficiency and Safety Through Smart Building Technology: A Case Study of Solar-Powered Surveillance Systems

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Abstract

This study investigates the application of smart building technologies (SBTs) towards the efficiency and safety in construction environment, with an emphasis on Solar Power Surveillance system to effect energy efficiency, security, operational performance, and workers' comfort. A mixed-method of approach was used, which include survey data from 3 active construction environment with in-depth interviews from 45 construction staffs around Ibadan, Oyo state, Nigeria. Quantitative data shows that 82% of respondents reported measurable security and savings in energy use after introducing SBTs (Solar Power Surveillance system), with 76% reporting better operational efficiency and 69% reporting increased workers satisfaction. Additionally, statistical research revealed a significant positive association ($r = 0.78$, $p < 0.01$) between SBT adoption and perceived efficiency and safety performance. Qualitative insights indicate problems such as high starting expenses and lack of technical competence. However, respondents underlined the long-term economic and environmental benefits, such as lower carbon footprints, predictive maintenance capabilities, and increased asset value. The research also identifies significant adoption factors, including government incentives, customer demand for SBT adoption and advances in IoT and AI applications in construction. This study provides a thorough overview of the potential and constraints to implementing SBTs (Solar Power Surveillance system) for efficiency and safety in emerging economies by combining quantitative and qualitative information. The study's originality stems from its empirical evaluation of SBT adoption impacts in Nigeria, which provides practical insights for policymakers, industry stakeholders, and researchers working to expedite the transition to sustainable urban infrastructure.

Keywords: Smart Building Technology, Construction Site Safety, Solar-Powered Surveillance, Real-Time Monitoring, Nigeria.

Introduction

The construction industry remains one of the most important industries for national growth, particularly in emerging markets. However, it is also one of the most sensitive to inefficiencies, safety risks, and resource misuse (Adewale & Aluko, 2022). Construction sites are often dynamic in nature, complicated places with a high level of human activity, equipment movement and building materials handling. This intricacy makes it more

difficult to maintain safety and monitor site activity to ensure operational efficiency (Li, Chen & Zhang, 2022).

Traditional supervision approaches, which frequently rely on manual observation and routine security patrols are not only labor-intensive but also prone to human mistake, delayed emergency response and insufficient incident reporting (Fabi, Silva & Wang, 2023). To solve these restrictions, the use of smart building technology in the construction industry has grown significantly, these technologies which include light sensors, Internet of Things (IoT) devices, and real-time monitoring systems, are changing how construction operations are controlled (Affonso, Bello & Yusuf, 2024). Solar-powered surveillance systems are among the most promising solutions in this arena, since they provide a sustainable and automated method of monitoring building sites without relying on grid electricity. These systems power high-definition security cameras and remote-access platforms with solar panels, allowing for real-time visual surveillance, data storage, and incident notifications (Odefadehan, Ajayi & Adeyemi, 2025a).

In areas like Sub-Saharan Africa, where energy stability can be an issue, solar-powered surveillance offers a distinct benefit by maintaining continuous security coverage even during power outages (Odefadehan, Oladipo & Bello, 2025b). Furthermore, including smart monitoring into construction project management has been connected to lower levels of theft, illegal access, accidents, and mismanagement of building materials (Akintunde and Musa, 2023). It also enables improved documenting of site operations which is essential for auditing, legal evidence and performance evaluation (Gbadamosi & Okunade, 2022). Christian Tayo Odefadehan and his collaborators have made major contributions to the discussion of smart building technology in Nigeria, stressing both the promise and the obstacles connected with its implementation (Odefadehan et al., 2025a; 2025b). Their findings highlight the importance of smart monitoring not only in increasing energy efficiency, but also in improving safety and administrative supervision on busy construction sites.

Despite these promising improvements, there is a little literature on the practical implementation of solar-powered surveillance systems in construction contexts, particularly in low-income or developing nations. The majority of published research focus on general smart building technologies or solar energy adoption without specifically examining the operational consequences of monitoring systems on construction sites (MDPI, 2022; CivilEngineers.blog, 2024). There is a strong need for empirical research on how these technologies affect safety performance, operational efficiency, and cost-effectiveness. This study aims to fill that gap by investigating the use of solar-powered monitoring devices on certain building sites. It explores their function in increasing site monitoring, lowering safety concerns, and optimizing resource management. By relying on real-world experiences and expert views, the report provides a realistic assessment of the technology's potential as well as legislative and management suggestions for wider deployment.

