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Simulation-Based Energy Analysis and Stakeholder Adoption of Solar PV-Integrated Smart HVAC and Lighting Systems in An Office-Commercial Building

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Abstract

Office-commercial buildings are among the major consumers of electricity due to the continuous operation of heating, ventilation, and air-conditioning (HVAC) and lighting systems. Increasing energy demand, rising electricity costs, and environmental concerns highlight the need for efficient and sustainable energy solutions. Integrating solar photovoltaic (PV) systems with smart HVAC and lighting technologies presents a promising approach to improving energy efficiency while reducing dependence on grid electricity.

This study aimed to evaluate the projected energy efficiency improvements through a simulation-based analysis of a solar PV–integrated smart HVAC and lighting system and to assess stakeholder readiness in terms of perceived usefulness and adoption intention. Data were obtained from energy audits, building load profiles, and a structured survey questionnaire administered to building stakeholders. The study focused on: (1) analyzing baseline energy consumption and electrical load profile; (2) developing a simulation-based integrated system design; (3) determining projected energy consumption and energy savings; (4) testing the significant difference between baseline and projected energy consumption; and (5) assessing stakeholder perception and adoption intention. Weighted mean, percentage analysis, and paired sample t-test were used for data analysis.

Results revealed that the building has a total annual energy consumption of 7,929,423.80 kWh, with HVAC systems accounting for 62.35% of total usage. The proposed system, consisting of a 510 kWp solar PV installation and smart HVAC and lighting controls, is capable of generating approximately 710.991 MWh/year. Simulation results showed a projected reduction in energy consumption to 6,364,929.43 kWh, resulting in annual energy savings of 1,564,494.37 kWh or a 19.73% improvement in energy efficiency. Statistical analysis confirmed a significant difference between baseline and projected energy consumption ($t = 58.70$, $p < 0.001$), indicating the effectiveness of the proposed system.

Furthermore, stakeholder assessment results indicated a very high level of perceived usefulness (WM = 4.67) and adoption intention (WM = 4.68), both interpreted as “Strongly Agree.” These findings suggest strong stakeholder support for the implementation of solar PV–integrated smart building systems. Overall, the study demonstrates that integrating renewable energy and smart technologies can significantly enhance building energy performance while aligning with stakeholder readiness for adoption.

Keywords: Solar PV, Smart HVAC, Smart Lighting, Energy Efficiency, Simulation-Based Analysis, Stakeholder Adoption, Office-Commercial Building

1. Introduction

Energy efficiency and sustainable energy management have become critical priorities for office-commercial buildings due to rising electricity costs, increasing environmental concerns, and the growing demand for reliable and resilient energy systems. Office-commercial buildings typically accommodate a mix of office spaces, retail units, and service-oriented areas that require continuous operation of heating, ventilation, and air-conditioning (HVAC) systems, as well as lighting systems. These systems account for a significant portion of total energy consumption, making efficient energy use essential for reducing operational costs and minimizing environmental impact.

In the Philippine context, many office-commercial buildings remain highly dependent on grid-supplied electricity and conventional building systems that are often characterized by limited automation and suboptimal energy performance. Aging HVAC and lighting systems further contribute to excessive energy consumption and operational inefficiencies, making it challenging for building owners and managers to meet national energy efficiency and sustainability targets. As commercial activities expand and building operations become more complex, electricity demand continues to increase, reinforcing the need for innovative and energy-efficient solutions.

One promising approach to improving energy efficiency in office-commercial buildings is the integration of solar photovoltaic (PV) systems with smart HVAC and lighting technologies. Solar PV systems provide a renewable source of electricity that can offset grid consumption, particularly during peak daytime operations when commercial buildings experience the highest energy demand. Meanwhile, smart HVAC and lighting systems utilize sensors, automation, and advanced control strategies to optimize energy use based on occupancy, environmental conditions, and operational requirements. Previous studies have demonstrated that combining renewable energy technologies with intelligent building systems can significantly reduce energy consumption and operational costs while maintaining acceptable indoor environmental conditions.

However, the successful implementation of these technologies is not solely dependent on technical performance. Organizational and human factors play a crucial role in ensuring the effectiveness and sustainability of energy efficiency initiatives. Stakeholder readiness, defined in this study as perceived usefulness and adoption intention, significantly influences the adoption and long-term operation of smart building systems.

Given these considerations, there is a need to evaluate both the technical and organizational aspects of integrating solar PV with smart HVAC and lighting systems in office-commercial buildings. This study focuses on conducting a simulation-based energy analysis to estimate projected energy consumption and efficiency improvements, while also assessing stakeholders' perceived usefulness and adoption intention toward adopting such systems. By combining simulation-based modeling with stakeholder assessment, the study aims to provide a comprehensive understanding of the potential benefits and feasibility of implementing solar PV–integrated smart building systems in an office-commercial building context.

