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# Comparison of Predicted and Measured Annual Performance of a Roof-Top Grid-Connected PV System in the Irish Climate

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# COMPARISON OF PREDICTED AND MEASURED ANNUAL PERFORMANCE OF A ROOF-TOP GRID-CONNECTED PV SYSTEM IN THE IRISH CLIMATE

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## ABSTRACT

The problem of energy scarcity has reached a global scale as a result of the majority of energy production relying on non-renewable sources of energy. Solar photovoltaic cells use the photovoltaic effect to convert solar energy into electrical energy. Solar energy can reduce emissions of carbon dioxide ($CO_2$) associated with the generation from fossil fuels as the only $CO_2$ emissions are those embodied in their manufacture. A 268.8 $m^2$ area roof-top grid-connected PV system with a total capacity of 49.92kW$_p$ was installed at Warrenpoint (54.11$^o$N and 6.26$^o$W) in Ireland. 192 "Renesola" PV modules were installed with a nominal peak output of 260Wp and efficiency at standard test conditions (STC) of 18.5%. System outputs were measured at 15-minute intervals over a year. A system simulation was carried out to predict average annual energy yield, average system efficiency, and average system performance ratio.

The system simulation showed that an annual average energy yield of 12,695.2 MJ (3,526.4 kWh) was generated at an average system performance ratio of 85% and average system efficiency of 15.8%. System measurements showed an average annual energy yield of 12,035.8 MJ (3,343.5 kWh) at an average system performance ratio of 85.17% and system efficiency of 15.82%.

The system performance ratio measured was greater than the performance ratio predicted by system simulation by 0.17%. The system's measured efficiency was greater than that given by the system simulation by 0.02%. The average annual energy yield (12,695.2 MJ) predicted by the simulation was greater than the system's measured annual energy yield (12,035.8 MJ) by 659.4 MJ.

**KEYWORDS:**
System simulation, system measurement, system performance ratio, energy yield, photovoltaics, and renewable energy.

## Introduction

The problem of energy scarcity has reached a global scale as a result of the majority of energy production relying on non-renewable sources of energy (Okorieimoh, 2019a). Solar photovoltaic cells use the photovoltaic effect to convert solar energy into electrical energy (Okorieimoh et al., 2020). Solar energy can reduce emissions of carbon dioxide ($CO_2$) associated with the generation from fossil fuels as the only $CO_2$ emissions are those embodied in their manufacture (Norton, 1999). The performance of a PV system is heavily influenced by the meteorological conditions of the site locations, such as solar irradiation and ambient temperature (Shukla et al., 2016c). Transient variation in ambient temperature, wind velocity, shade, and dust reduce the output of PV panels (Okorieimoh et al., 2019b). A PV system must be properly dimensioned to generate continuous energy throughout the year (Chandrakant et al., 2018). This necessitates a thorough investigation to make the best, most efficient, and least expensive decision (Missoum et. al., 2016). The PV system is distinguished by several performance parameters, including energy yield, ambient temperature, and performance ratio (Shukla et al., 2016b).

## Related work

Several research studies on the review of literature on PV system performance investigation have been conducted. For example, Khatib et al. (2013) researched techniques for optimising the size of solar PV systems. As a result, it is critical to conduct a thorough analysis of various site locations to obtain accurate results. Various studies have also been conducted on the performance parameters of installed PV power plants in various geographical site locations and climatic conditions. Messinaa et al. (2014) investigated two 2.4 kWp grid-connected PV systems installed at two distinctly site locations: Tepic and Temixco-Morelos. Their findings revealed that the Temixco-Morelos solar PV system supplied nearly 90% of the electrical energy needed for the house, and they identified grid-connected PV systems as useful in urban and suburban areas. In an evaluation study of the performance of a 10 MW grid-connected solar PV power plant in India, Shiva and Sudhakar (2015) discovered an annual performance ratio of 86.12%. Sharma and Goel (2017) evaluated the performance of an 11.2 kW rooftop grid-connected PV system in Eastern India, resulting in a performance ratio of 78%. Therefore, a study titled “Comparison of Predicted and Measured Annual Performance of a Roof-top Grid-Connected PV System in the Irish Climate” would be carried out to evaluate this. This paper review seeks to find a comparison of predicted (simulated) and measured annual performance of a roof-top grid-connected PV system in the Irish climate with particular emphasis on:

1. The importance of system simulation in achieving a maximum annual PV performance yield.
2. Factors influencing the performance of solar PV systems.
3. The reduction of transient (shading) and degradation effects on solar PV systems.
4. PV modules do not achieve the expected durability and reliability within the 20-25 year warranty periods.

