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Feasibility Study on the use of rooftop solar-powered Air conditioning in Residential Building, Case study: Phnom Penh City, Cambodia

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Abstract: The residential sector faces challenges due to increasing energy demand, with air conditioning systems playing a crucial role. This research examines the feasibility of utilizing rooftop solar power to supply air conditioning systems in a residential building in Phnom Penh. A simulation model of the house was constructed using SketchUp and OpenStudio software. Integration of a rooftop solar photovoltaic (PV) system with OpenStudio was analyzed to determine its capability to power the house. Results show that solar power reduces monthly energy consumption to 186 kWh and annual consumption to 2,231 kWh. Solar energy production varies with weather conditions, being higher during hot months and lower during cooler months. To implement the solar power solution, a 13-cell PV panel installation is recommended—the annual energy savings for the air conditioning system amount to $422.28. The payback period for this investment is within three years, followed by a subsequent benefit period of 22 to 27 years, depending on the solar panel's lifespan. Utilizing solar power in residential buildings offers energy savings, environmental protection, and positive economic impacts, addressing the challenges of increasing energy demand.

Index Terms – OpenStudio, Photovoltaic, Residential Building, Air Conditioning System, Energy Consumption.

I. INTRODUCTION

Cambodia is a tropical country in Southeast Asia, and faces the challenge of hot temperatures and high humidity, which can negatively impact human health [1]. Furthermore, climate change and global warming are increasing the demand for air conditioning, resulting in a significant rise in energy consumption [2].

To address this issue and achieve energy efficiency, computer simulation is a valuable tool for assessing building performance [3]. By using solar energy to supply electricity to the air conditioning system, solar-powered air conditioners provide a way to reduce energy consumption. [4]. A solar-powered air conditioning system's effectiveness is influenced by things including solar collector size, sunshine availability, and system design. In Cambodia's climate, where the capital city of Phnom Penh experiences an average annual solar radiation of 1800 kWh/m^2 and an average annual temperature of 27 ℃ [5], [6], the need for an effective cooling solution is crucial.

Building energy simulation plays a vital role in evaluating energy performance and making informed design decisions [7]. Before construction, it enables building owners and designers to evaluate the energy efficiency of their construction endeavors [8]. SketchUp, a popular 3D drawing program used by architects, designers, and students, integrates with OpenStudio, an energy simulation tool [9]. This integration allows users to create energy models of buildings, providing insights into the energy performance of different design options [10].

A plugin for SketchUp is provided by the OpenStudio software package of free and open-source programs for building energy assessments [11]. It enables users to view and edit 3D models, run simulations using the EnergyPlus engine, and export results in various formats. Widely adopted by architects, engineers, builders, and researchers, OpenStudio facilitates in-depth analysis of building energy performance. The integration of SketchUp and OpenStudio allows consumers to simulate and evaluate the energy performance of their building designs, considering factors such as solar power and air conditioning.

The building envelope, consisting of walls, roofs, windows, doors, and foundations, plays a crucial role in controlling the flow of temperature, air, and humidity inside and outside the building [12], [13]. A well-insulated and airtight building envelope can help reduce heating and cooling costs while improving indoor air quality.

Solar energy, abundant in Cambodia due to its geographical location, offers great potential for renewable energy generation. Photovoltaic (PV) systems, which convert sunlight into electricity, are commonly used to harness solar energy. PV systems, consisting of solar panels, inverters, and other components, can offset energy consumption from the grid and reduce greenhouse gas emissions [14]. The feasibility and economic viability of PV systems depend on factors such as solar resource availability, system size, installation costs, and government incentives [15].

The economics of residential photovoltaic systems with air conditioning have been studied [16]. The payback period for a PV system with air conditioning varies based on factors such as the cost of the PV system, cost of electricity, energy-saving potential, and local incentives. The payback period is a simple method for determining the time it takes for a project to recover its initial investment [17].

In this context, this paper focuses on modeling and simulating building energy using the free software provided by the US Department of Energy, supported by the SketchUp drawing plug-in OpenStudio. By inputting data on building envelope parameter

properties, selecting load and weather data, and running simulations, the study aims to provide insights into the cooling load, energy generation from photovoltaic systems, and annual hourly energy consumption over a year.

II. RESEARCH METHODOLOGY

The research methodology focuses on simulating building energy performance using a SketchUp plug-in called OpenStudio. The process involves many stages, as illustrated in Figure 1.