2. Method

The present study adopts a descriptive–analytical research design with a simulation-based approach. The method was appropriate for the study focuses on describing the current energy consumption characteristics of HVAC and lighting systems in an office-commercial building, specifically ABC Commercial Building, analyzing projected energy efficiency improvements under a proposed solar PV–integrated smart HVAC and lighting system using modeling and simulation, and assessing the level of stakeholder readiness for adopting such integrated energy technologies.

A descriptive–analytical design allows the systematic documentation and analysis of existing conditions and projected outcomes without requiring the physical installation of the proposed system.

The research process follows a structured sequence beginning with a baseline energy assessment and stakeholder readiness measurement. In this stage, energy audits of existing HVAC and lighting systems are conducted to establish baseline electricity consumption patterns and electrical load profiles within the selected office-commercial building. At the same time, stakeholder readiness is assessed through structured survey questionnaires administered to building owners, property managers, and facilities personnel to determine their perceived usefulness and adoption intention for adopting solar PV–integrated smart HVAC and lighting systems.

The study utilizes both primary and secondary data sources to assess projected energy efficiency improvements and stakeholder readiness for the adoption of solar PV–integrated smart HVAC and lighting systems in an office-commercial building. These data sources provide the technical and organizational information necessary to support simulation-based energy analysis and readiness assessment.

Primary data are obtained from two main sources. First, baseline energy consumption data are collected through on-site energy audits of existing HVAC and lighting systems within the selected office-commercial building. Second, primary data are collected through structured survey questionnaires administered to key stakeholders.

Secondary data include historical electricity consumption records of the office-commercial building, equipment specifications and design information of existing HVAC and lighting systems, and applicable national and international energy efficiency guidelines such as those issued by the Department of Energy (DOE), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and other relevant organizations. In addition, peer-reviewed journals, books, technical reports, and previous research studies related to energy efficiency assessment, smart building technologies, and solar PV integration are reviewed to support system modeling assumptions, simulation parameters, and interpretation of results.

The population of the study consists of twenty (20) selected stakeholders-respondents of ABC Commercial Building which was distributed among the identified stakeholder groups, such as building owners, property managers, and facilities personnel who are directly involved in building operations, facility management, energy consumption monitoring, and decision-making related to energy-efficient technologies.

A purposive sampling technique was employed in selecting the respondents to ensure that only individuals directly associated with building management and energy-related operations participated in the study. The stakeholder survey focused on assessing perceived usefulness and adoption intention toward the proposed integrated energy system.

The instruments used in this study consist of energy audit tools, structured survey questionnaires, and energy simulation tools. These instruments were selected to support the collection of technical and behavioral data necessary for simulation-based energy analysis and stakeholder adoption assessment in an office-commercial building setting.

A structured survey questionnaire was developed to assess stakeholders' perceived usefulness and adoption intention regarding the implementation of solar PV–integrated smart HVAC and lighting systems.

Following expert validation, a pilot test was conducted among selected respondents with similar characteristics to the target population to identify unclear or ambiguous items. Feedback from the pilot testing phase was used to further refine the instrument before final distribution. The reliability of the questionnaire was assessed using Cronbach's alpha coefficient, where a value of 0.70 or higher was considered acceptable, indicating internal consistency of the instrument.

Energy simulation tools were utilized to model the proposed solar PV–integrated smart HVAC and lighting system and to estimate projected electricity consumption under defined operating conditions.

A statistician was consulted to ensure the accuracy and appropriateness of the statistical methods and computations used in the study, including the weighted mean, paired sample t-test, and percentage analysis. This ensured that the data analysis procedures followed standard statistical practices and produced reliable results.

To measure stakeholders' perceived usefulness and adoption intention toward the proposed solar PV–integrated smart HVAC and lighting system, a five-point Likert scale was utilized. Each response was assigned a numerical value ranging from 1 to 5, where higher values indicate stronger agreement with the given statements. The weighted mean of the responses was computed to determine the overall level of perception and adoption among stakeholders.

Table 1: Five-Point Likert Scale

Assigned Points	Numerical Range	Verbal Interpretation
5	4.51 – 5.00	Strongly Agree
4	3.51 – 4.50	Agree
3	2.51 – 3.50	Neutral
2	1.51 – 2.50	Disagree
1	1.00 – 1.50	Strongly Disagree

Data collection is conducted in a systematic and sequential manner to ensure the accuracy, reliability, and validity of the data used in the study.

The first stage involves a baseline energy assessment, wherein on-site energy audits are conducted to measure the electricity consumption of existing HVAC and lighting systems in the selected office-commercial building, specifically ABC Commercial Building. Energy meters and audit tools are used to document operational characteristics and electricity usage patterns. Historical electricity consumption records are also reviewed and analyzed to validate observed measurements and establish representative baseline energy conditions. Measurements are conducted during normal building operations to ensure that the data reflect typical system usage and occupancy patterns.

The second stage consists of administering structured survey questionnaires to assess stakeholder readiness among building owners, property managers, and facilities personnel. The survey gathers data on their level of perceived usefulness and adoption intention for adopting solar PV–integrated smart HVAC and lighting systems. Participation in the survey is voluntary, and respondents are informed of the purpose of the study and the confidentiality of their responses. Completed questionnaires are collected, encoded, and prepared for statistical analysis, with individual responses aggregated to ensure anonymity.