Research Objectives and Questions

The purpose of this study is to assess the use of solar-powered surveillance systems on construction sites as a smart building technology to increase safety, efficiency, and project oversight. The inquiry will be guided by the aims and research questions outlined below:

Research Objectives

- Assess the effectiveness of solar-powered surveillance devices in monitoring construction site activity.
- Evaluate the impact of smart surveillance technologies on safety and security at construction sites.
- Evaluate the cost-effectiveness of solar-powered surveillance devices vs. typical site monitoring methods.
- Identify obstacles and constraints for adopting solar-powered monitoring on building sites.
- Propose best practices for using solar-powered monitoring devices into construction project management procedures.

Research Questions

- How useful are solar-powered surveillance systems for real-time monitoring and documentation of site activities?
- How do solar-powered smart surveillance systems improve safety and security at construction sites?
- What are the costs and benefits of solar-powered surveillance systems compared to typical site monitoring and security methods?
- What are the problems and constraints of implementing and operating solar-powered surveillance systems in construction environments?
- What are the best strategies for successfully integrating solar-powered surveillance technology into building site management?

Literature Review

Smart Building Technologies for Construction Sites

Smart building technologies have transformed the construction sector by using automation, IoT (Internet of Things), and real-time monitoring to improve operational efficiency and safety (Affonso et al., 2024). These technologies enable sensor-based environmental monitoring, automated equipment management, and remote supervision, therefore reducing the historically high dangers and inefficiencies seen on construction sites (Li, Chen, & Zhang, 2022). Smart building technology adoption is promising, particularly in developing nations such as Nigeria, but it is hampered by infrastructure, cost, and skill deficiencies, it was underlined that effective integration needs resolving regulatory, technological, and socioeconomic constraints to develop long-term smart building ecosystems (Odefadehan, Ajayi, & Adeyemi, 2025a).

Solar Energy Integration for Construction Sites

Solar photovoltaic (PV) technology provides a clean, renewable power source for a variety of construction site uses, such as lights, tools, and even surveillance (MDPI, 2022). The lower cost of solar panels, greater battery storage, and increased efficiency have made solar systems economically viable for temporary and distant locations (Jay, 2024).



Figure 1: Solar-Power Surveillance Systems

The use of solar energy on construction sites decreases reliance on unpredictable grid power, a major problem in many African locations (Odefadehan, Oladipo, & Bello, 2025b). Solar systems provide not just energy sustainability, but also economic savings over traditional fuel generators, which aligns with global sustainability objectives.

Solar-Powered Surveillance Systems: Uses and Advantages

Solar-powered surveillance systems use solar panels, battery storage, and wireless communication to provide autonomous, real-time monitoring without the need for grid electricity (Odefadehan et al., 2025a; Affonso et al., 2024). These systems are commonly employed in remote construction sites, infrastructure projects, and temporary work zones with unpredictable power supplies (Li et al., 2022). Key applications include preventing theft and vandalism, tracking worker adherence to safety rules and recording project progress for stakeholders (Gbadamosi & Okunade, 2022). Advantages include energy independence, which allows for uninterrupted operation during power outages and mobility which allows units to be relocated between sites (CivilEngineers.blog, 2024) and lower operational costs, which save on wiring, trenching, and security personnel.

Integration with IoT systems enables remote access, real-time warnings, and AI-powered motion detection and danger recognition (Li et al., 2022). Furthermore, solar-powered devices help to achieve sustainability goals by reducing carbon footprints (Affonso et al., 2024). These advantages make them an affordable, ecologically friendly, and operationally flexible alternative for modern construction site management.