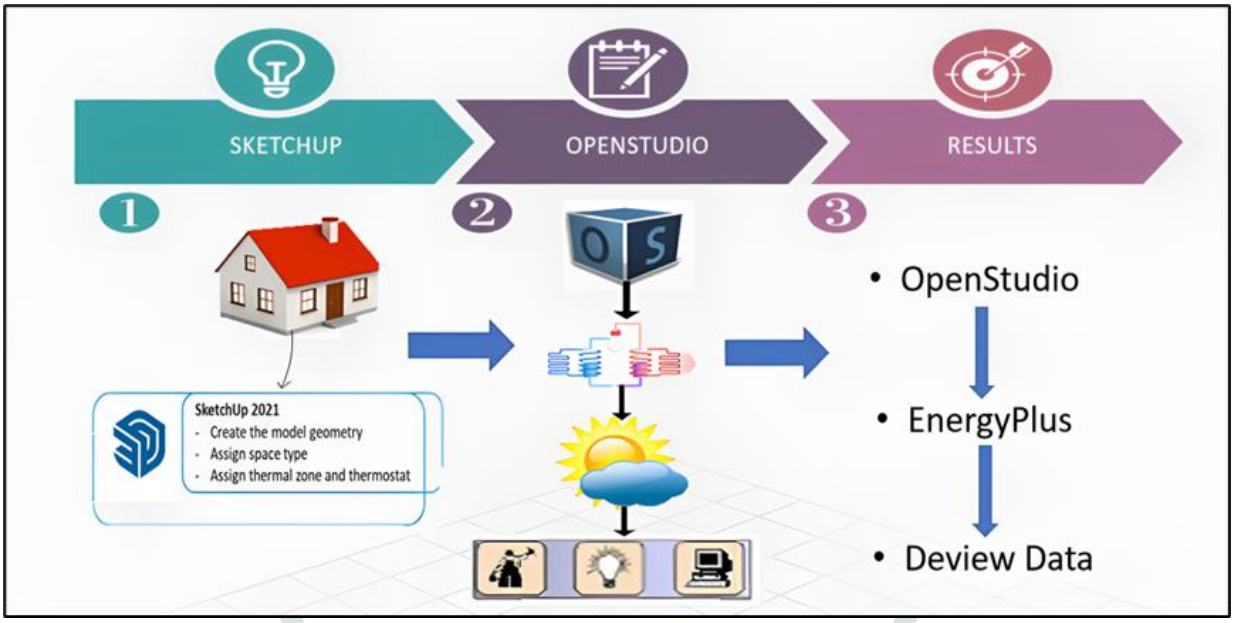


Figure 1. Methodology for model simulation in the building

The steps are as follows:

- Create a sketch of the building envelope: this can be done in 3D modeling software by using SketchUp to draw a building and the building needs to create the model geometries such as walls, roofs, doors, windows, space type, and foundation of the building before importing the sketch into OpenStudio.
- Import the Sketch into OpenStudio: In this step we will be able to assign construction materials to the building and set of thermal properties, such as the thermal conductivity, and thermal resistance. These properties are used to calculate the heat transfer through the building envelope. Furthermore, in this step, we can assign the weather file and the weather file contains information about the climate of the location where the building is located after simulation. This information is used to calculate the heating and cooling load of the building.
- Results: The simulation will get the results in OpenStudio or EnergyPlus. After that, it can be converted to Dview data for tracking the energy performance of the building in hourly, monthly, and yearly intervals.

3.1 Overview of the Flat Building

In this study, the building was designed to simulate a typical garment factory and was based on a real sample house in Phnom Penh. The location chosen is Phnom Penh, which has a latitude of 11.55 and a longitude of 104.85. For the weather file in (EnergyPlus) EPW, we can download the free format available from EnergyPlus. The site information, including the weather data file, is specified in the site tab of the application.

The building is a single-space structure, in this study is a two-story structure divided into three zones. The ground floor comprises a guest room, a toilet, and a kitchen dining room, while the first floor has two bedrooms. The building has a flat design with a floor area of 41.8 m^2 and a height of 3 m per floor. The rooftop is sloped and constructed using reinforced concrete. The windows cover approximately 1.8% of the building's surface area.

The building structure is implemented in OpenStudio, considering two thermal conditions. The outside dimensions of the building are 14 m x 5 m. The first-floor features two windows on each wall, measuring 0.6 m x 1.20 m, totaling 2.25 m^2 as shown in Figure 2.

The internal parameters of the system are adjusted to represent a typical household with four people and average occupancy levels for residential homes. The electrical equipment is configured to operate based on the occupancy schedule, taking into account both the ground-floor and first-floor loads. The split air conditioner is set to cool the house to 21 degrees Celsius during the day and 24 degrees Celsius at night. The scenario also considers natural ventilation. External conditions are regulated using weather files obtained from the EnergyPlus website, which provide a comprehensive record of the weather conditions in the specific location, including factors like solar gains, outdoor temperature.

To access the energy consumption as cooling load of the simulated building, the investigation focused on the hours of 7:00 am to 11:00 am and 13:00 pm to 17:00 pm throughout the year. The occupancy density of the building was considered to be four people. The cooling setpoint was set at 25°C, while the lighting intensity was 16 W/m^2, and the plug and process load were 48 W/m^2.