Therefore, this study focuses on comparing the predicted and measured annual performance of a roof-top grid-connected PV system in the Irish climate. The study looked at the importance of forecasting a site location before PV system installations. This is necessary because the output power of PV systems is usually affected by meteorological variables such as humidity, wind speed, solar radiation, and ambient temperature.

## Methodology

### Site Location and Climate Description

A PV examined in this study is located on the Electricity Supply Board (ESB) site at Upper Dromore Road, Warrenpoint, Northern Ireland at 54.11$^o$N latitude and 6.26$^o$W longitude. The installations have a total PV area of 268.8 $m^2$. The location and site-specific information are shown in Figure 1.


Figure 1. Location and Satellite view of ESB site situated at Upper Dromore Road, Warrenpoint, Northern Ireland, UK

Warrenpoint is in a cool-humid with average daily air temperatures ranging from 4.6$^o$C (87.6% relative humidity) in January to 14.5$^o$C (82.4% relative humidity) in July, as shown in Figure 2.

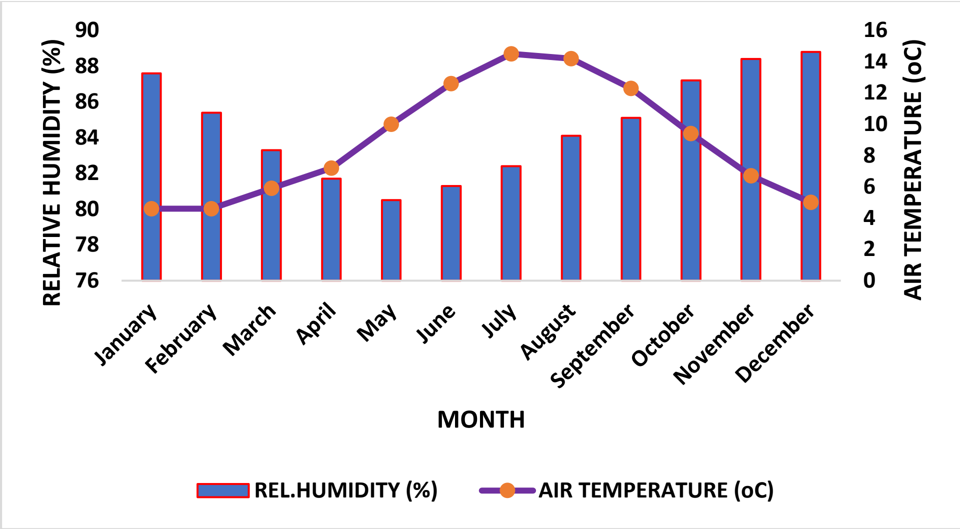
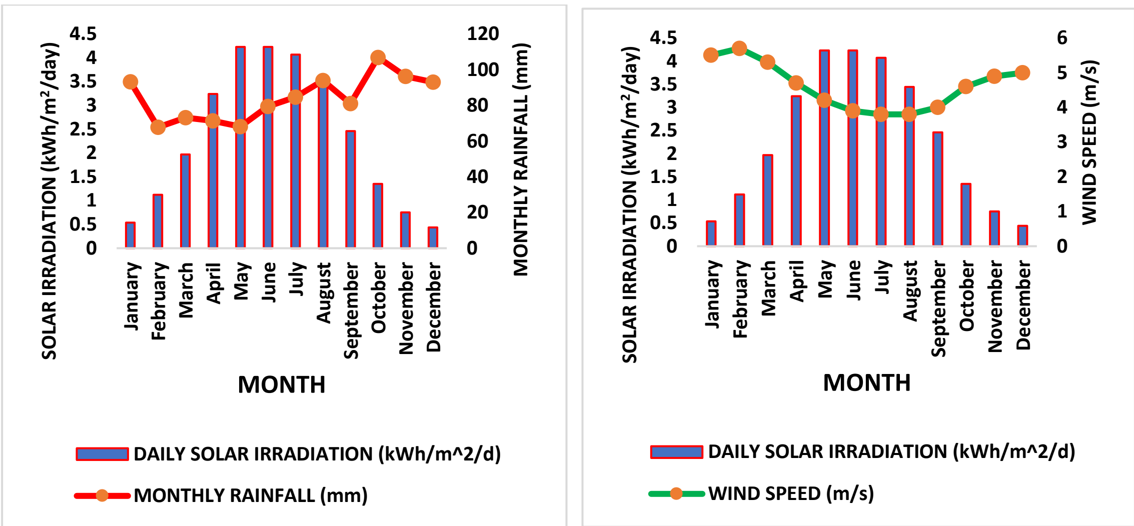