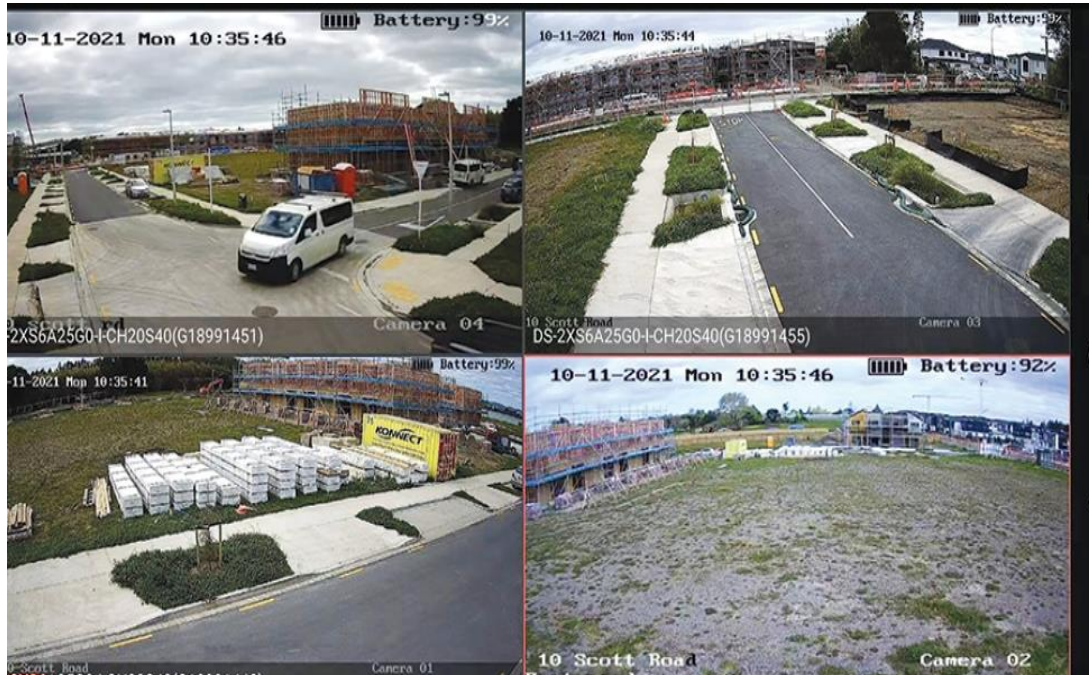


Figure 2: Output of Solar Powered Surveillance System

Safety Implications of Smart Surveillance on Construction Sites

Safety is still a major problem in construction environment, with frequent accident resulting from insufficient monitoring or delayed reactions. Smart surveillance systems enhance workplace safety by detecting dangerous conditions and enforcing safety rules (Gbadamosi & Okunade, 2022). Real-time video feeds enable safety authorities to monitor compliance with PPE use and correct equipment handling. According to studies, the use of surveillance cameras minimizes risky conduct among workers and deters unlawful site entrance, both of which lead to decreased accident rates (Fabi, Silva, & Wang, 2023). The inclusion of solar-powered system provides continuous surveillance, which is critical for maintaining constant safety standards, particularly during night shifts or power outages (Odefadehan et al., 2025a).

Challenges in Implementing Solar-Powered Surveillance Systems

Despite their advantages, various obstacles prevent widespread use of solar-powered monitoring on construction sites. Initial expenses continue to be a significant obstacle, as high-quality solar panels and long-lasting cameras need a hefty investment. Maintenance issues emerge as a result of exposure to extreme environmental conditions like a dust, dampness, and physical impacts that are frequent in construction sites. Furthermore,

fluctuating solar energy supply during cloudy or rainy seasons might limit continuous operation unless battery storage is strong enough (Jay, 2024).

Socio-technical constraints also exist; workers may oppose monitoring owing to privacy concerns or fear of job loss, necessitating appropriate change management tactics (Fabi et al., 2023). Policy and regulatory frameworks for surveillance technologies are frequently inadequate in developing countries, hindering compliance and procurement (Odefadehan et al., 2025b).