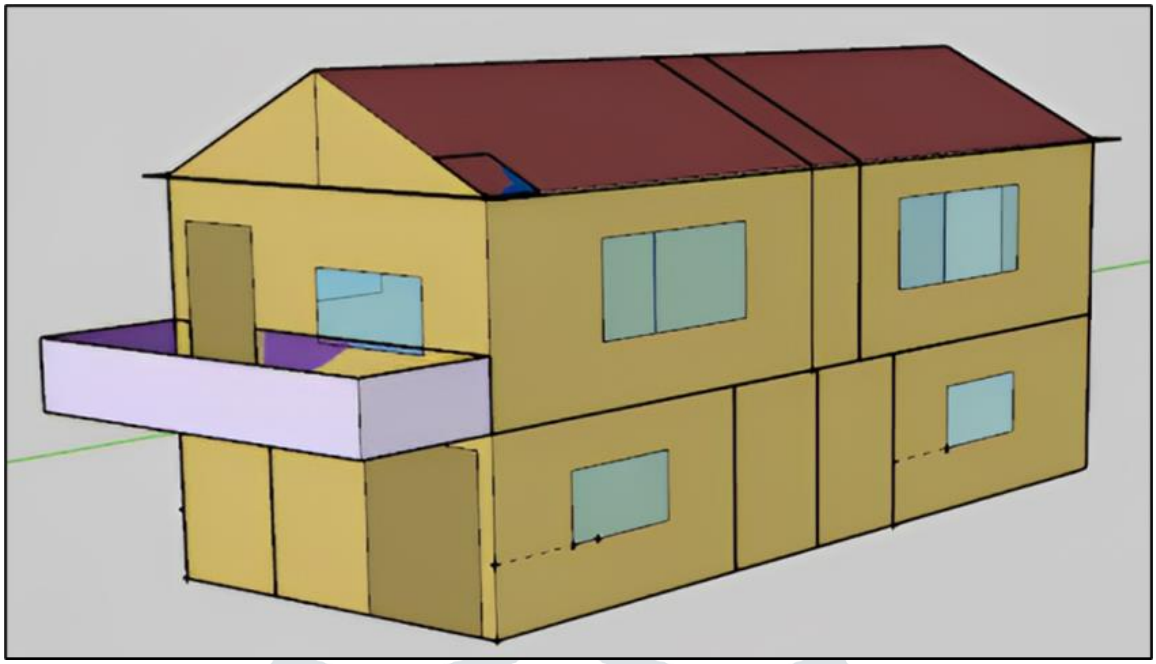


Figure 2. Simplified 3D model of the studied building

To accurately assess the cooling loads for a home accommodating a family of four people (consisting of two parents and two children), it is crucial to consider the operating times of the HVAC system, specifically from 5:00 AM to 5:00 PM, as well as the frequency at which the building's occupants utilize it during this period. By analyzing these parameters, we can determine the internal loads imposed on the living space and establish the necessary design criteria. This information is vital for accurately identifying and addressing the cooling requirements of the home during the daytime hours the schedule following as the Table 1.

Table 1. People's activities on the model flat during the hours

Hourly	Percentages
18-7	100
7-11	50
11-13	75
13-18	50

3.2 Specification of the Building Envelope Materials

We can build and drop the material in construction from the library or download it from online BCL(Building Components Library), the building construction assembly has a door, floor, roof, ceiling, and wall that we can construct in OpenStudio construction set. The building construction was made with hollow brick walls and plaster on the outside, single glass window, and a clay tile roof. The thickness and the construction's global coefficients of the heat transfer (U). The main elements of the building as shown in Table 2, Table 3, and Table 4 along with some of their physical characteristics are used for building simulation in Openstudio. The building material properties were assigned in the OpenStudio tab for the thickness, thermal conductivity, density, and the solar absorptance.

Table 2. Thermal properties of construction materials

Construction	**Layer**	**Thickness (mm)**	**Thermal Conductivity (W/m.K)**	**Density (kg/m^3)**
Exterior wall	Color Painting	-	0.2	1050
	Cement Plaster	15	0.721	1762
	Hollow brick	100	0.52	1300
	Cement Plaster	15	0.87	1700
	Color Painting	-	0.2	1050
Interior wall	Color Painting	-	0.2	1050
	Cement Plaster	15	0.721	1762
	Hollow brick	100	0.52	1300
	Cement Plaster	15	0.87	1700
	Color Painting	-	0.2	1050
Ground Floor	Reinforced Concrete	70	1.55	2400
	Cement Mortar	60	1.15	1800
	Ceramic Tile	8.5	1.05	2000
First-Floor	Ceramic Tile	9.5	1.05	2000
	Cement Mortar	60	1.15	1800
	Reinforced Concrete	70	1.55	2400
	Air Space	300	1.18	-
	Ceiling Board	9.5	0.35	840
Rooftop	Clay Tile	6	0.85	1900
	Cement Mortar	60	1.15	1800

	Reinforced Concrete	70	1.55	2400
	Air Space	300	-	-
	Ceiling Board	9.5	0.35	840

National Technical Regulation Energy Efficiency Building, Vietnam: QCVN 09:2013/BXD

Table 3. Thermal properties of single-glazed window

Material	Thickness (mm)	Thermal Conductivity (W/m.k)	Density (kg/m^3)
Glazed Window	3	0.93	2500

Table 4. Thermal properties of opaque openings material

Material	Thickness (mm)	Thermal Conductivity (W/m.k)	Density (kg/m^3)
Wooden door	40	0.35	550

3.3 Split Air conditioning system model

For this study, a split system unit was considered for this building simulation. The model FTN35PXV1/ RN35FAXV1 is shown in Figure 3. The normal heating and cooling capacities for this combined system are 2.5 kW to 3.52 kW. The parameters are measured for normal conditions with the measuring temperature being an indoor temperature of 27 ℃ for dry-bulb, 19 ℃ for wet-bulb and the outdoor temperature 35 ℃ for Dry-bulb.

