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Case Study of the Effect of Tilt Angle on Output Power and Efficiency of Photovoltaic Using Two Solar Irradiation Measurement Methods

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ABSTRACT

Geographically, Indonesia has huge renewable solar energy, which is potentially utilized as source of the electrical energy. The latest photovoltaic technology can be applied to effectively harvest electrical energy. Correspondingly, the small power plant of 50 kWp in currently installed at Pamulang University. Meanwhile, solar irradiation and tilt angle have a significant impact on photovoltaic efficiency. So, a case study is needed on the effect of solar irradiation and tilt angle on the output voltage open circuit and current short circuit to determine the influence on photovoltaic efficiency. This case study compares two measurement methods of solar irradiation, measurement of photovoltaic voltage and current under existing tilt angle conditions. Only 5.0 % difference in solar irradiation using the Lux Meter 721 W/m^2 and Solar Survey 684 W/m^2 is a non-significant difference, so both measuring devices are feasible use. The difference in efficiency is only 5.2% with measurements using a Lux Meter of 19.3% and a Solar Survey of 20.4%, this value is better than the ideal efficiency value of 20.6% in conditions of the existing photovoltaic tilt angles are 2°, 4° and 6°. This means that the angle of inclination does not have a significant effect on efficiency, but this efficiency is strongly influenced by the value of solar irradiation.

1. Introduction

The increasing need for electrical energy has depleted the supply of fossil energy reserves, so it is necessary to use alternative energy sources from new renewable energy as a solution to the fossil energy crisis [1,2]. The use of electrical energy ranges from 15-20 % and shifts to 80-85 % of final energy due to technological developments in the transportation, industrial, household and commercial sectors as users of electric power [3].

In tropical areas, not only solar radiation but ambient temperature is also one of the necessary constraints that must be considered when designing and predicting solar Photovoltaic (PV) module

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performances [4]. Indonesia's geographical location on the equator has the potential to have abundant sources of solar energy [5,6]. Indonesia's geographical location has a positive impact on the potential for new renewable energy (EBT) with photovoltaic technology. However, the design of the photovoltaic module in generating the output power and irradiation and tilt angle have a strong impact on efficiency [7-9]. It is necessary to carry out case studies and analyze the effect of solar irradiation and tilt angle on power output and photovoltaic efficiency of the Unpam Viktor 50 kWp On-Grid Roof Solar Power Plant (PLTS) [10,11], so that it can be ensured that the installed system can operate optimally.

Previous research has been carried out, in 2007 in Hong Kong with the Simulation Method using TRNSYS with Mono-crystalline Photovoltaics at Tilt Angles of 10° and 30° [12]. In 2021 in India, the simulation method uses Pvsyst 7.1.7 with 130 modules of 130 modules of 180 Wp Poly-Crystalline Photovoltaics at a Tilt Angle of 35° [13]. In 2021 in Pakistan with the simulation method using the RETScreen Expert and NASA's POWER website with 380 Wp Photovoltaic with a module efficiency of 19.15 % at a Tilt Angle of 35° [14]. In 2022 in South Africa with the Simulation Method using PVsyst with 300Wp Mono-crystalline Photovoltaic for 7 modules at a Tilt Angle of 0° to 90° [15].

This research is still limited to a simulation, so it is necessary to carry out an experimental study in Indonesia by measuring and calculating 108 modules of Mono-crystalline 485 Wp and an efficiency of 20.6% using Angle Meters, Lux Meters, Solar Surveys and Seaward Testers on installed systems with variations in tilt angle [16]. Measuring solar irradiation using the method of two measuring instruments, tilt angle, Voc and Isc. Calculation of conversion of sunlight intensity to solar irradiation, input-output power and photovoltaic efficiency, without addressing the issue of a highly effective weight of thermal comfort and energy consumption [17].

2. Methodology

2.1 Process Flow

The research phase starts with field observations to obtain specifications and the number of photovoltaic installed. Perform measurements of slope angle, intensity of sunlight, solar irradiation, Voc and Isc. Perform calculations of the conversion of lux to solar irradiation, input power and analysis of conversion results. Perform calculations of output power, and efficiency of photovoltaic.