The third stage involves system design and simulation-based energy analysis. Based on the baseline energy assessment, a conceptual design of a solar PV–integrated smart centralized HVAC and lighting system is developed. Energy simulation tools are used to model the proposed system and estimate projected electricity consumption and potential energy efficiency improvements under defined operating conditions. Simulation parameters are based on documented building characteristics, measured energy data, and accepted engineering assumptions.

Energy consumption data from audits and historical records are cross-checked for completeness and consistency prior to analysis to ensure consistency and data quality. Any inconsistencies or missing data are addressed through verification with available records or justified assumptions based on standard energy assessment practices.

All collected data are systematically organized, tabulated, and analyzed to support the interpretation and discussion of findings related to projected energy efficiency improvements and stakeholder readiness for the adoption of solar PV–integrated smart HVAC and lighting systems.

3. Results and Discussion

Table 2: Baseline Energy Consumption of the Private Company

Months	Electricity Consumption (kWh)	PHP
January	612,015.95	5,834,607.63
February	651,563.00	6,031,025.16
March	632,007.95	6,301,869.95
April	699,929.65	6,975,594.90
May	708,719.90	6,690,062.57
June	722,857.45	6,803,383.47
July	675,913.00	6,508,306.12
August	655,020.80	6,431,803.74
September	680,503.95	6,626,840.32
October	641,283.65	6,409,617.21
November	657,450.15	6,676,390.30
December	592,158.35	6,055,722.94
Total	7,929,423.80	77,345,224.31
Average	660,785.32	6,445,435.36

Table 2 presents the baseline monthly and annual electricity consumption of the selected office-commercial building for the year 2025. The total annual consumption reached 7,929,423.80 kWh, with an average monthly consumption of approximately 660,785.32 kWh.

The data show that electricity consumption is relatively consistent throughout the year, with slightly higher values observed during the months of April to June. These periods correspond to increased cooling demand due to higher ambient temperatures. The highest monthly consumption was recorded in June (722,857.45 kWh), while the lowest occurred in December (592,158.35 kWh).

These variations indicate that seasonal temperature changes significantly influence electricity consumption, primarily due to increased reliance on air-conditioning systems.

Further analysis of energy consumption by system shows that HVAC systems account for approximately 62.35% of total energy consumption, while office equipment contributes 22.37%, mechanical systems 8.44%, and lighting systems 6.83%. This indicates that cooling demand remains the dominant contributor to electricity usage, although other systems also have notable contributions to the overall load.

The high energy consumption attributed to HVAC systems suggests that the building is heavily dependent on air-conditioning operations, which is typical in tropical climates such as the Philippines. This finding is consistent with previous studies indicating that HVAC systems are the primary energy consumers in buildings due to continuous cooling requirements.

However, the proportion observed in this study falls at the higher end of the typical range (40–60%), suggesting potential inefficiencies such as:

- Overcooling operation
- Lack of optimized control strategies
- Continuous operation at peak capacity
- Possible system oversizing

These findings highlight the critical need for targeted energy efficiency interventions, particularly in HVAC systems. The implementation of smart HVAC controls, optimized temperature settings, and integration of solar PV systems can significantly reduce energy consumption and improve overall building energy performance.

Table 3: Estimated Daily Electrical Load Profile

Time Period	Load kW
0800H – 1000H	3,800
1000H – 1200H	4,300
1200H – 1400H	4,800
1400 – 1600H	4,600
1600 – 1800H	4,200

Table 3 presents the estimated daily electrical load profile of ABC Commercial Building. The results indicate that electricity demand increases from approximately 3,800 kW during 8:00–10:00 AM to a peak of about 4,800 kW between 12:00–2:00 PM, before gradually decreasing toward the late afternoon. The observed peak during midday corresponds to periods of maximum building occupancy and increased cooling requirements.

The load profile is primarily influenced by Heating, Ventilation, and Air Conditioning (HVAC) systems, which account for approximately 62.35% of the total annual energy consumption. As outdoor temperatures rise toward midday, cooling demand increases significantly, resulting in higher electricity consumption. The sustained elevated load from late morning to mid-afternoon reflects continuous operation of HVAC systems under high cooling demand conditions.

This observation is consistent with previous studies identifying HVAC systems as the dominant energy consumers in commercial buildings, particularly in tropical climates.