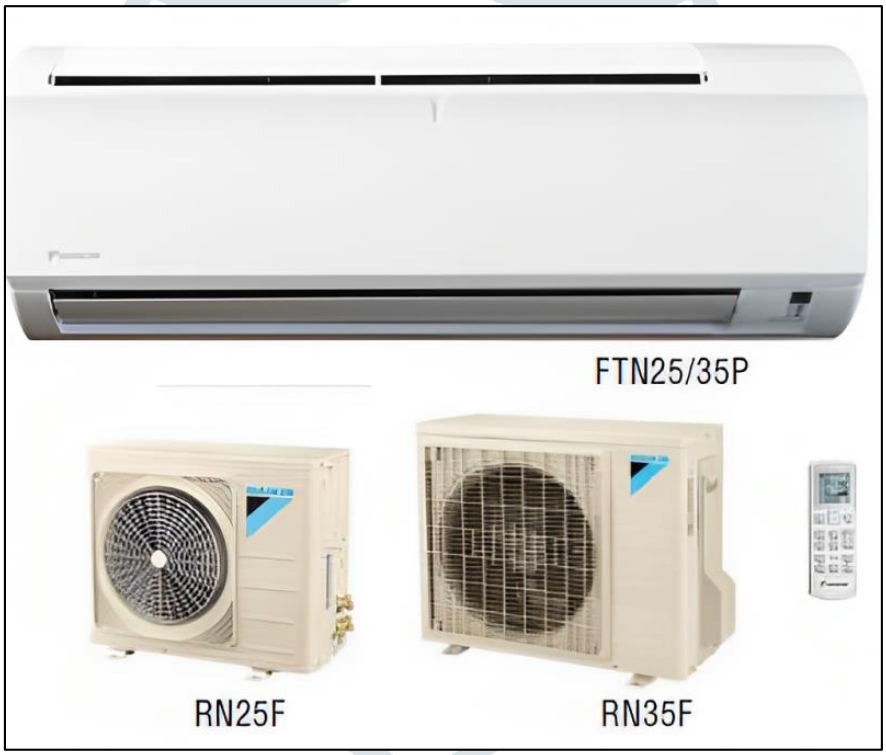


Figure 3. Indoor and outdoor units of split system[18]

3.4 Photovoltaic system

We first need to determinate the energy needed. Cambodia has a high potential for solar energy. Cambodia receives an average of 8 hours of sunshine per day, year-round. The country also has a high solar irradiation rate, which is a measure of the amount of solar energy received per square meter. The daily average solar irradiation rate in Cambodia is 5 kWh/m^2, and it peaks at 5.6 kWh/m^2 in central Cambodia. This potential has been well recognized by the Royal Government of Cambodia [19] Solar power is a clean, renewable energy source that can help Cambodia reduce its reliance on imported fossil fuels. Solar panels can be easily installed and generate electricity from the sun, which is free and available every day. Before adding the solar PV panel, as we know, the capacity energy consumption/cooling load of an air conditioner is used to design the capacity of a solar PV system (2.5 kW is used for this simulation). Then, we can create a photovoltaic panel in SketchUp by using OpenStudio user script tools. PV panels were set on the rooftop facing south-west as shown in Figure 4. The PV panel was selected model EGE-165/180M-36, the fixed cell efficiency was set as 0.18, an in-plane radiance of 1000 W/m^2 as standard testing condition (STC) defined by [20] and there are 13 cells for installation on rooftop. The specific energy of these PV modules is 0.61 kWh/kWp [19]. The type of cell is monocrystalline (1480×670×30mm) and the power output is 180 Wp [21].