Figure 2. Monthly Average Temperature and Relative Humidity Warrenpoint.

Daily solar irradiation on a horizontal surface in Warrenpoint ranges from 0.44 kWh/m$^2$ in December to 4.23 kWh/m$^2$ in May. Monthly rainfall ranges from a low of 67.76 mm in February to a high of 106.95 mm in October (see Figure 3 (a)). Wind speeds are generally high and range from an average of 3.8 m/s to 5.7 m/s at this location (see Figure 3 (b)) (http://www.nrcan.gc.ca/energy/software-tools/7465).




a. b.

Figure 3. Daily solar irradiation, rainfall, and wind speed for ESB Warrenpoint system site (http://www.nrcan.gc.ca/energy/software-tools/7465).

**System Monitoring and Method of Data Acquisition and Assessment**

The data acquisition system used in this research consists of two sensor boxes and a data logger. The sensor boxes measure the total in-plane solar radiation on the PV modules. The sensor boxes connected to the data logger were recorded at 15 minutes intervals. Quarter-hourly interval data is used because of its homogeneousness with other data used in the analysis of the following:

- Energy output;
- Percentage of energy yield;
- Performance ratio of the system; and
- The efficiency of the system.

**Results and Discussion**

**System Simulations**
PV system simulation is performed using a sunny web design platform (https://www.sunnydesignweb.com/sdweb/#/Home).

Figure 4 shows the simulation of the ESB Murdocks Warrenpoint grid-connected PV system.


Figure 4. The PV system simulation description of a grid-connected solar system of ESB Murdocks Warrenpoint Plant (https://www.sunnydesignweb.com/sdweb/#/Home).

**Cable Sizing**

The power loss of the selected cable size was estimated in Table 5 for DC and low voltage (LV) is 0.16% and 1.15%, respectively, while the medium voltage (MV) recorded no loss. This is in line with the recommendation of SMA Solar Technology AG (www.sunnydesignweb.com) which suggests a relative power loss with a rated operation of less than 1% on the AC or DC side.

Table 5. The power loss of the selected cable sizing (www.sunnydesignweb.com)

| | DC | LV | MV | Total |
|---|---|---|---|---|
| Power loss at nominal operation | 69.62 W | 459.80 W | 0.01 mW | 529.42 W |
| Rel. power loss at rated nominal operation | 0.16% | 1.15% | 0.00% | 1.31% |
| Total cable length | 160.00 m | 30.00 m | 100.00 m | 290.00 m |
| Cable cross-sections | 2.5 mm$^2$ | 6 mm$^2$<br>5.5 mm$^2$ | 150 mm$^2$ | 2.5 mm$^2$<br>6 mm$^2$<br>5.5 mm$^2$<br>150 mm$^2$ |

The electricity generated from the rooftop grid-connected PV system in Figure 4 passes through a transformer and feeds to the grid as shown in Figure 5. From the grid-connection, it is noted that the relative power loss at DC at rated nominal operation is 0.16%, LV shows a relative power loss at the rated nominal operation of 1.15%. In contrast, MV shows no relative power loss at rated nominal operation. The configuration of a 40 W inverter and a copper cable size showing relative power loss at rated nominal operation is shown in Table 1.