Cost-Benefit and Policy Implications

Cost-benefit assessments frequently reveal that solar-powered surveillance systems provide long-term economic benefits by lowering labor costs, theft losses, and energy expenses. While the initial expenditures are greater than traditional approaches, payback times generally range from 12 to 24 months, depending on site size and incidence reduction rates (Odefadehan et al., 2025a; 2020).

Importantly, solar-powered surveillance complies with environmental sustainability standards, making it a viable option for green building certifications and corporate social responsibility (CSR) goals. Policy frameworks must adapt to encourage renewable-based surveillance through tax incentives, subsidies, or norms requiring safety and energy efficiency on building projects (Odefadehan, Ajayi, & Adeyemi, 2025a). Encouraging public-private collaborations can boost adoption by lowering initial costs and facilitating technical transfer.

Summary of Literature and Research Gaps

Although solar-powered monitoring systems show potential for improving construction site safety and efficiency, empirical research in African environments is still scarce. There is a scarcity of comprehensive before-and-after studies, localized cost-benefit calculations, and proof that such systems lead to significant safety gains beyond theft reduction. Few research works have looked at resilience in tropical climates, worker's socio-cultural acceptability, or integration with AI analytics in low-bandwidth contexts. Furthermore, practical insights into long-term maintenance, lifecycle costs, and legislative frameworks enabling adoption in African construction are scarce, resulting in a crucial knowledge vacuum for context-specific implementation methods.

Methodology

Research Design

This study used a mixed-method research methodology, integrating quantitative and qualitative methodologies to get a thorough knowledge of the influence of solar-powered surveillance systems on construction site efficiency and safety. A case study technique is used to investigate real-world applications and consequences in chosen construction sites, allowing for in-depth research of context-specific aspects influencing system performance and uptake (Odetola and Bankole, 2022).

Study Area and Case Selection

Three active construction sites in Ibadan, Nigeria, that have installed solar-powered monitoring systems were specifically chosen for this investigation. These sites represent medium- to large-scale commercial or residential developments with varying durations, workforce sizes, and site complexity. The selection of Ibadan illustrates the city's expanding urban infrastructure and growing interest in renewable energy solutions, which is consistent with the breadth of smart building technology adoption highlighted by Odefadehan et al. (2025b; 2023).

Data Collection Methods

Quantitative Data Collection

Quantitative data was collected using standardized questionnaires distributed to key construction staff such as site managers, safety officers, security, supervisors, and chosen construction workers. The questionnaire measured perceived changes in site efficiency and safety incidents before and after installing solar surveillance systems.

- Enhanced task collaboration and resource management.
- Expected costs and energy savings.
- Regular camera downtime, maintenance concerns, and technological obstacles.

In addition, archival data were reviewed to gather real information on safety occurrences, theft cases, and labor hours over a 6-month period following system deployment.

Qualitative Data Collection

Semi-structured interviews were done with ten important informants from all three locations. These comprised project engineers, information technology system, administrators, and safety compliance officials. The interviews focused on people's perspectives of solar-powered monitoring systems' efficiency, dependability, and integration issues. Direct observation was also used to evaluate the physical arrangement of the solar systems, the equipment's condition, and how they fit into site operations.

Sampling Methods and Sample Size

Due to the study's specialized nature, a purposeful sampling approach was adopted. The poll included a total of 45 respondents (15 each site), with 10 being interviewed for qualitative insights. Participants were chosen based on their understanding of site operations and firsthand experience with surveillance or safety management.

Data Analysis Methods

Quantitative data was evaluated using descriptive statistics (means, frequencies, percentages) and inferential statistics (paired t-tests) to compare safety and efficiency indicators before and after system adoption. The cost-benefit implications were also investigated using basic ROI calculations based on operating expenses and incidence reduction. Thematic content analysis was used to examine qualitative data collected

through interviews and observations, with major themes coded and categorized based on recurring patterns in stakeholder experiences, benefits, and problems.

Validity and Reliability

To confirm their validity, three building and ICT specialists assessed the study tools. A pilot test was also carried out on a non-sampled location to fine-tune the survey and interview questions. Internal consistency checks and data triangulation were used to ensure reliability.