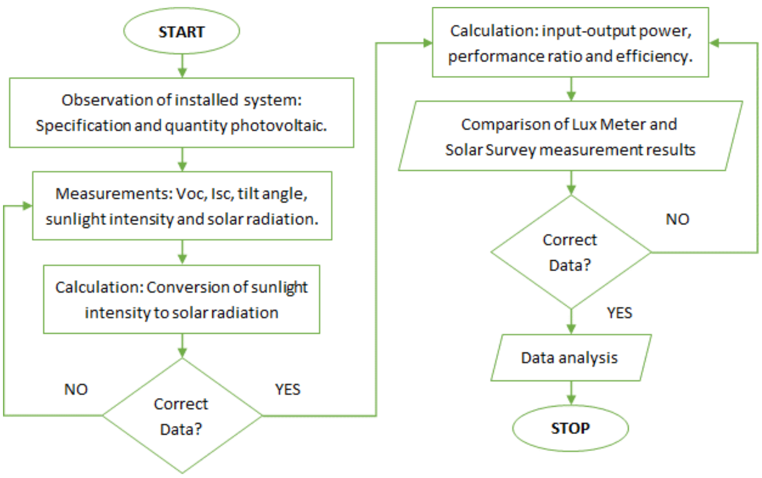


Fig. 1. Research process flow

2.2 Sites

Pamulang University Viktor is located on Jalan Puspiptek, Serpong, Banten, Indonesia. Geographically it is located at coordinates -06.346191°,106.691699° [18].

Fig. 2. Location of PLTS Pamulang University Viktor [18]

2.3. Materials

Observations at the location of the On-Grid 50 kWp Solar Power Plant (PLTS) Unpam Viktor's roof aim to obtain data on the specifications of the installed photovoltaic.

Table 1
HiKu5 Mono PERC CS3Y-485MS [19]

ELECTRICAL DATA | STC*		MECHANICAL DATA	
CS3Y	485MS	Specification	Data
Nominal Max. Power (Pmax)	485 W	Cell Type	Mono-crystalline
Opt. Operating Voltage (Vmp)	44.4 V	Cell Arrangement	156 [2 X (13 X 6)]
Opt. Operating Current (Imp)	10.94 A	Dimensions	2252 X 1048 X 35 mm
Open Circuit Voltage (Voc)	53.1 V	Weight	25.7 kg (56.7 lbs)
Short Circuit Current (Isc)	11.62 A	Front Cover	3.2 mm tempered glass
Module Efficiency	20.6 %	Frame	Anodized aluminium alloy
Operating Temperature	-45°C ~ +85°C	J-Box	IP68, 3 bypass diodes
Max. System Voltage	1500 V or 1000 V	Cable	4 mm^2 (IEC), 12 AWG (UL)
Module Fire Performance	TYPE 1 or TYPE 2	Cable Length	500 mm/350 mm
Series Fuse Rating	20 A	Connector	4 series or H4 UTX or MC4-EVO2
Application Classification	Class A	Per Pallet	30 pieces
Power Tolerance	0 ~ + 10 W	Per Container	600 pieces

Next, prepare a measurement tool, in the form of a Tajima SLT100/-E Angle Meter to measure the tilt angle of the installed photovoltaic.

Table 2
Angle Meter Tajima SLT100-E product description [20]

Product	SLT100-E
EAN	4975364040831
Measuring Range	130° – 0 – 130°

The AS823 Digital Lux Meter is used to measure the intensity of sunlight (Lux) and the measurement results are then converted to solar irradiation (W/m^2).

Table 3
AS823 Digital Lux Meter specification [21]

Model Number	AS823
Description	Lux Meter
Serial Number	6027370
Date of Manufacture	2021-12-30
Measuring Range	1 to 100000 Lux
Sampling Rate	1.5 times/sec
Measurement Repeatability	± 2 %

To ensure that the AS823 Digital Lux Meter measuring instrument has a small error rate, the measuring instrument is calibrated. Calibration determines the accuracy and quality of measurements recorded with the equipment [22].

Table 4
Certificate of calibration smart sensor AS823 Digital Lux Meter [23]

Reference Document	Temperature	RH
JJG245-2005	23 °C ~ 27 °C	50 % ~ 75 %
Normalized Value (Lux)	Actual Value (Lux)	Permissible Error (Lux)
100	99	-1.0
150	153	3.0
200	202	2.0
500	489	-2.0
1000	998	-2.0
1500	1503	3.0
2000	1996	-4.0
3000	3006	6.0

The results of measuring the intensity of sunlight using a AS823 Lux Meter which has been converted to solar irradiation, are then compared with the results of direct measurements of solar irradiation using the Solar Survey 200R.