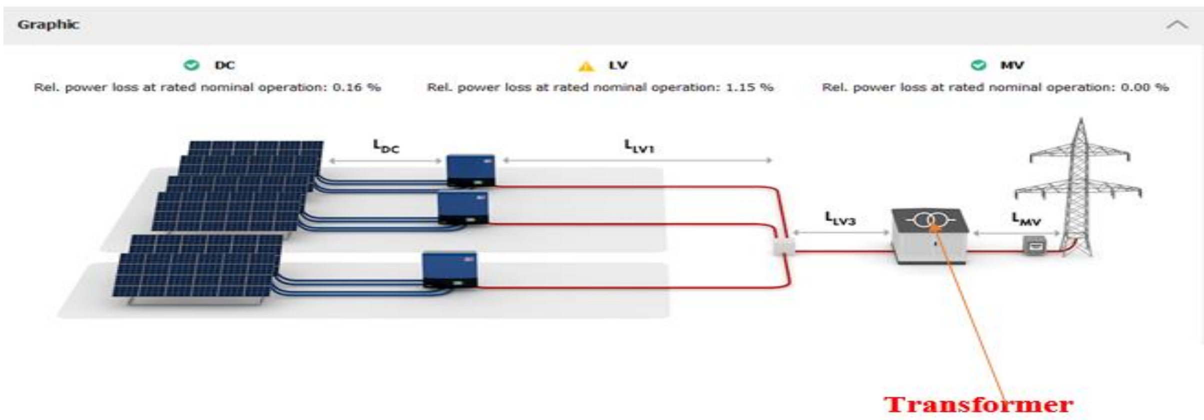



Figure 5. Grid-connected PV systems feed-in electricity to the grid

Table 1. Configuration of inverter and copper cable sizing with relative power loss at rated nominal operation.

| | | Cable material | Single length | Cross section | Cable resistance | Current | Voltage | Voltage drop | Rel. power loss |
|---|---|---|---|---|---|---|---|---|---|
| **ROOF-TOP GRID-CONNECTED SYSTEMS** | | | | | | | | | 0.16 % |
| **Subproject 1** | | | | | | | | | 0.16 % |
| 2 x STP 20000TL-30 PV system section 1 | A | Copper | 10.00 m | 2,5 mm² | R: 0.000 Ω | 7.56 A | 688.72 V | 1 V | 0.15 % |
| | B | Copper | 10.00 m | 2,5 mm² | R: 0.000 Ω | 24.24 A | 688.06 V | 1.1 V | 0.16 % |

Table 2. PV system and Inverter performance

**Inverter**

| Type | 1. PV array 1 48 / 48 | 2. PV array 2 144 / 144 | 3. | Displacement power factor cos φ | Limitation of AC active power |
|---|---|---|---|---|---|
| **2 x STP 20000TL-30** PV system section 1 **PV/Inverter compatible** | A: 1 x 24 | B: 3 x 24 | | 1.00 | 20.00 kW |

**Peak power: 49.92 kWp** **Nominal power ratio: 82 %** **Energy usability factor: 100 %**

**Performance**

Nominal power ratio: 82 %

135 % 70 %

Inverter efficiency: 97.6 %

90 % 100 %

| | |
|---|---|
| Annual energy yield: | 42,317.75 kWh |
| Spec. energy yield: | 848 kWh/kWp |
| Performance ratio: | 86 % |
| Full load hours: | 1057.9 h |
| Line losses (in % of PV energy): | --- % |

**PV/Inverter compatible**

| Parameter | Inverter | Input A | Input B | Input C |
|---|---|---|---|---|
| Max. DC power | 20.44 kW | 6.24 kWp | 18.72 kWp | |
| Min. DC voltage | 150 V | 651 V | 651 V | |
| Typical PV voltage | | 690 V | 690 V | |
| Max. DC voltage (PV) | 1000 V | 976 V | 976 V | |
| Max. operating input current per MPPT | 33/33 A | 7.6 A | 24.2 A | |
| Max. input short-circuit current per MPPT | 43/43 A | 8.0 A | 25.8 A | |

In Table 2, the grid-connected PV system consists of:

(i) PV modules generating power.
(ii) a Maximum Power Point Tracker (MPPT) ensures optimum DC power output (Manju and Sagar, 2017).
(iii) Grid-connected DC/AC inverter to convert DC output to AC power to be fed
(iv) into the power grid as shown in Figure 4 (Laib et al., 2018).