Table 4: Lighting Inventory

Area	Type	Status	Qty	Category	Rating	Hrs/day
Lift Lobbies (14 lift lobby) and Restrooms	LED Striplights (5m)	Operational	626	LED	60	13
Gf-14th Floor - Hallway	Downlight (L)	Operational	2761	LED	15	14
Gf-14th Floor - Hallway	Downlight (S)	Operational	654	LED	13	14
Pantry and Cafeteria	Pantry hanging Led Bulb	Operational	190	LED	9	14
Parking and storage	T8 Lights	Operational	71	LED	16	14
storage	T8 lights	Operational	94	LED	16	13
GF	Panel Lights 60x60	Operational	286	LED	20	13
Lift Lobbies (14 lift lobby)	Elevator Lobby Downlight	Operational	586	LED	13	16
storage	Square Led Downlight	Operational	694	LED	15	14
14th floor, 6th and 5th floors	Track Light (White)	Operational	1058	LED	30	14
Gf-14th Floor - Hallway	Round Pinlight	Operational	589	LED	13	14
Gf-14th Floor - Workstation	Linear Lights	Operational	8045	LED	40	14
14th floor, 6th and 5th floors	Track Light (Black)	Operational	234	LED	15	14
14th floor, 6th and 5th floors	Mini Track Light	Operational	180	LED	9	14

Table 4 presents the inventory of lighting systems installed in ABC Commercial Building. The results show that the building predominantly utilizes LED lighting fixtures, including strip lights, downlights, panel lights, linear lights, and track lights, distributed across various functional areas such as hallways, workstations, lift lobbies, and common spaces. A large number of fixtures, particularly linear lights in workstations and downlights in circulation areas, operate for extended hours ranging from 13 to 16 hours per day. This indicates continuous lighting demand throughout building operations. The use of LED technology suggests improved energy efficiency compared to conventional lighting; however, the high quantity and long operating hours contribute significantly to the building's overall electricity consumption.

Table 5: Aircon Inventory

Area	**Type** (Window, Split, Package, Floor Type)	**Status** (Operational, Non-Operational, Standby)	**Category** (Inverter, Non-Inverter)	**Rating** (Watts)	**Operation**	
					Hours per Day	**Days per Week**
TOWER B						
GF	VRV	Operational	Inverter	29,600	12	5
2F	VRV	Operational	Inverter	87,800	12	5
3F	VRV	Operational	Inverter	135,800	12	5
4F	VRV	Operational	Inverter	132,500	12	5
5F	VRV	Operational	Inverter	140,100	12	5
6F - Cafeteria	VRV	Operational	Inverter	202,700	12	5
7F	VRV	Operational	Inverter	224,600	12	5
8F	VRV	Operational	Inverter	214,200	12	5
9F	VRV	Operational	Inverter	234,400	12	5
10F	VRV	Operational	Inverter	224,400	12	5
11F	VRV	Operational	Inverter	238,000	12	5
12F	VRV	Operational	Inverter	238,000	12	5
14F	VRV	Operational	Inverter	238,000	12	5
15F	VRV	Operational	Inverter	191,400	12	5
Auditorium	VRV	Operational	Inverter	67,000	12	5
FCC-CCTV room	Split type	Operational	Inverter	3,400	12	5
MDF room	Split type	Operational	Inverter	3,400	12	5
TOWER A						
GF	VRV	Operational	Inverter	32,100	12	5
2F	VRV	Operational	Inverter	70,800	12	5
3F	VRV	Operational	Inverter	110,400	12	5
4F	VRV	Operational	Inverter	113,400	12	5
5F	VRV	Operational	Inverter	97,100	12	5
6F - Cafeteria	VRV	Operational	Inverter	213,300	12	5
7F	VRV	Operational	Inverter	224,600	12	5
8F	VRV	Operational	Inverter	214,200	12	5
9F	VRV	Operational	Inverter	234,400	12	5
10F	VRV	Operational	Inverter	235,400	12	5
11F	VRV	Operational	Inverter	238,000	12	5
12F	VRV	Operational	Inverter	238,000	12	5
14F	VRV	Operational	Inverter	240,600	12	5
15F	VRV	Operational	Inverter	239,300	12	5

Table 5 shows the inventory of air-conditioning systems in ABC Commercial Building, which are primarily composed of inverter-type Variable Refrigerant Volume (VRV) systems installed across multiple floors in both Tower A and Tower B. These systems operate for approximately 12 hours per day, five days a week, and are characterized by high power ratings, reflecting substantial cooling requirements throughout the building. Additional split-type units are installed in specialized areas such as the FCC-CCTV room and MDF room. The extensive use of VRV systems across different floors indicates centralized and continuous cooling operations, highlighting HVAC systems as the major contributor to the building's energy consumption. These data provide essential input for the baseline energy assessment and simulation-based analysis.

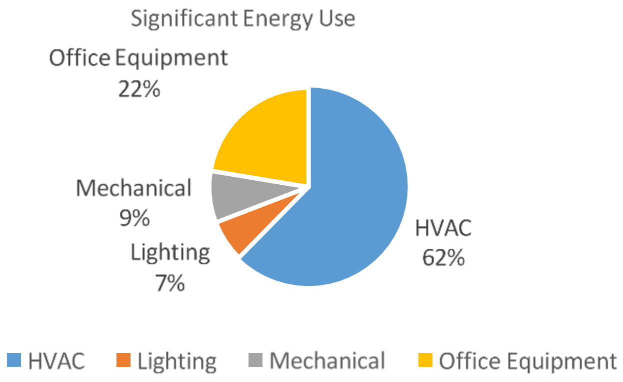

Fig 1: Significant Energy Use

In addition to HVAC systems, office equipment (22.37%), mechanical systems (8.44%), and lighting systems (6.83%) contribute to the overall load profile of ABC Commercial Building. Office equipment contributes to the base and daytime load due to continuous usage during working hours, while lighting and mechanical systems provide relatively smaller but steady contributions to total energy demand.