Table 5
Solar Survey 200R Series Technical Specification [24]

Irradiance	
Display Range	100 – 1500 W/m^2 or 30 – 500 $BTU/hr\text{-}ft^2$
Measurement Range	100 – 1250 W/m^2 or 30 – 400 $BTU/hr\text{-}ft^2$
Resolution	1 W/m^2 or 1 $BTU/hr\text{-}ft^2$

Simultaneously with measuring the intensity of sunlight using a Lux Meter and solar irradiation using Solar Survey, measurements of the open circuit voltage and short circuit current of the photovoltaic were carried out using the Seaward PV200 Tester.

Table 6
PV200 PV Tester electrical specifications [25]

Display Range (Open Circuit Voltage)	0.0 VDC - 1000 VDC
Measuring Range Resolution	5.0 VDC - 1000 VDC
Accuracy Enunciators	0.1 VDC Maximum
Display Range	± (0.5 % + 2 Digits)
Measuring Range Resolution	DC Voltage Polarity Correct or Reversed
Display Range (Short Circuit Current)	0.00 ADC - 15.00 ADC
Measuring Range	0.50 ADC - 15.00 ADC
Maximum Power	10 kW
Resolution	0.01 ADC Maximum
Accuracy	± (1 % + 2 Digits)
Maximum Power Rating	10 kW

2.4 Measurement Methods

Measurement of sunlight intensity using the AS823 Digital Lux Meter [21] in units of lux is then converted to solar irradiation in units of W/m2, then compared with the results of direct solar irradiation measurements using Solar Survey 200R [24] in W/m2 units. Each measurement was taken 7 times from 9:00 AM to 4:00 PM.

Fig. 3. Measurement of lux meter and solar survey

Measurement of the tilt angle using the Tajima SLT100-E Angle Meter [20], to find out how many degrees of tilt the photovoltaic is installed. The results of measuring the tilt angle of the photovoltaic show three tilt angle values, namely: 2°, 4° and 6°.

Fig. 4. Tilt angle measurement

An illustration of the position of the three tilt angles on the photovoltaic installation can be seen in the following figure.

Fig. 5. Illustration of the results of measuring the angle of inclination

2.5 Empirical Methods

The measuring of the intensity of sunlight using the AS823 Digital Lux Meter can be converted into solar irradiation values with 120 Lux equals 1 W/m2 = 0.0083 [26], then:

$$Solar\ Radiation = The\ average\ results\ of\ measuring\ the\ intensity\ of\ sunlight \times 0.0083 \quad (1)$$

Based on the data sheet, the surface area of the photovoltaic is obtained [19]:

$$Solar\ PV\ Module\ Area\ (A) = Long\ Solar\ PV\ Module\ (P) \times Width\ of\ Solar\ PV\ Module\ (L) \quad (2)$$

With the photovoltaic area (A), the amount of input power from the photovoltaic can be calculated:

$$Input\ power\ (P_{in}) = Solar\ Radiation\ Intensity\ (E) \times Solar\ PV\ Module\ Area\ (A) \quad (3)$$

To get the output power value of the photovoltaic, you must first know the value of the fill factor (FF) with variable data sourced from the photovoltaic data sheet [19], then the magnitude of the ill factor (FF):

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (4)$$

Efficiency of the system is determined by the energy input and work in the system [27]. Then calculated using mathematical equations with average measurement results V_{oc} value and I_{sc}. The power output can be expressed as:

$$P_{out} = V_{oc} \times I_{sc} \times FF \quad (5)$$

To get the efficiency value of the solar module using the equation [28]:

$$Efficiency\ (\eta) = \frac{Power\ output\ (as\ electricity)}{Power\ input\ (as\ solar\ radiation)} \quad (6)$$

3. Results

3.1 Comparison of Solar Irradiation

The average of measuring the intensity of sunlight using the AS823 Digital Lux Meter is 86,915 Lux with 120 Lux equals 1 W/m^2 = 0.0083 [19].