**System Simulation Results**

**Energy Yield and Performance Ratios**

From the results of the simulation, the system performance ratio was 86%, the specific energy ratio was 848 kWh/kW$_p$, and the annual energy output (energy yield) was 42,318 kWh (152,344.8 MJ) giving a $CO_2$ reduction after 20 years as 433 t (see Table 3). From Table 4, the average annual energy yield was 3.526.4 kWh (12.695.2 MJ), the average annual percentage of energy yield was 8.3%, the average annual performance ratio was 85% and the average annual system efficiency was 15.8%. The Specific Energy Ratio ($E_{Specific}$), the Energy Percentage yield (%$E_{yield}$) and the System Efficiency ($\eta_{System}$) of the designed solar PV system are calculated using (1), (2) and (3):

$$E_{Specific} = \frac{Total\ Energy\ Yield}{PV\ Module\ Capacity} \tag{1}$$

$$\%\ E_{yield} = \frac{Energy\ Yield}{Total\ Energy\ Yield} \times 100\% \tag{2}$$

$$\eta_{System} = \eta_{PV\_Module\_STC} \times PR_{System} \tag{3}$$

Where:

Total Energy Yield or annual energy yield is the total number of kilowatts hours (kWh) generated by the grid-connected PV system in a year.

PV Module Capacity is the rated, nominal or maximum capacity of the grid-connected PV system measured under standard test conditions (temperature of 25 °C, solar irradiance 1,000 W/m², and air mass of 1.5).

Energy Yield is the number of kilowatts hours (kWh) generated by the grid-connected PV system in a particular period.

Table 3. Summary of System simulation

| | |
|---|---|
| Total number of PV modules | 192 |
| Peak power | 49.92 kWp |
| Number of PV inverters | 2 |
| Nominal AC power of the inverters | 40.00 kW |
| AC active power | 40.00 kW |
| Active power ratio | 80.1% |
| Annual energy yield | 42,318 kWh |
| Energy usability factor | 100% |
| Performance ratio | 86% |
| Specific energy yield | 848 kWh/kWp |
| Line losses (in % of PV energy) | --- |
| Unbalanced load | 0.00 VA |
| $CO_2$ reduction after 20 years | 433 t |

Table 4. Annual System Simulation Results

| Month | Energy yield [kWh] | Energy yield [MJ] | Energy yield percentage [%] | System performance ratio [%] | System efficiency, $\eta_{System}$ [%] |
|---|---|---|---|---|---|
| January | 908 | 3269 | 2 | 82 | 15.2 |
| February | 1663 | 5987 | 4 | 85 | 15.8 |
| March | 3304 | 11894 | 8 | 87 | 16.2 |
| April | 4973 | 17903 | 12 | 88 | 16.3 |
| May | 6410 | 23076 | 15 | 87 | 16.2 |
| June | 6383 | 22979 | 15 | 87 | 16.2 |
| July | 5954 | 21434 | 14 | 86 | 16.0 |
| August | 5141 | 18508 | 12 | 86 | 16.0 |
| September | 3655 | 13158 | 9 | 86 | 16.0 |
| October | 2201 | 7924 | 5 | 84 | 15.6 |
| November | 1054 | 3794 | 2 | 82 | 15.2 |
| December | 671 | 2416 | 2 | 80 | 14.9 |
| Total | 42,317 | 152,342 | | | |
| Average | 3,526.4 | 12,695.2 | 8.3 | 85 | 15.8 |

## SYSTEM MEASUREMENTS

### System Measurements

The measured system's average annual performance ratio was 85.17%, its specific energy yield was 803.67 kWh/kW$_P$, and its annual energy yield was 40,122 kWh (144,430.1 MJ) (see Table 5). The average annual energy yield was 3,343.5 kWh (12,035.8 MJ), the average annual energy yield percentage was 8.3%, and the average annual system efficiency was 15.82%, according to Table 10.

### Performance Comparison of Measured and Simulated Results

The system simulation and system measurement results show that the measured system performance ratio of the ESB system, $PR_{ESB}$, was 0.17% greater than the performance ratio of the system simulation, $PR_{SysSim}$. In contrast, the measured system efficiency of the ESB system, $\eta_{ESB}$, was 0.02% greater than the system simulation efficiency of the system,$\eta_{SysSim}$.