From an energy management perspective, the identified peak load period represents a critical opportunity for optimization. The peak demand period coincides with peak solar irradiance hours (10:00 AM–2:00 PM), indicating strong potential for solar photovoltaic (PV) integration. This alignment suggests that solar PV systems can effectively offset peak electricity demand, thereby reducing reliance on grid-supplied electricity and improving overall energy efficiency.

Previous studies have demonstrated that solar PV integration is most effective when electricity generation coincides with peak demand periods, maximizing energy utilization and reducing peak load stress (Al-Badi *et al*., 2021; Sedaghat *et al*., 2024) [4, 21].

Overall, the load profile supports the feasibility of implementing a solar PV–integrated energy system, particularly targeting HVAC operations during peak demand periods. The integration of solar PV with smart HVAC control strategies can enhance building energy performance, reduce peak demand, and contribute to sustainable energy management practices.

Table 6: Actual Rooftop Area Available for Solar PV Installation

Area	Roof Section Description	Area (sqm)
Area 1	807.54	sqm
Area 2	789.35	sqm
Area 3	112.81	sqm
Area 4	147.13	sqm
Total Area	1,856.83	sqm

To determine the feasibility of installing a solar photovoltaic (PV) system, both the available rooftop area and solar energy potential of ABC Commercial Building were assessed.

The solar photovoltaic (PV) potential of the building was evaluated using data from the *Global Solar Atlas*, a geospatial solar resource database developed by Solargis and the World Bank. The Global Tilted Irradiation at optimum angle (GTI opta) for the selected site is 1,811.4 kWh/m²/year, based on an azimuth angle of 180° and a tilt angle of 13°, which are appropriate for solar installations in the Philippines

Table 6 presents the total available rooftop area for solar PV installation is 1,856.83 m², which provides sufficient space for the proposed solar PV system.

Assuming a standard solar panel size of approximately 2.0 m² per module, the total number of panels that can be installed is estimated as:

$$\frac{1{,}856.83}{2.0} \approx 928 \text{ panels}$$

With each panel rated at 550 W, the total installed capacity is computed as:

$$928 \times 550W = 510{,}400W \approx 510 \text{ kWp}$$

Based on both solar irradiance conditions and available rooftop area, a 510 kWp solar PV system was selected for the study.

The proposed PV system is intended to offset a portion of grid electricity consumption, particularly during peak demand hours (10:00 AM–2:30 PM), when both solar irradiance and building energy demand are at their highest.

The proposed solar PV system has an estimated annual energy generation or energy yield of approximately 710.991 MWh/year. This projected annual energy output indicates that the system can significantly contribute to reducing grid electricity consumption and improving the overall energy efficiency performance of the building.

Furthermore, the distribution of PV panels across multiple roof sections enhances system performance by minimizing shading effects and improving solar exposure throughout the day.

Table 7: Estimated Solar PV Output

Items	Value	Unit
Global tilted irradiation at optimum angle	1,811.40	kWh/m2
Total Area	1,856.83	sqm
Size, Solar Panel	2.00	sqm
Rating, Solar Panel	550.00	W
Performance Ratio (PR)	0.80	%
No. of Panel	928.00	pcs
PV Capacity (RC)	510.00	kWp
Capacity factor (CF)	0.16	%
Average hours per year (Solar Irradiance)	8,760.00	hours
Yield (RC*CF*H)	714,816.00	kWh/year
Degradation Factor	0.0050	%
% Self Consumption	1.00	
DU Total customer charge	9.5370	Php/kWh
Annual increase in DU generation /customer charge	0.02	%
% Net export	-	%
DU Generation rate	4.3749	Php/kWh
O&M/year/kWp	900.00	Php
Annual increase in O&M	0.01	%
Cost of Installed PV System	50,000.00	Php/kWh
Total cost of installed PV system	25,500,000.00	Php
DU rate	9.75	Php/kWh
Avoided Cost from the Distribution Utility	6,969,456.00	Php
Payback Period Calculation	3.66	years

Table 7 shows the results show that the proposed 510 kWp solar PV system can generate approximately 714,816 kWh/year, which can significantly offset the building's electricity consumption.

Using the capacity factor method, the proposed 510 kWp solar PV system is estimated to generate approximately 714,816 kWh/year.

This result is derived as follows:

$$510 \times 0.16 \times 8{,}760 = 714{,}816 \text{ kWh/year}$$

The selected capacity factor of 0.16 (16%) reflects typical performance of solar PV systems in the Philippines, considering local solar irradiance, system losses, and operational conditions.

The results indicate that the proposed PV system can significantly offset the building's electricity consumption, particularly during daytime peak demand periods when solar generation is at its highest.