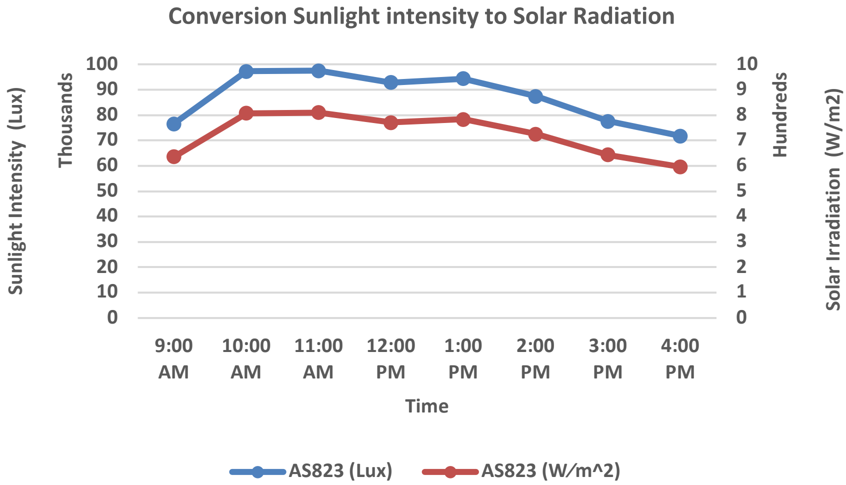


Fig. 6. Conversion sunlight intensity to solar irradiation

The results of converting the intensity of the sun to solar irradiation values are obtained solar irradiation is 721 W/m^2. Meanwhile, the average of solar irradiation measurements using the Solar Survey 200R is 684 W/m^2, it can be seen that comparison of the two results of solar irradiation measurements in the following figure.

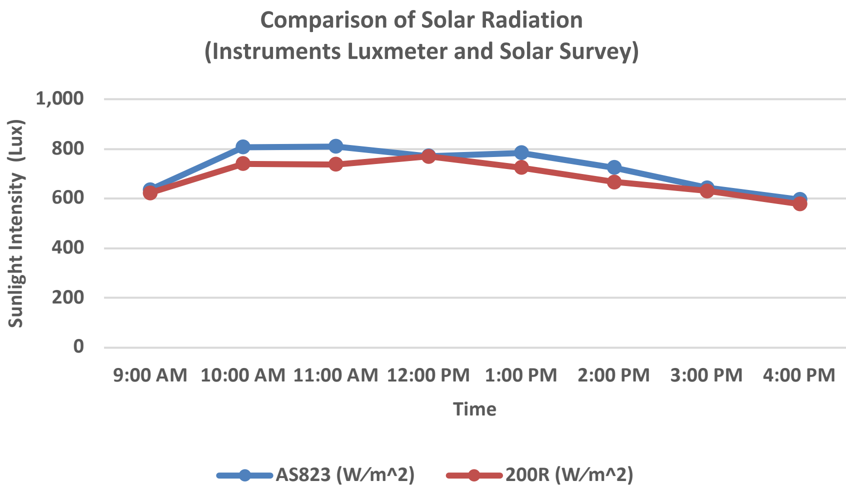


Fig. 7. Comparison of solar irradiation

The results of measuring the intensity of sunlight using the AS823 Digital Lux Meter which has been converted to solar irradiation, only have a difference a measurement error of 0.052 % with the results of direct solar irradiation measurements from the Solar Survey 200R. Thus, the measurement method using both types of measuring instruments can be declared feasible to use.

3.2 Comparison of Input Power

With the photovoltaic area (A) = 2.4 m^2, the amount of input power from the photovoltaic 1.69 kW. To get the output power value of the photovoltaic, you must first know the value of the fill factor (FF) with variable data sourced from the photovoltaic data sheet [11], then the magnitude of the ill factor (FF) is 0.78. The average measurement results open circuit voltage (Voc) value of 47.6 V and a short circuit current (Isc) of 9.1 A, then the power output is 335.99 W.