The annual energy yield (152,342 MJ) from simulation results was greater than the annual energy yield of system measurement (144,430.1 MJ) by 7,911.9 MJ. This long variation in energy yield value is due to the most overcast and cloudy months observed within the site location from December to February as a result of the least amount of solar radiation as opposed to the system simulation, which shows the least energy yield in December (see Figure 6). There are more frequent fluctuations in the performance ratios across the months in system measurements than in system simulations (see Figure 6 and Table 5, 4). The most common causes of these fluctuations were inverter failures and inverter malfunctions.

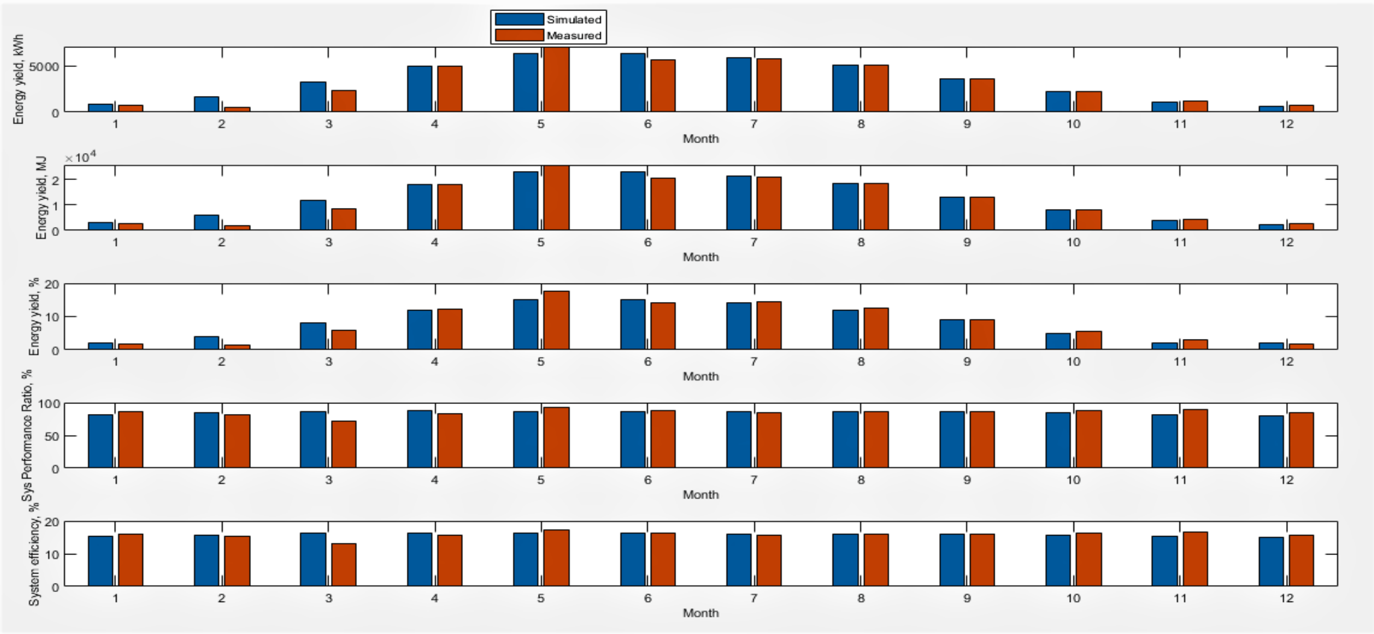



Figure 6. Comparison of measured and simulated performances of ESB Warrenpoint roof-top grid-connected PV system.

Table 5. Measured performance of ESB Warrenpoint PV System

| Month | Energy yield [kWh] | Energy yield [MJ] | Energy yield percentage [%] | System performance ratio [%] | $\eta_{System}$ [%] |
|---|---|---|---|---|---|
| January | 756 | 2720 | 1.88 | 86.5 | 16.1 |
| February | 549 | 1975.3 | 1.37 | 82.0 | 15.2 |
| March | 2373.1 | 8543.1 | 5.92 | 71.0 | 13.2 |
| April | 4945 | 17802.16 | 12.33 | 83.7 | 15.5 |
| May | 7110 | 25595 | 17.72 | 92.0 | 17.1 |
| June | 5724 | 20606.5 | 14.27 | 87.6 | 16.3 |
| July | 5817 | 20940 | 14.50 | 84.3 | 15.7 |
| August | 5081 | 18291 | 12.66 | 85.6 | 15.9 |
| September | 3566.1 | 12838 | 8.90 | 86.8 | 16.1 |
| October | 2239.4 | 8062 | 5.60 | 88.5 | 16.4 |
| November | 1259 | 4531 | 3.14 | 90.0 | 16.7 |
| December | 702 | 2526 | 1.75 | 84.0 | 15.6 |
| Total | 40,122 | 144,430.1 | | | |
| Average | 3,343.5 | 12,035.8 | 8.3 | 85.17 | 15.82 |