Furthermore, under a net metering scheme, the generated electricity is primarily utilized for on-site consumption (100% self-consumption assumption), thereby reducing dependence on grid-supplied electricity and lowering overall energy costs.

Table 8: Estimated Solar PV Output (IEA PVPS Method)

Items	Value	Unit
Global tilted irradiation at optimum angle	1,811	kWh/sqm
Total Area	1,857	sqm
Size, Solar Panel	2.00	sqm
Rating, Solar Panel	550.00	W
Performance Ratio (PR)	0.80	%
No. of Panel (TBD)	928	pcs
Installed Capacity (RC)	510	kWp
Annual Energy Generation, Yield (RC*CF*H)	739,051.20	kWh/year

Table 8 resents using the IEA PVPS methodology, the proposed solar PV system is estimated to generate approximately 739,051.20 kWh/year.

This estimate is derived based on the available rooftop area and solar irradiance:

$$E = 1{,}856.83 \times 1{,}811 \times 0.80$$

The performance ratio (PR) of 0.80 (80%) accounts for system losses such as inverter efficiency, temperature effects, shading, wiring losses, and other operational factors. This value is consistent with typical PV system performance under real operating conditions (International Energy Agency [IEA], 2022).

Compared to the capacity factor method (714,816 kWh/year), the IEA PVPS method provides a slightly higher estimate due to the direct incorporation of site-specific solar irradiance and system performance parameters. This method is considered more representative of actual system performance under real-world conditions.

The results further confirm the feasibility of the proposed 510 kWp solar PV system in significantly contributing to the building's energy demand and reducing dependence on grid electricity.

Table 9: Summary of ACU Capacity and Measured Room Temperature

Floor	ACU Type (Inv./Non-Inv./VRF)	ACU Rating (kW)	Room Temp. °C
Ground Floor	VRV	29,600	23.1
Second Floor	VRV	87,800	22.8
Third Floor	VRV	135,800	23.8
Fourth Floor	VRV	132,500	23.5
Fifth Floor	VRV	140,100	22.7
Sixth Floor	VRV	202,700	24.5
Seventh Floor	VRV	224,600	24.8
Eight Floor	VRV	214,200	23.1
Nineth Floor	VRV	234,400	22.9
Tenth Floor	VRV	224,400	24.7
Eleventh Floor	VRV	238,000	23.6
Twelfth Floor	VRV	238,000	24.7
Fourteenth Floor	VRV	238,000	24
Fifteenth Floor	VRV	191,400	23.7
Roof deck	-	-	-

Table 9 presents the distribution of Air Conditioning Unit (ACU) capacity and measured room temperatures across different floors of the building. All systems utilize Variable Refrigerant Volume (VRV) technology, which is designed to provide efficient and flexible cooling by adjusting refrigerant flow based on demand.

The measured room temperatures range from 23.1°C to 24.8°C, which are generally at or slightly below the recommended comfort temperature range of 24°C to 26°C for office buildings. Several floors, including the ground floor and eighth floor, recorded temperatures as low as 23.1°C, indicating potential overcooling conditions.

Overcooling results in unnecessary energy consumption, particularly in HVAC systems, which account for approximately 62.35% of total building energy use. Maintaining temperatures below the recommended range increases compressor workload and prolongs system operation, leading to higher electricity consumption.

From an energy efficiency perspective, even small deviations in temperature setpoints can significantly affect energy use. Studies indicate that lowering the thermostat setting by 1°C can increase cooling energy consumption by approximately 3–5%, highlighting the importance of proper temperature control.

To address these inefficiencies, the following measures are recommended:

- Adjusting temperature setpoints to recommended levels (**24°C–25°C**)
- Implementing smart HVAC control systems
- Integrating occupancy-based and demand-controlled cooling strategies

Overall, the results support the need for a solar PV–integrated smart HVAC system, which can optimize cooling performance, reduce unnecessary energy consumption, and improve overall building energy efficiency.

Table 10: Difference Between Baseline Energy Consumption and Projected Energy Consumption Under the Proposed Integrated System Design

Groups	Mean	SD	t^a	p^b	Interpretation
Baseline energy consumption (2025)	660785.31	38994.86	58.701	<.001	Significant
Projected energy consumption	530410.78	31301.08			

Table 10 showed the result of a paired-sample t-test to determine if there is a significant difference between baseline energy consumption in the year 2025 and the projected energy consumption under the proposed integrated system design. Results indicated that the projected energy consumption (M=530410.78; SD=31301.08) was significantly lower than the baseline energy consumption (M=660785.31; SD=38994.86) with a

t-value of 58.701 and a probability value of <.001 which was lower than the test of significance at.05. This means that there is a significant reduction in energy consumption under the proposed integrated system design, implying its effectiveness to significantly decrease the energy consumed.