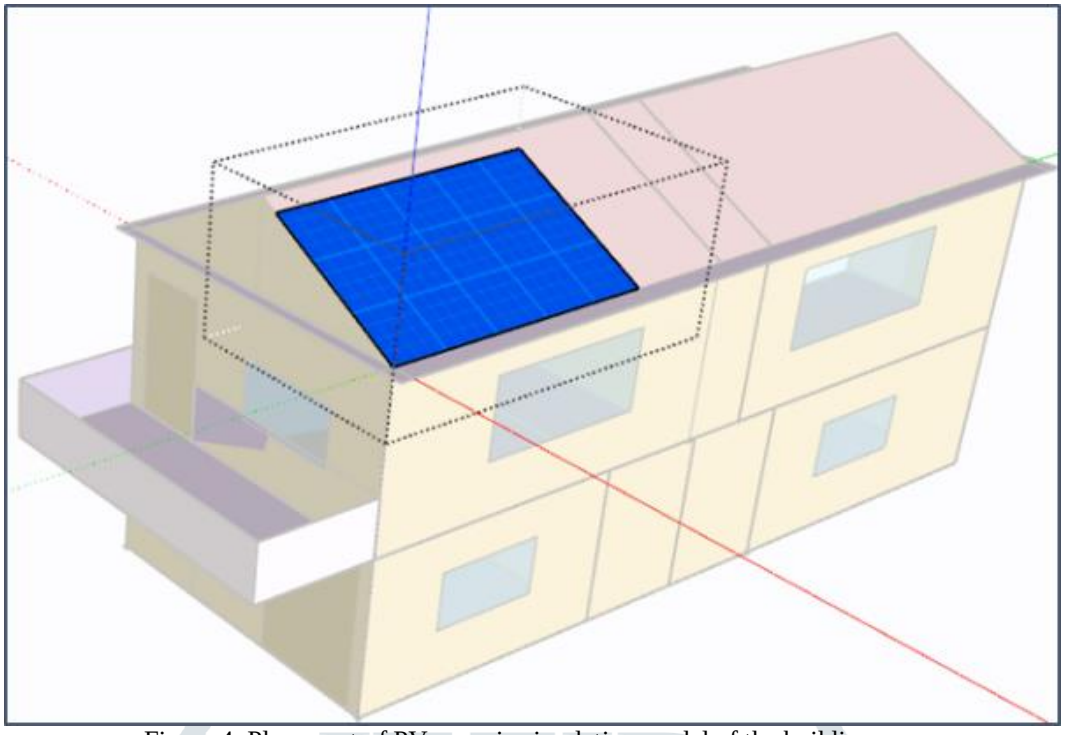


Figure 4. Placement of PV array in simulation model of the building

III. RESULTS AND DISCUSSION

4.1 Overview of annual energy use

The results of this study focus on the electricity consumption in a residential building, including the cooling load of the HVAC system, lighting, electric appliance equipment, and fan. The pie chart in Figure 5, shows the annual energy used in the building, without taking into account any photovoltaic (PV) production.

The pie chart is divided into four sections:

- Cooling load (62%): This is the largest section, accounting for over half of the total energy used and the case study in this scenario.
- Lighting (18%): This is the second largest section, accounting for nearly one-fifth of the total energy used.
- Equipment (16%): This includes energy used by computers, machinery, and other equipment in the residential building.
- Fan (4%): This is the smallest section, accounting for only a small fraction of the total energy used.

