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Measured Performance of a 1.72 kW Rooftop Grid Connected Photovoltaic System in Ireland

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Thank you for your assistance.
Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland

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A B S T R A C T

This paper presents results obtained from monitoring a 1.72 kWp photovoltaic system installed on a flat roof of a 12 m high building in Dublin, Ireland (latitude 53.4°N and longitude 6.3°E). The system was monitored between November 2008 and October 2009 and all the electricity generated was fed into the low voltage supply to the building. Monthly average daily and annual performance parameters of the PV system evaluated include: final yield, reference yield, array yield, system losses, array capture losses, cell temperature losses, PV module efficiency, system efficiency, inverter efficiency, performance ratio and capacity factor. The maximum solar radiation, ambient temperature and PV module temperature recorded were 1241 W/m² in March, 29.5 °C and 46.9 °C in June respectively.

The annual total energy generated was 885.1 kW h/kWp while the annual average daily final yield, reference yield and array yield were 2.41 kW h/kWp/day, 2.85 kW h/kWp/day and 2.62 kW h/kWp/day respectively. The annual average daily PV module efficiency, system efficiency and inverter efficiency were 14.9%, 12.6% and 89.2% respectively while the annual average daily performance ratio and capacity factor were 81.5% and 10.1% respectively. The annual average daily system losses, capture losses and cell temperature losses were 0.23 h/day, 0.22 h/day and 0.00 h/day respectively.

Comparison of this system with other systems in different locations showed that the system had the highest annual average daily PV module efficiency, system efficiency and performance ratio of 14.9%, 12.6% and 81.5% respectively. The PV system’s annual average daily final yield of 2.4 kW h/kWp/day is higher than those reported in Germany, Poland and Northern Ireland. It is comparable to results from some parts of Spain but it is lower than the reported yields in most parts of Italy and Spain. Despite low insolation levels, high average wind speeds and low ambient temperature Ireland’s suitability.

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1. Introduction

Electricity generation in Ireland is largely based on exhaustible fossil fuels such as oil, gas and coal of which imports in 2008 accounted for 90% of all production. World reserves of these fossil fuels are fast diminishing which will inevitably lead to increased energy prices causing serious concerns for Ireland in terms of economic competitiveness and security of supply. It is therefore imperative that economic growth should be decoupled from the existing heavy dependence on fossil fuels. In order to reduce its dependence on fossil fuels, and to play its part in global warming mitigation, Ireland must develop viable renewable energy supply and efficiency policies which are sustainable in the long-term.
In April 2008, the Irish Government announced a new micro and small scale electricity generation programme for Ireland. Fifty pilot trial micro-generation installations were due to be installed in 2009 with an average plant size of 1.25 kWp [5]. This communiqué highlighted the Irish Government’s desire to implement a micro-generation programme. In February 2009, the Irish Government announced the implementation of a feed-in-tariff of 19 € cents per kW h for electricity from micro-generation [6]. For such a programme to be successfully implemented, it is imperative that both field trials to provide information on the annual energy yield of typical installations and studies to determine the economics as well as environmental benefits of PV systems in Ireland be undertaken for informed policy implementation.

The aim of this paper is to present results obtained from field performance monitoring of a 1.72 kW roof mounted PV system in Dublin, Ireland. Data collected between November 2008 and October 2009 was analysed to evaluate the suitability of PV systems for installation in residential buildings in Ireland. The PV system is described while different performance evaluation parameters are presented based on collected data. The performance parameters calculated include: annual energy generated, array yield, final yield, reference yield, PV module, system efficiency, inverter efficiency, performance ratio, capacity factor, array capture losses, system losses and cell temperature losses. Results obtained give an indication of system performance and provide a basis for economic and environmental impact appraisal of PV generated electricity and inform policy formulation to promote uptake of the technology in Ireland. Performance data are compared with those obtained in other locations around Europe and the Middle East.

### 2. The PV system

The PV system was installed on the rooftop of the Focas Institute building, Dublin Institute of Technology, Ireland. It consisted of eight modules covering a total area of 10 m² with an installed capacity of 1.72 kWp within the range of typical domestic installations. The Sanyo HIP-215NHE5 modules were each of 215 Wp capacity and comprised 72 solar cells made of thin mono-crystalline silicon wafer surrounded by ultra-thin amorphous silicon layers. The modules had an efficiency of 17.2% under standard test conditions and were connected in series. The unshaded modules were fixed, inclined at an angle of 53° equal to the latitude of Dublin, facing south at an azimuth angle of 0°. The roof was approximately 12 m high and the modules were mounted on metal frames that were 1 m high.