Table 11: Projected Energy Efficiency

Month	2025, kWh	Projected	Difference
Jan	612,015.95	491,263.73	120,752.22
Feb	651,563.00	523,008.05	128,554.95
Mar	632,007.95	507,311.26	124,696.69
Apr	699,929.65	561,831.85	138,097.80
May	708,719.90	568,887.76	139,832.14
Jun	722,857.45	580,235.94	142,621.51
Jul	675,913.00	542,553.74	133,359.26
Aug	655,020.80	525,783.62	129,237.18
Sep	680,503.95	546,238.89	134,265.06
Oct	641,283.65	514,756.85	126,526.80
Nov	657,450.15	527,733.66	129,716.49
Dec	592,158.35	475,324.08	116,834.27
Total	7,929,423.80	6,364,929.43	1,564,494.37
Average	660,785.32	530,410.79	130,374.53
% Savings		19.73%	

The total energy savings is computed as:

$$Total\,Savings = 7{,}929{,}423.80 - 6{,}364{,}929.43 = 1{,}564{,}423.80 \text{ kWh/year}$$

$$\%Savings = \frac{1{,}564{,}423.80}{7{,}929{,}423.80} \times 100$$

$$= 19.73\%$$

Table 11 presents the projected improvement in energy efficiency of the proposed solar PV–integrated smart HVAC and lighting system based on the comparison between baseline and projected electricity consumption. Results showed that the baseline annual electricity consumption of ABC Commercial Building was 7,929,423.80 kWh, while the projected electricity consumption under the proposed integrated system design decreased to 6,364,929.43 kWh. This resulted in a total projected energy reduction of 1,564,494.37 kWh annually, equivalent to approximately 19.73% energy savings.

The findings further indicate that the average monthly electricity consumption decreased from 660,785.32 kWh under baseline conditions to 530,410.79 kWh under the proposed system design, with an average monthly reduction of 130,374.53 kWh. The reduction in energy consumption was consistently observed across all months, suggesting that the proposed system can effectively improve overall building energy performance throughout the year.

The projected reduction in electricity consumption is primarily attributed to the integration of rooftop solar PV generation, smart HVAC control strategies, and smart lighting technologies. The smart HVAC system contributed to energy reduction through temperature optimization, occupancy-based control, and improved scheduling operations, while the smart lighting system reduced unnecessary lighting consumption through daylight sensors, occupancy sensors, and zoning controls. In addition, the rooftop solar PV system helped offset part of the building's daytime electricity demand, particularly during peak load periods.

Overall, the results indicate that the proposed integrated system design can significantly improve energy efficiency and reduce dependence on grid-supplied electricity. The findings support previous studies emphasizing that the integration of renewable energy systems and smart building technologies can substantially enhance energy performance in commercial buildings.

Table 12: Stakeholders' Perceived Usefulness of Solar PV–Integrated Smart HVAC and Lighting Systems

Indicators	WM	SD	Interpretation
1. The proposed system will reduce electricity consumption in the building.	4.75	.444	Strongly Agree
2. The system will improve overall energy efficiency of the building.	4.75	.444	Strongly Agree
3. The system will enhance the operational performance of HVAC and lighting systems.	4.45	.510	Strongly Agree
4. The system will reduce operational costs associated with energy consumption.	4.85	.366	Strongly Agree
5. The system will contribute to the long-term sustainability of the building.	4.55	.510	Strongly Agree
Average Weighted Mean	4.67	.227	Strongly Agree

Note: Scoring Range: 4.20-5.00 (Strongly Agree) 3.40 – 4.19 (Agree); 2.60 – 3.39 (Neutral); 1.80 – 2.59 (Disagree); 1.00 – 1.79 (Strongly Disagree)

Table 12 presents the stakeholders' perceived usefulness of the proposed solar PV–integrated smart HVAC and lighting system. Results showed that all indicators obtained weighted mean scores ranging from 4.45 to 4.85, all interpreted as "Strongly Agree." The highest-rated indicator obtained a weighted mean of 4.85 (SD =.366), indicating that stakeholders strongly believe that the proposed system can help reduce operational costs. Meanwhile, the lowest-rated indicator obtained a weighted mean of 4.45 (SD =.510), which still falls under the "Strongly Agree" category, indicating positive stakeholder perception regarding the system's ability to enhance operational performance of HVAC and lighting systems.

The overall average weighted mean of 4.67 with a standard deviation of.227 indicates that stakeholders generally have a very positive perception regarding the usefulness of the proposed system. The relatively low standard deviation values further suggest consistency in the responses of participants. These findings imply that stakeholders recognize the potential benefits of integrating solar PV and smart building technologies in improving energy efficiency, reducing electricity consumption, and supporting long-term sustainability of the building.