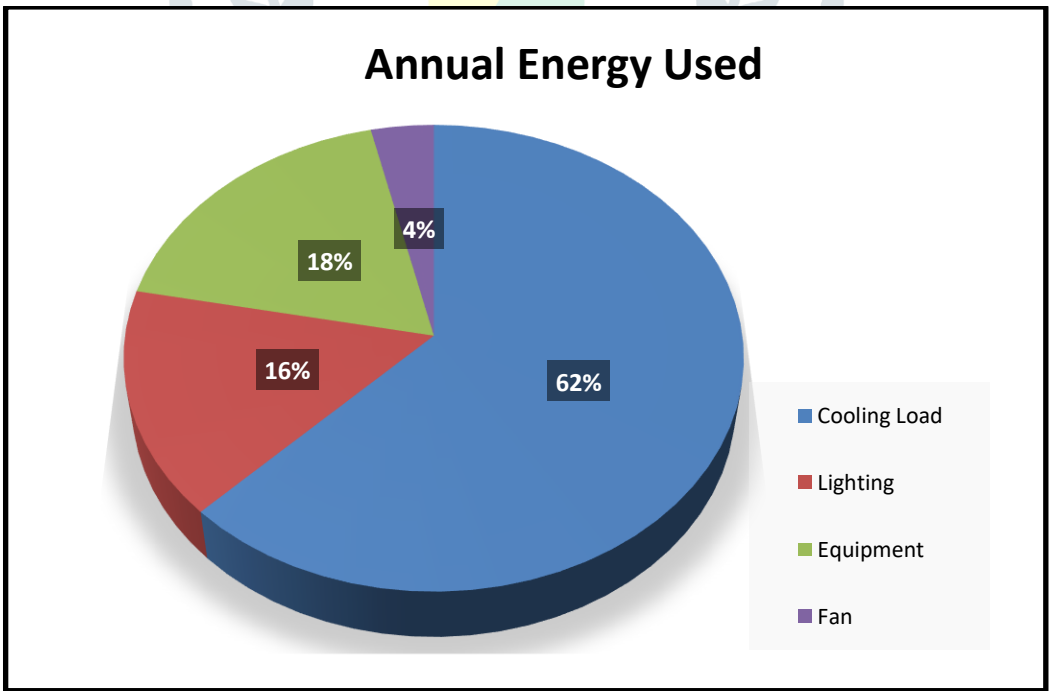
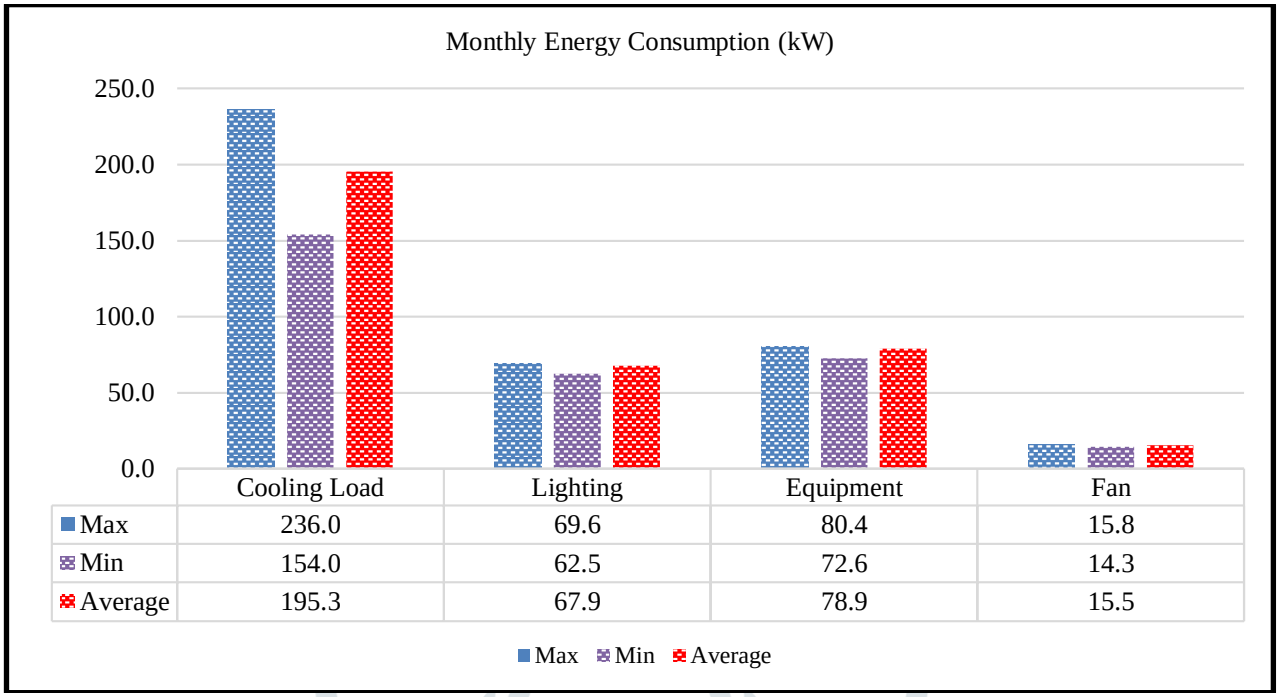


Figure 5. Number of flowers on the 100% flowering day

The result in Figure 6, the graph shows the average monthly energy consumption of a house, broken down by the different types of appliances that use energy. The average monthly energy consumption of a house is 250 kWh. The biggest energy consumer is the cooling load, which accounts for 236 kWh per month. This is followed by lighting, which accounts for 69.6 kWh per month. Equipment accounts for 80.4 kWh per month, and fans account for 15.8 kWh per month.

The graph also shows the maximum, average, and minimum energy consumption for each type of appliance. The cooling load has the highest maximum energy consumption, at 154 kWh per month. The lighting has the highest average energy consumption, at 69.6 kWh per month. The equipment has the highest minimum energy consumption, at 72.6 kWh per month.

Overall, the graph shows that the cooling load is the biggest energy consumer in a house. However, lighting, equipment, and fans also use a significant amount of energy.



	Cooling Load	Lighting	Equipment	Fan
Max	236.0	69.6	80.4	15.8
Min	154.0	62.5	72.6	14.3
Average	195.3	67.9	78.9	15.5

Figure 6. Monthly energy consumption

4.3 Hourly Weather Temperature Data in Phnom Penh

According to the investigation for the temperature outputs of the yearly simulated, it was simulated for one year starting from 00:00 on January 1st to December 31st. The running simulation of this result was 8760 hours, it was divided into two parts of temperature (Wet-bulb and Dry-bulb). The maximum dry temperature is 37.2 ℃, the minimum 20 ℃, and the average is 28 ℃. The hotter temperature is mostly from May to July. The maximum wet temperature is 29.4 ℃, minimum 13.9 ℃ and the average is 23.68℃. The coldest temperature mostly occurs from December to January as shown in Figure 7.