The PV modules were left uncleared throughout the monitoring period to mimic operation in a domestic dwelling. A single phase Sunny Boy SB 1700 inverter was used to convert DC to AC which was fed directly into the building. The inverter had a rated maximum efficiency of 93.5% and maximum AC power of 1700 W. The solar irradiation sensor had an accuracy of ±8% and a resolution of 1 W/m². The PV module temperature sensor was a JUMO PT 100-U type with accuracy of ±0.5 °C.
A Thies small wind transmitter with accuracy of ±5% was used. Fig. 1 shows pictures of the PV modules and inverter installation. The PV module and array specifications are shown in Table 1 while Table 2 shows the Sunny Boy inverter specifications. The PV system installed cost was €13,200, which consisted of the PV modules, inverter, electrical accessories, support structure and installation. Fig. 2 shows a breakdown of the PV system installed cost.

### 3. Monitoring and data acquisition

The data acquisition system consisted of a Sunny Boy 1700 inverter, Sunny SensorBox and Sunny WebBox. The Sunny SensorBox was used to measure in-plane total solar radiation on the PV modules. Additional sensors for measuring ambient temperature, wind speed and temperature at the back of one of the PV modules were connected to the SensorBox. The SensorBox and inverter were connected to the Sunny WebBox via a serial RS485 link and a Power Injector. Data recorded on 5 min intervals in the WebBox was extracted via an SD card and read directly into a computer.

### 4. Monitoring results

#### 4.1. Weather data

Fig. 3 shows monthly average daily total in-plane solar insolation, long-term in-plane average for Dublin and wind speed.

The data acquisition system monitored the following weather parameters:

- **In-plane solar insolation**
- **Ambient temperature**
- **PV module temperature**
- **Wind speed**
- **Wind direction**

Wind speed and temperature at the back of one of the PV modules were recorded using additional sensors. The data was collected at 5 min intervals and the average was calculated over the monitored period. The monthly average wind speed varied between 2.6 m/s in April and 5.3 m/s in May.

The monthly average ambient temperature varied between 7.4 °C in January and 24.1 °C in June. The annual total measured and long-term in-plane solar insolations were 1043.1 kWh/m² and 1034.5 kWh/m², respectively. The monthly average daily wind speed varied between 2.6 m/s in April and 5.3 m/s in May.

Fig. 4 shows monthly average daily ambient air and PV module temperature over the monitored period. The monthly average ambient temperature varied between 7.4 °C in January and 24.1 °C in June. The annual total measured and long-term in-plane solar insolations were 1043.1 kWh/m² and 1034.5 kWh/m², respectively. The monthly average daily wind speed varied between 2.6 m/s in April and 5.3 m/s in May.
Table 3 shows the fraction of solar radiation, average ambient air temperature, PV module temperature, and wind speed for different levels of solar radiation.

<table>
<thead>
<tr>
<th>In-plane solar radiation (W/m²)</th>
<th>Fraction of solar radiation (%)</th>
<th>Ambient temperature (°C)</th>
<th>PV module temperature (°C)</th>
<th>Wind speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–99</td>
<td>30.3</td>
<td>13.9</td>
<td>14.3</td>
<td>3.6</td>
</tr>
<tr>
<td>100–199</td>
<td>22.6</td>
<td>15.4</td>
<td>17.9</td>
<td>4.1</td>
</tr>
<tr>
<td>200–299</td>
<td>12.8</td>
<td>16.0</td>
<td>20.6</td>
<td>4.3</td>
</tr>
<tr>
<td>300–399</td>
<td>7.9</td>
<td>16.0</td>
<td>22.1</td>
<td>4.5</td>
</tr>
<tr>
<td>400–499</td>
<td>5.9</td>
<td>16.0</td>
<td>23.7</td>
<td>4.7</td>
</tr>
<tr>
<td>500–599</td>
<td>4.9</td>
<td>16.2</td>
<td>25.3</td>
<td>4.7</td>
</tr>
<tr>
<td>600–699</td>
<td>4.2</td>
<td>16.5</td>
<td>27.5</td>
<td>4.8</td>
</tr>
<tr>
<td>700–799</td>
<td>3.8</td>
<td>17.5</td>
<td>30.2</td>
<td>4.7</td>
</tr>
<tr>
<td>800–899</td>
<td>3.8</td>
<td>18.1</td>
<td>33.3</td>
<td>4.4</td>
</tr>
<tr>
<td>900–999</td>
<td>3.0</td>
<td>18.3</td>
<td>34.8</td>
<td>4.6</td>
</tr>
<tr>
<td>1000–1099</td>
<td>0.8</td>
<td>16.8</td>
<td>30.9</td>
<td>5.9</td>
</tr>
<tr>
<td>1100–1199</td>
<td>0.1</td>
<td>16.8</td>
<td>29.5</td>
<td>5.8</td>
</tr>
<tr>
<td>1200–1299</td>
<td>0.0</td>
<td>12.1</td>
<td>29.0</td>
<td>5.8</td>
</tr>
</tbody>
</table>