Table 13: Stakeholders' Adoption Intention of Solar PV–Integrated Smart HVAC and Lighting Systems

Indicators	WM	SD	Interpretation
1. I intend to support the implementation of the proposed system.	4.60	.502	Strongly Agree
2. I am willing to adopt this system in the building.	4.75	.444	Strongly Agree
3. I would recommend the adoption of this system.	4.70	.470	Strongly Agree
4. I am willing to be involved in its implementation.	4.80	.410	Strongly Agree
5. I support the integration of solar PV and smart technologies in the building.	4.55	.510	Strongly Agree
Average Weighted Mean	4.68	.278	Strongly Agree

Note: Scoring Range: 4.20-5.00 (Strongly Agree) 3.40 – 4.19 (Agree); 2.60 – 3.39 (Neutral); 1.80 – 2.59 (Disagree); 1.00 – 1.79 (Strongly Disagree)

Table 13 presents the stakeholders' adoption intention toward the proposed solar PV–integrated smart HVAC and lighting system. Results showed that all indicators obtained weighted mean scores ranging from 4.55 to 4.80, all interpreted as "Strongly Agree." The highest-rated indicator obtained a weighted mean of 4.80 (SD =.410), indicating that stakeholders are highly willing to be involved in the implementation of the proposed system. On the other hand, the lowest-rated indicator obtained a weighted mean of 4.55 (SD =.510), which still reflects a strong level of support for integrating solar PV and smart technologies within the building.

The overall average weighted mean of 4.68 with a standard deviation of.278 indicates a very high level of adoption intention among stakeholders. The relatively low variability in responses signifies that participants consistently expressed strong willingness to support, recommend, and participate in the implementation of the proposed system. These findings suggest that stakeholders are receptive to the adoption of energy-efficient technologies and recognize the value of solar PV–integrated smart HVAC and lighting systems in improving building energy performance and sustainability. The results further support previous studies emphasizing that perceived usefulness significantly influences stakeholders' intention to adopt energy-efficient technologies.

4. Conclusion

Based on the findings of the study, the following conclusions were drawn:

- The office-commercial building exhibits high electricity consumption primarily driven by HVAC systems, indicating significant opportunities for energy efficiency improvements through optimized system operation and renewable energy integration.
- The existing electrical load profile of the building shows that peak demand occurs during midday operating hours, particularly between 10:00 AM and 2:30 PM, which coincides with periods of maximum HVAC utilization and peak solar irradiance. This indicates that the building is highly suitable for solar PV integration to offset daytime electricity demand.
- A simulation-based solar PV–integrated smart HVAC and lighting system was successfully developed based on the building's existing energy conditions, rooftop solar potential, and operational requirements. The proposed system includes a 510 kWp rooftop solar PV system, smart HVAC controls, and smart lighting strategies designed to optimize electricity consumption.
- The projected energy consumption under the proposed integrated system design was significantly reduced compared to the baseline energy consumption. The simulation results showed a projected annual energy consumption of 6,364,929.43 kWh/year, resulting in projected energy savings of approximately 1,564,494.37 kWh/year or 19.73% reduction from baseline consumption.
- There is a statistically significant difference between the baseline energy consumption and the projected energy consumption under the proposed solar PV–integrated smart HVAC and lighting system. The paired sample t-test yielded a p-value of less than 0.05, leading to the rejection of the null hypothesis. This confirms that the proposed integrated system is effective in significantly reducing electricity consumption and improving building energy efficiency.
- The proposed solar PV–integrated smart HVAC and lighting system can effectively improve building energy efficiency by reducing grid electricity consumption and optimizing HVAC and lighting operations through smart control strategies.
- Stakeholders demonstrated very high perceived usefulness and adoption intention toward the proposed integrated system, indicating strong organizational support and positive stakeholder perception regarding the implementation of solar PV and smart building technologies.
- Perceived usefulness has a moderate to strong positive relationship with adoption intention and significantly predicts stakeholders' willingness to adopt the proposed system. This confirms the applicability of the Technology Acceptance Model (TAM) in explaining stakeholder behavior toward energy-efficient technologies.

Overall, the study confirms that the integration of solar PV systems with smart HVAC and lighting technologies is both technically feasible and organizationally acceptable for improving energy efficiency in office-commercial buildings.

5. Recommendation

Based on the conclusions of the study, the following recommendations are proposed:

- Building management should implement the proposed solar PV–integrated smart HVAC and lighting system to reduce electricity consumption, improve operational efficiency, and minimize dependence on grid-supplied electricity.

- Smart HVAC control strategies such as temperature setpoint optimization, occupancy-based control, and automated scheduling should be adopted to further reduce unnecessary energy consumption in commercial buildings.
- Smart lighting technologies including occupancy sensors, daylight sensors, and zoning controls should be implemented to optimize lighting energy efficiency and reduce electricity wastage.
- Organizations planning to adopt smart building technologies should strengthen stakeholder capability through technical training, capacity-building programs, and awareness campaigns to support effective system implementation and operation.
- A comprehensive financial feasibility analysis, including cost-benefit analysis, payback period, and return on investment, should be conducted prior to actual implementation of the proposed integrated system.
- Building management should establish an Energy Management System (EnMS) to continuously monitor, evaluate, and sustain energy efficiency improvements within the facility.
- Future researchers may include additional variables such as organizational readiness, financial capability, technical readiness, and policy support to improve the explanatory power of stakeholder adoption models.
- Future studies may further explore the integration of battery energy storage systems, hybrid renewable energy systems, and real-time energy monitoring technologies for enhanced building energy management.
- Similar simulation-based studies should be conducted in other office-commercial buildings to validate and generalize the findings of this research.

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