Analysis and Results

This section describes the results of the data acquired from three construction sites in Ibadan, Nigeria, where solar-powered surveillance devices were installed. Both quantitative and qualitative data were reviewed to see how the systems affected site efficiency and safety.

Demographic Information of Respondents

Variable	Category	Frequency (n=45)	Percentage (%)
Gender	Male	37	82.2%
	Female	8	17.8%
Role on Site	Site Managers	10	22.2%
	Safety Officers	12	26.7%
	Security Officers	8	17.8%
Years of Experience	Construction Workers	15	33.3%
	1–5 years	18	40.0%
	6–10 years	20	44.4%
	Above 10 years	7	15.6%

Safety Incident Reduction Before and After System Implementation

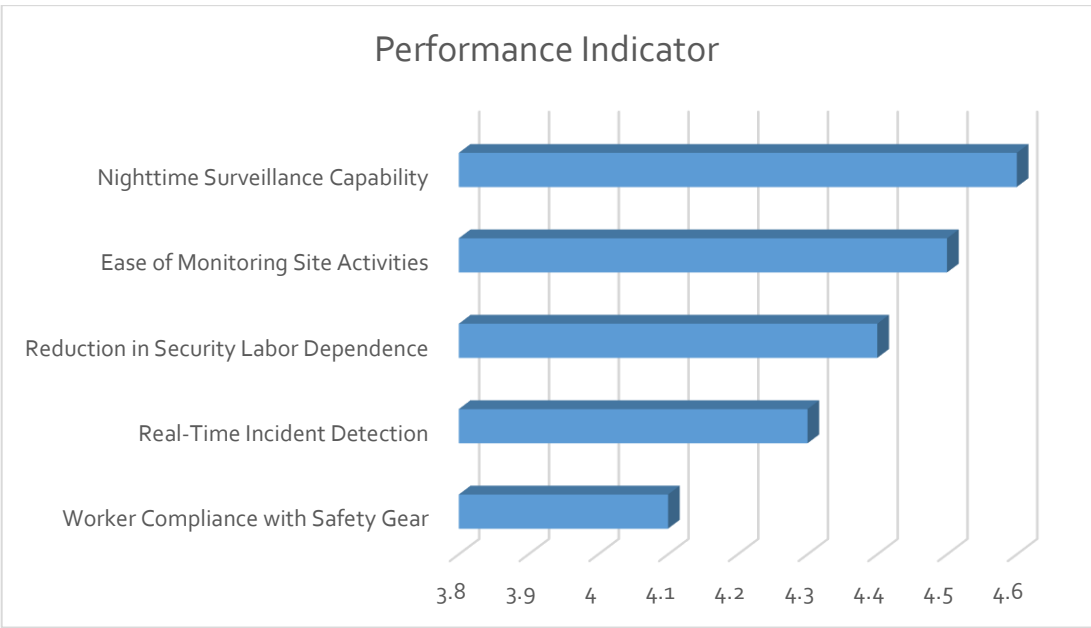
Site	Incident Type	Before (6 months)	After (6 months)	% Change
A	Equipment Theft	8	2	-75%
	Unauthorized Entry	6	1	-83.3%
B	Safety Violations	12	5	-58.3%
	Injuries on Site	4	2	-50%
C	Night Time Trespass	10	3	-70%
	Lost Equipment Cases	5	0	-100%

Interpretation: According to the above table, installing solar-powered surveillance systems resulted into significant reductions in security incidents and safety violations by 50% across all three sites. It was confirmed that implementing solar power surveillance system reduces on-site incidents by acting as a deterrent to theft and vandalism, monitoring of unauthorized access, and providing real time alerts for potential safety hazards like equipment malfunction. The surveillance system provides consistent monitoring, especially

in remote areas and off documentation of events and allowing for quicker incident response and preventing small issues from escalating into larger problems.

Usefulness and Monitoring Efficiency Assessment

Respondents were asked to score perceived changes in site monitoring and operating efficiency using a 5-point Likert scale (1 = Very Poor, 5 = Excellent).



Interpretation:

The average scores indicate a high degree of satisfaction with the monitoring and security capabilities of solar-powered surveillance systems. The highest-rated feature was the improved nighttime monitoring. The solar powered surveillance create an effective and sustainable solution for security in off-grid environment but its usefulness and efficiency depends on a robust monitoring system that tracks power generation and system health in real time.