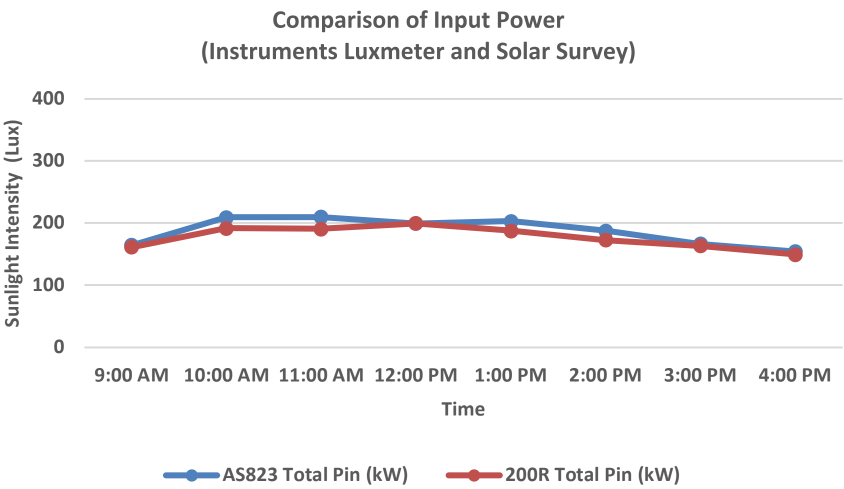
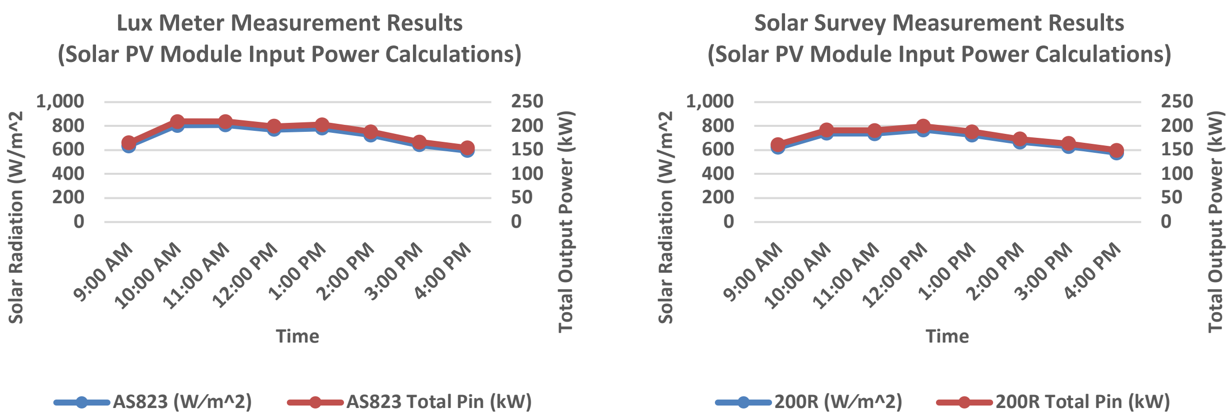


Fig. 8. Comparison of input power

Comparison of the results of calculating the input power of photovoltaic with measurements of solar irradiation using the Lux Meter and Solar Survey has almost the same results with the smallest difference occurring at 12.00 with an input power value of 0.001%.



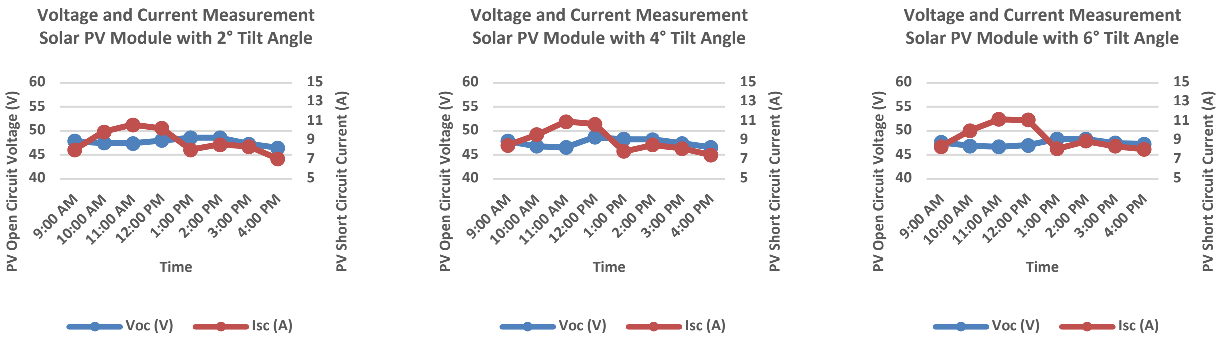
(a) (b)

Fig. 9. Comparison of solar irradiation and input power (a) with luxmeter, (b) with solar survey

The amount of solar irradiation correlates strongly with the power input of the photovoltaic, both in measurements using a lux meter (a) and a solar survey (b).

3.3 Tilt Angle Analysis

To get the value of the Voc and Isc of the photovoltaic, measurements were carried out 7 times at every various angle of inclination using the Seaward PV200 Tester [25].



(a) (b) (c)

Fig. 10. Voltage and current measurement photovoltaic with (a) 2°, (b) 4° (c) 6° tilt angle

If the voltage is low, the current is high and when the voltage is high, the current is low. This is due to the constant load conditions. The occurrence of these voltage changes correlates strongly with the characteristics of the output voltage and current on the photovoltaic which is strongly influenced by the value of solar irradiation received by the photovoltaic.