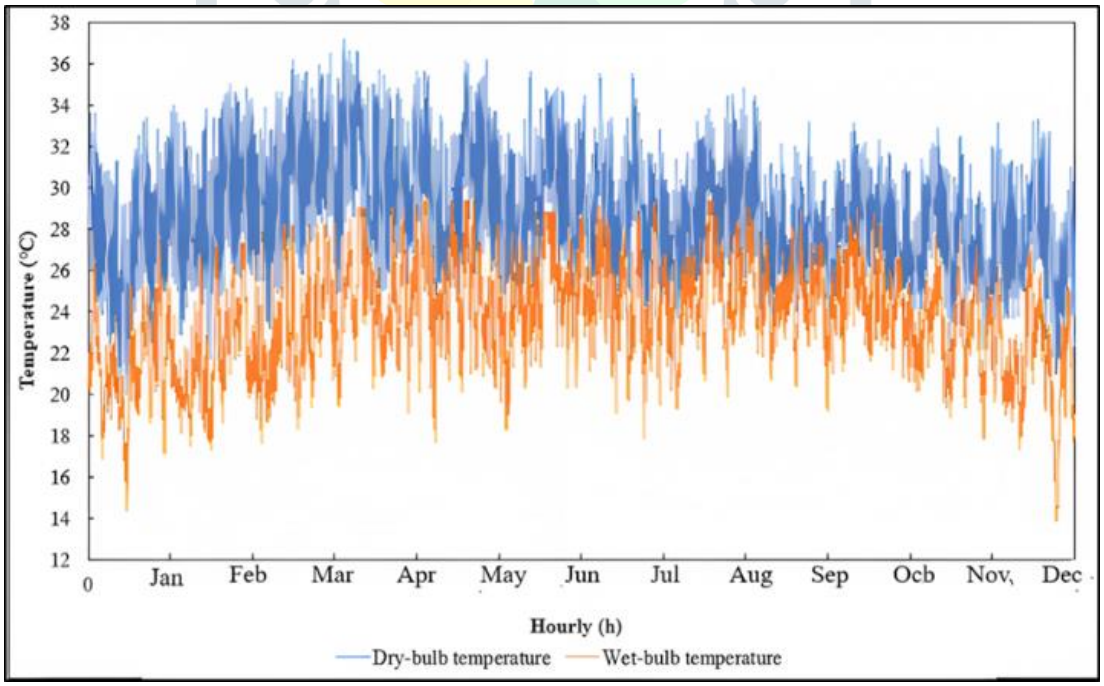


Figure 7. Weather temperature data in Phnom Penh

4.4 The yearly PV production

Based on the result obtained in Figure 8, the amount of solar power generated by a photovoltaic system in watts per hour in one year. The results of simulation from the rooftop of solar PV panels, the highest amount of PV production is at noon, with 2100 watts per hour, there is a general trend of increasing PV production throughout the day, as the sunrise shines more directly on the PV system. The average amount of PV production per hour is about 404.72 watts per hour.

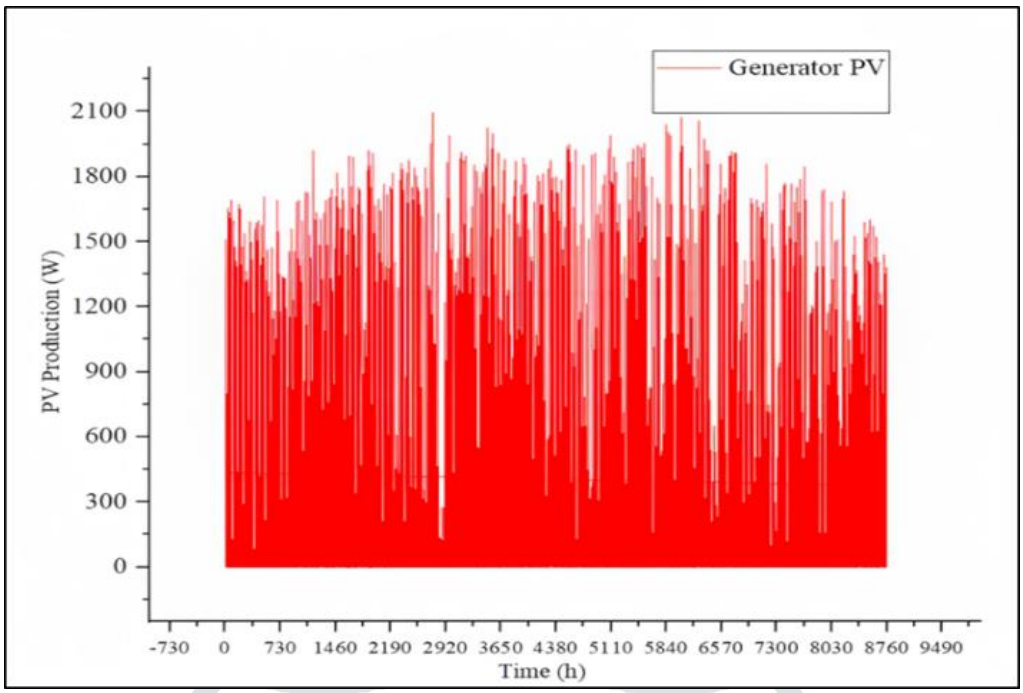


Figure 8. Yearly PV production

4.5 Monthly Energy Consumption and Payments

The results in Table 5, show the PV production for the year was 2,344 kWh, and the total payment was $422 per year. The highest monthly production was in July, with 233Wh, and the lowest monthly production was in September, with 178 Wh.