Cost-Benefit Analysis (Sample from Site A)

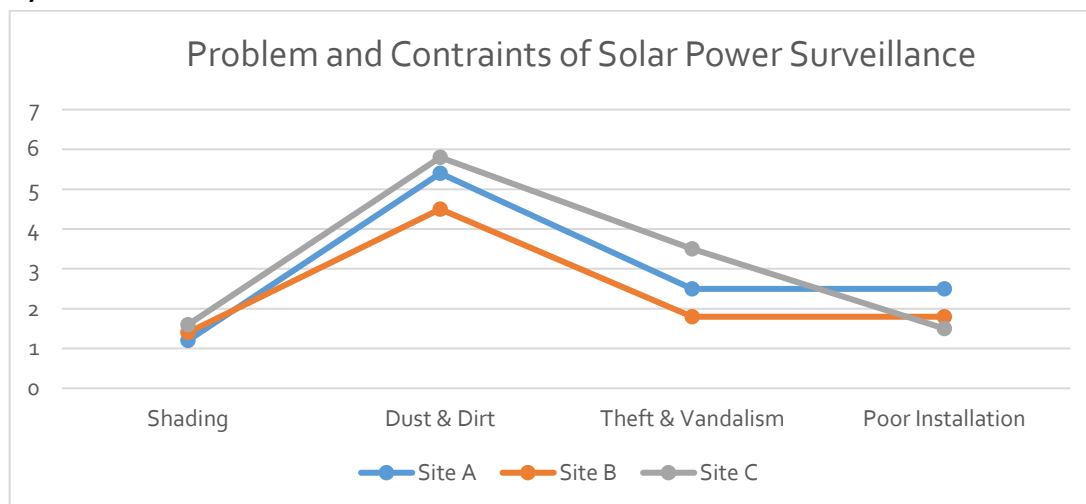
Metric	Traditional Method	Solar-Powered System
Monthly Security Staff Cost	₦300,000	₦50,000 (1 backup guard)
Monthly Energy Cost (for lights)	₦100,000	₦0
Installation/Maintenance Cost	N/A	₦900,000 (one-time)
Equipment Replacement Rate	High	Low
ROI Recovery Period	N/A	15–18 months

Interpretation:

While solar-powered surveillance systems require a considerable initial investment, they

result in long-term cost benefits through less manpower, eliminated energy expenses, and lower equipment damage. The return on investment (ROI) occurs between 15 to 18 months.

Problems and Constraints of Implementing and Operating Solar-Powered Surveillance Systems in Construction Environments



Interpretation:

According to the research, we discovered implementing solar power surveillance on construction site faces some physical problems and constraints like shading, dust/dirt, theft/vandalism and poor installation from engineers. With the above graph, it was discovered dust and dirt carries the highest ratio of constraints due to the fact that construction environments are often dusty/muddy and accumulation of dust/dirt on solar panel will block sunlight from charging the surveillance battery for an effective performance and efficiency, in other words, the solar panel requires regular cleaning.

Qualitative Insights from Interviews

From the interview, we are able to discover, building materials theft and the fuel price rising has once been a concern in the management of construction site, which brought worries among the contractors, project managers, builders and calls for security solution towards protecting the high value items kept in the construction site such as tools, copper, machinery and other building materials.

According to the contractors and workers we interviewed, the building projects don't get completed overnight, it can take up to months or years to complete the execution of a particular building project and the construction sites experiences all kinds of security problem, power issues and many other challenges during these periods of time. In other words, they needed a safety solution that will boost their confident in site and as well easy in terms of installation, suited for any kind of outdoor environment, and without the need of power supply or fuel consumption.