**Inverter Percentage Conversion Loss**

When the inverter converts the DC energy from the solar PV system to AC energy, some energy is lost, which could be due to the cable, PV module, or inverter. As shown in Table 6, this is estimated as inverter percentage conversion loss using equation (4) and the values vary according to the number of energy losses from the inverter stated in equation (5).

The percentage conversion loss is calculated as follows (4):

$$\text{Inverter percentage conversion loss} = \frac{DC\ Energy - AC\ Energy}{DC\ Energy} \times 100\% \qquad (4)$$

That is, the inverter efficiency (Mondol et al., 2007):

$$\eta_{\text{inverter}} = \frac{E_{AC}}{E_{DC}} \times 100\% \qquad (5)$$

Where: $\eta_{\text{inverter}}$ is the inverter efficiency that is the ratio of output energy (AC energy) to input energy (DC energy) multiplied by 100%.

Table 6. Monthly DC Energy and AC Energy, inverter efficiency, and percentage conversion loss of quarter-hourly system measurement obtained from the ESB Warrenpoint System.

| Month | DC Energy [MJ] | AC Energy [MJ] | Inverter Efficiency (η) (%) | Inverter Percentage Conversion Loss [%] |
|---|---|---|---|---|
| January | 2763 | 2720 | 98.40 | 1.6 |
| February | 1978.6 | 1975.3 | 99.80 | 0.17 |
| March | 8640.2 | 8543.1 | 98.90 | 1.12 |
| April | 17810.3 | 17802.16 | 99.95 | 0.046 |
| May | 26092 | 25595 | 98.10 | 1.51 |
| June | 20628 | 20606.5 | 99.90 | 0.104 |
| July | 20980 | 20940 | 99.81 | 0.191 |
| August | 18320 | 18291 | 99.84 | 0.158 |
| September | 12990 | 12838 | 98.82 | 1.17 |
| October | 8121 | 8062 | 99.27 | 0.73 |
| November | 4540 | 4531 | 99.80 | 0.2 |
| December | 2540 | 2526 | 99.45 | 0.55 |
| Total | 145,403.1 | 144,430.1 | | |
| Average | 12,116.9 | 12,035.8 | 99.42 | 0.629 |

Therefore, the system simulations' results are compared with the ESB system measurements as outlined in Table 7.

Table 7. Comparing the outcome of system simulations with the ESB system measurement

| System Simulation | ESB System Measurement |
|---|---|
| 1. Average annual system performance ratio of 85%. | Average annual system performance ratio of 85.17%. |
| 2. The specific energy yield is 848 kWh/kWp. | The specific energy yield is 803.67 kWh/kWp. |
| 3. The annual energy yield is 42,317 kWh (152,342 MJ). | The annual energy yield is 40,122 kWh (144,430.1 MJ). |
| 4. The average annual energy yield percentage is 8.33%. | The average annual energy yield percentage is 8.33%. |
| 5. The average annual system efficiency is 15.8% | The average annual system efficiency is 15.82%. |

**Conclusion**

External environmental factors such as humidity, dust accumulation, wind velocity, shading, ambient temperature and operating cell temperature negatively influenced the PV output performance. To avoid these external environmental factors, it is necessary to inspect the proposed geographical location before installing PV systems. This inspection is done through a prediction or simulation study using the geographical location coordinates (longitude and latitude), azimuthal angle, and PV parameters stated on the datasheet. The annual output of the simulation would help to predict if the proposed site location is viable or not. Instead of using standard methods for installing a solar PV system, it is important to consider frequent factors such as wind directions and speeds, which have transient effects on solar PV system output performance.

Also, since the shading effect has the strongest influence on the output power decrease of PV modules, it should be considered during the design phase of PV systems to avoid shading as much as possible.

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