5. Performance analysis

In order to analyse the energy related performance of a grid connected PV system, some important parameters are to be computed using data collected during its operation in a given location. These parameters include: the total energy generated by the PV system \( E_{AC} \), the array yield \( Y_A \), final yield \( Y_F \), reference yield \( Y_R \), performance ratio \( PR \) and capacity factor \( CF \). These normalized performance indicators are relevant since they provide a basis under which PV systems can be compared under various operating conditions.

5.1. Energy output

The total daily \( E_{AC,d} \) and monthly \( E_{AC,m} \) energy generated by the PV system are obtained as:

\[
E_{AC,d} = \sum_{t=1}^{T-24} E_{AC,t} \quad \text{and} \quad E_{AC,m} = \sum_{d=1}^{N} E_{AC,d}
\]

where \( N \) is the number of days in the month.

The instantaneous energy output was obtained by measuring the energy generated by the PV system after the DC/AC inverter on 5 min intervals. Fig. 6 shows the monthly total energy generated by the PV system over the monitored period which varied between 35.6 kW h/kWp in December and 111.7 kW h/kWp in June. The annual total energy generated by the PV system was 885.1 kW h/kWp. Fig. 7 shows variation of AC power output against solar radiation. It is seen that power output had a linear relationship with solar radiation with a correlation coefficient \( R^2 \) of 0.9929.

5.2. Array yield

The array yield \( Y_A \) is defined as the energy output from a PV array over a defined period (day, month or year) divided by its rated power and is given as [8]:

\[
Y_A = \frac{E_{DC}}{P_{PV,\text{rated}}} \quad \text{(1)}
\]

The daily array yield \( Y_{A,d} \) and monthly average daily array yield \( Y_{A,m} \) are given as [29]:

\[
Y_{A,d} = \frac{E_{DC,d}}{P_{PV,\text{rated}}} \quad \text{and} \quad Y_{A,m} = \frac{1}{N} \sum_{d=1}^{N} Y_{A,d}
\]

5.3. Final yield

The final yield is defined as the annual, monthly or daily net AC energy output of the system divided by the rated or nominal...
The daily final yield \(Y_{F,d}\) and the monthly average daily final yield \(Y_{F,m}\) are given as:

\[
Y_{F,d} = \frac{E_{AC,d}}{P_{PV\text{, rated}}} \quad \text{and} \quad Y_{F,m} = \frac{1}{N} \sum_{d=1}^{N} Y_{F,d}
\]

### 5.4. Reference yield

The reference yield is the total in-plane solar insolation \(H_t\) (kW h/m²) divided by the array reference irradiance (1 kW/m²). It is the number of peak sun-hours and is given as [8]:

\[
Y_R = \frac{H_t}{1 \text{ (kW m}^2\text{)}}
\]

Fig. 8 shows the monthly average daily PV system’s final, reference and array yields over the monitored period. The monthly average daily final, reference and array yields varied between 1.2–3.7 kW h/kWp/day, 1.1–4.6 kW h/kWp/day and 1.3–4.0 kW h/kWp/day in December and June respectively. The annual average daily final, reference and array yields were 2.41 kW h/kWp/day, 2.85 kW h/kWp/day and 2.62 kW h/kWp/day respectively.

### 5.5. PV module efficiency

The instantaneous PV module conversion efficiency is calculated as [11]:

\[
\eta_{PV} = \frac{P_{DC}}{G \times A_{m}}
\]

The monthly PV module efficiency \(\eta_{PV,m}\) is calculated as [7]:

\[
Y_{F,a} = \frac{E_{AC,a}}{P_{PV\text{, rated}}}
\]