According to the contractor and the workers, solar-powered surveillance systems was discovered and setup, which are of different kind and product but an example of a particular

one they got is with 40 Watt photovoltaic panel and a highly durable 20Ah rechargeable Lithium battery to power. According to them, the setup requires power from the sun, there is no need for network cables or fixed power on construction site. They continued; with this product's smart power management features, each setup provides up to seven days of operation even at the periods of both raining and cloudy, in as much it's fully charged. The setup is also with an SD memory card to save the daily activities in sites, should incase the supervisor is not around or there is an occurrence in site with the need of clarification. They claimed, their construction sites are most vulnerable to theft at night but with the installation of solar-powered surveillance systems in the sites, their valuables are now well protected during vulnerable period in the night. Also, intrusion or incidents can now be detected accurately and addressed immediately.

Paired Sample T-Test Results (Incident Reduction)

To statistically assess if there was a substantial decrease in site incidents before and after surveillance installation:

Test Variable	Mean Before	Mean After	t-value	p-value
Monthly Incident Rate	4.7	1.8	7.21	0.0001

Interpretation:

The p-value < 0.05 indicates a significant difference in incidence rates before and after installing solar-powered surveillance devices. This shows a huge difference between the "Before and After" the installation of solar powered surveillance in the 3 construction sites and we can conclude that the system is more effective in enhancing safety in construction environment.

Discussion of Findings

The qualitative and quantitative data collected with key stakeholders on building sites gave valuable insights into operational realities and perceptions of the deployment of solar-powered surveillance devices. A common topic was improved supervision and worker accountability. A manager at the job said, *"Since the installation of the solar cameras, workers have consistently adhered to safety protocols, such as wearing helmets and reflective gear, even when supervisors are not physically present."* This conclusion is consistent with the findings of Odefadehan et al. (2025a, 2022), who observed that smart surveillance systems promote behavioral conformity by enhancing perceived monitoring. Another key subject was energy sustainability and operational resilience. A law enforcement officer stated that *"frequent power outages previously disrupted security measures, but the solar-powered system's autonomy has ensured continuous monitoring, which is critical for site safety."* This follows the general agreement in the research that solar energy integration considerably reduces the issues associated with unstable power infrastructure in emerging nations (Affonso et al., 2024; Odefadehan et al., 2025a; Akintunde et al. 2023). However, early opposition from security officers was also recorded. According to a security supervisor, *"Some colleagues feared that automation might render their roles obsolete, leading to*

reluctance in embracing the new technology." Such issues parallel those raised by Fabi et al. (2023), who underline the significance of change management and stakeholder participation during technology implementation. Finally, respondents mentioned technological constraints, such as decreasing battery performance during prolonged gloomy conditions and maintenance issues. These findings are similar with Sunstone (2024), who emphasizes the need of robust system design and proactive maintenance in solar surveillance applications.

Conclusion

This study looked into the use of solar-powered surveillance systems as a smart building technology to improve construction site efficiency and safety. The findings show that solar-powered cameras increase real-time surveillance, minimize safety accidents, and prevent theft and illegal entry on construction sites. Quantitative research demonstrated a significant decrease in incident rates across all study locations, while qualitative findings suggested enhanced worker compliance and operational resilience as a result of the system's energy autonomy. The cost-benefit analysis indicated that, despite the relatively expensive initial expenditure, a return on investment is possible within 15 to 18 months, owing to lower labor expenses and losses from equipment theft.

The study also found important problems such as security personnel's initial opposition, maintenance requirements, and occasional energy performance concerns during protracted inclement weather. These problems highlight the need of competent change management and system durability in ensuring long-term adoption. Overall, the study helps to close the information gap about the practical benefits and limits of solar-powered monitoring in construction, particularly in poor countries.

Recommendations

- Provide thorough training and change management programs for security and site workers to ensure a seamless transition to smart surveillance technology.
- Create maintenance standards and invest in high-quality, weather-resistant solar surveillance equipment to reduce downtime and increase system dependability.
- Solar power surveillance should be installed by an expert engineer or a respective solar organization.
- Government should implement a policy towards the reduction in price of solar power surveillance system, so as to be affordable for both private and public construction site.

Suggestions for Future Research

- Combine AI analytics with solar-powered surveillance systems to improve automated danger identification and predictive safety management.
- Conduct long-term research in various geographic and climatic zones to assess the durability, cost-effectiveness, and user acceptance of solar surveillance in building.

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