The fill factor value obtained is 0.78, variations in fill factor values are between 0.6 and 0.8 if the cell has ideal characteristics [29].

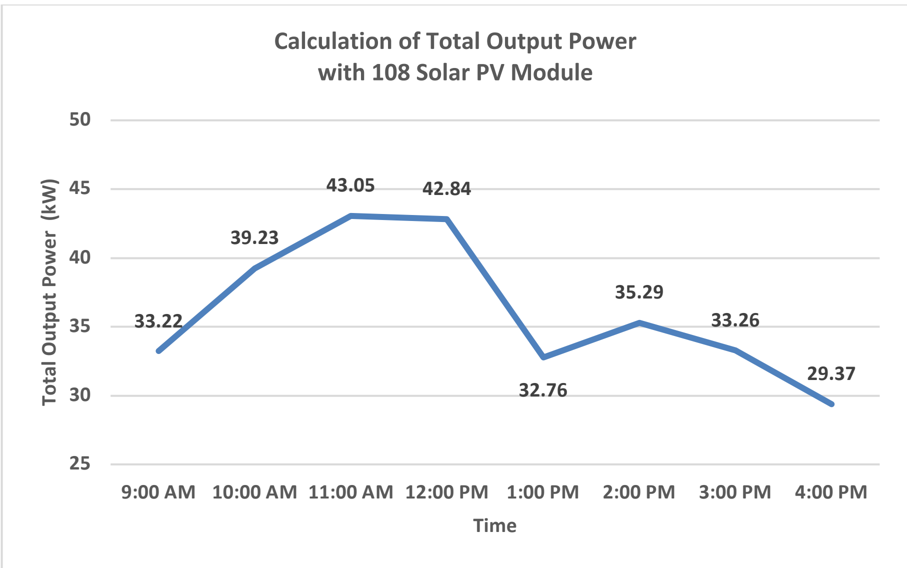


Fig. 11. Total output power photovoltaic with tilt angle variation

The total output power of 108 photovoltaic occurred at 11.00 AM of 43.05 kW. This is influenced by the peak of solar irradiation that hits the photovoltaic at that hour. The total output power of photovoltaic in one day is 289.02 kW.

3.4 Efficiency Analysis
3.4.1 Efficiency of Lux Meter Measurement

The output power is obtained based on the results of measuring voltage and current using a seaward PV200 [25] with a total of 36 kW, while the power input is obtained based on measurements of solar irradiation using a Lux Meter and calculation results with a total of 187 kW.

The efficiency of the photovoltaic based on solar irradiation measurements using a Lux Meter has an efficiency value of 19.3 %, this is better than the efficiency factor of the photovoltaic [19] which is 20.6%.

3.4.2 Efficiency of Solar Survey Measurement

The output power is obtained based on the results of measuring voltage and current using a seaward PV200 [25] with a total of 36 kW, while the power input is obtained based on measurements of solar irradiation using a Solar Survey and calculation results with a total of 177 kW.

The efficiency of the photovoltaic based on solar irradiation measurements using a Solar Survey has an efficiency value of 20.4 %, this is better than the efficiency factor of the photovoltaic [19] which is 20.6%.

4. Conclusions

The value of the intensity of solar lighting can be converted into a value of solar irradiation with 120 Lux equals 1 W/m^2 = 0.0083. Only 5.0 % difference in solar irradiation using the Lux Meter 721 W/m^2 and Solar Survey 684 W/m^2 is a non-significant difference, so both measuring devices are feasible use. In the conditions of the existing photovoltaic tilt angles, the Voc and Isc are measured at 2° of 47.7 V dan 8.9 A, 4° of 47.6 V dan 9.0 A and 6°. of 47.5 V and 9.3 A, this shows that the existing tilt angle variations no significant effect on the photovoltaic output voltage and current. While these values are still within the limits of Voc of 53.1 V and Isc of 11.62 A, this due to the strong correlation of dolar irradiation to the photovoltaic output voltage and current. The difference in efficiency is only 1.1 % with measurements using a Lux Meter of 19.3 % and a Solar Survey of 20.4 %, this value is better than the ideal efficiency value of 20.6 % in conditions of the existing photovoltaic tilt angles are 2°, 4° and 6°. This means that the angle of inclination does not have a significant effect on efficiency, but this efficiency is strongly influenced by the value of solar irradiation.

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