Table 5. Monthly HVAC energy consumption and payments

Monthly	Energy consumption (kW)	Energy Payments (USD)
January	193	29
February	167	30
March	210	38
April	182	33
May	236	43
June	230	42
July	233	43
August	227	41
September	178	33
October	171	31
November	154	28
December	163	30
Annual Energy Consumption	2344	422

4.6 Analysis of Investment Cost PV Installation on Rooftop

The investment cost divided by the annual cash flow yields the payback period [22]. The formula in (1) can be used to calculate the payback period.

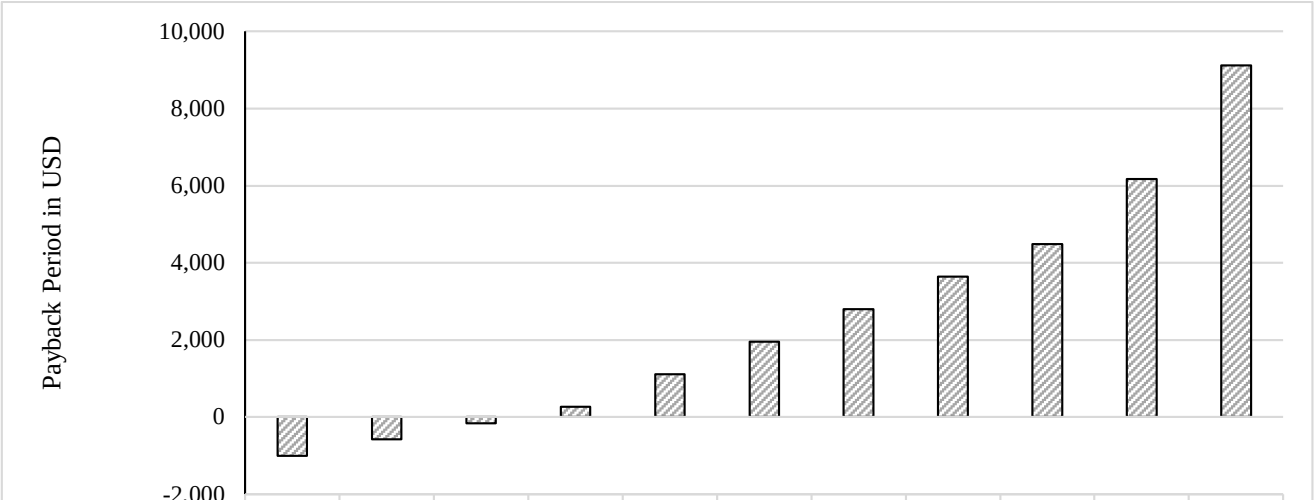
$$Payback\ Period = \frac{Initial\ Investment}{Periodic\ cash\ flow} \quad (1)$$

The initial investment for this study focused on the amount of installation of photovoltaics on rooftop and the periodic cash flow was tracked from amount of payment with monthly energy consumption estimated from simulation in the residential house. Energy consumption range in the residents will be used due to a tariff in 2022 observed from "Annual salient features of electricity development in the Kingdom of Cambodia " as shown in Table 6.

Table 6. The cost estimate of the grid [23]

Energy Consumption Rang	Payment Rang [$/kWh]
< 10 kWh/month	0.0951
11 to 50 kWh/month	0.12
51 to 200 kWh/month	0.1525
>200 kWh/month	0.1825

The result in Figure 9, presents the amount of PV solar that needs to be input from the rooftop is 13-cells and the power output (P_{max}) is 180 Wp and the price is $0.61 per watt peak [19]. So, the initial investment cost for installing the solar system is $1427.4 for installing the rooftop solar PV panel supply to air conditioning and the annual cash flow from saving energy for the air conditioning system is $422.28. The payback period is about 3.33 years, and after that, we will benefit from 20 to 25 years, depending on the lifespan of the solar panels.



	1	2	3	4	6	8	10	12	14	18	25
Investment Costs	-1,005	-583	-161	261	1,105	1,949	2,793	3,637	4,481	6,169	9,123

Figure 9. The estimated payback period for PV installation on Rooftop

IV. CONCLUSIONS AND RECOMMENDATIONS

This study's result shows that the energy consumption is the highest in a building, equaling to 378 kWh, followed by lighting and other equipment. The monthly energy consumption is highest in April and lowest in November. The cooling load is highest in the hot months 213 kWh and the lowest is 164 kWh in the cool months. The PV production is also highest in the hot months, but not as closely correlated with the cooling load consumption. The monthly average cooling load is 186 kWh, and the air conditioning needs 13 cells of PV panels to supply daytime.

The study also found that the installation of a solar PV panel system is a financially sound investment examines the feasibility of utilizing rooftop solar power to supply air conditioning systems in a residential building in Phnom Penh. The system will pay for itself in 3 years and will generate a net profit of $442, 28 per year after that.

Based on the findings of the study, the following recommendations are made:

- The building owner should consider installing a solar PV panel system to reduce their electricity costs.
- The building owner should optimize the operation of their cooling system to reduce their cooling load energy consumption.

V. ACKNOWLEDGMENT

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