### Table 4

Monthly variation of solar radiation, PV module temperature, ambient temperature.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar radiation (W/m²)</th>
<th>PV module temperature (°C)</th>
<th>Ambient temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>(R^2)</td>
</tr>
<tr>
<td>January</td>
<td>2.5</td>
<td>744.9</td>
<td>0.64</td>
</tr>
<tr>
<td>February</td>
<td>0.4</td>
<td>1023.4</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>4.8</td>
<td>1241.9</td>
<td>0.57</td>
</tr>
<tr>
<td>April</td>
<td>6.6</td>
<td>1184.5</td>
<td>0.76</td>
</tr>
<tr>
<td>May</td>
<td>5.8</td>
<td>1173.1</td>
<td>0.66</td>
</tr>
<tr>
<td>June</td>
<td>6.5</td>
<td>1105.9</td>
<td>0.72</td>
</tr>
<tr>
<td>July</td>
<td>6.6</td>
<td>1104.4</td>
<td>0.69</td>
</tr>
<tr>
<td>August</td>
<td>5.5</td>
<td>1153.0</td>
<td>0.64</td>
</tr>
<tr>
<td>September</td>
<td>4.6</td>
<td>1119.6</td>
<td>0.77</td>
</tr>
<tr>
<td>October</td>
<td>6.1</td>
<td>979.7</td>
<td>0.71</td>
</tr>
<tr>
<td>November</td>
<td>5.6</td>
<td>834.1</td>
<td>0.60</td>
</tr>
<tr>
<td>December</td>
<td>3.6</td>
<td>643.8</td>
<td>0.66</td>
</tr>
</tbody>
</table>

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5.6. System efficiency

The instantaneous PV system efficiency is calculated as [11]:

$$\eta_{PV} = \frac{P_{AC}}{P_{DC}}$$

(6)

The monthly system efficiency ($\eta_{sys,m}$) is calculated as [7]:

$$\eta_{sys,m} = \left( \frac{E_{AC,m}}{E_{DC,m}} \right) \times 100\%$$

(7)

5.7. Inverter efficiency

The instantaneous inverter efficiency is calculated as:

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}}$$

(8)

The monthly inverter efficiency ($\eta_{inv,m}$) is calculated as follows [7]:

$$\eta_{inv,m} = \left( \frac{E_{AC,m}}{E_{DC,m}} \right) \times 100\%$$

(9)

5.8. Performance ratio

The performance ratio (PR) indicates the overall effect of losses on a PV array’s normal power output depending on array temperature and incomplete utilization of incident solar radiation and system component inefficiencies or failures. The PR of a PV system indicates how close it approaches ideal performance during real operation and allows comparison of PV systems independent of location, tilt angle, orientation and their nominal rated power capacity [12,13]. The PV system efficiency is compared with the nominal efficiency of the photovoltaic generator under standard test conditions. Performance ratio is defined by the following equations as [14,15]:

$$\text{PR} = \frac{\eta_{sys}}{\eta_{STC}} = \frac{E_{AC}}{P_{DC,STC}} = \frac{E_{AC}}{G_{STC}\eta_{STC}}$$

(10)

where

$$\eta_{sys} = \frac{E_{AC}}{G_{DC}}$$

and

$$\eta_{STC} = \frac{P_{DC,STC}}{G_{STC}}$$

Performance ratio is also defined as a ratio of the final yield divided by the reference yield and it represents the total losses in the PV system when converting from DC to AC. Performance ratio is also expressed as [8,9,16]:

$$\text{PR} = \frac{Y_f}{Y_R} = \frac{E_{real}}{E_{ideal}} = \eta_{deg}\eta_{ideal}\eta_{soil}\eta_{inv}$$

(11)

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5.9. Capacity factor

The capacity factor (CF) is a means used to present the energy delivered by an electric power generating system. If the system delivers full rated power continuously, its CF would be unity. The capacity factor (CF) is defined as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it operated at full rated power \( (P_{\text{PV, rated}}) \) for 24 h per day for a year and is given as [8]:

\[
CF = \frac{Y_{FA}}{24 \times 365} = \frac{E_{AC}}{P_{\text{PV, rated}} \times 8760} = \frac{H_t \times PR}{P_{\text{PV, rated}} \times 8760} \quad (12)
\]

The CF for a grid connected PV system is also given as [17]:

\[
CF = \frac{\text{h/day of "peak sun"}}{24 \text{ h/day}} \quad (13)
\]

Fig. 12 shows variation of monthly average daily performance ratio and the PV system’s capacity factor over the monitored period. The performance ratio varied between 72.3% in February and 91.6% in December and the annual average performance ratio was 81.5%. The monthly average daily capacity factor varied between 5.0% in December and 15.5% in June with an annual average of 10.1%.

5.10. Energy losses

There exist a variety of sources through which energy losses occur in PV systems. These losses affect the performance of PV systems thereby justifying why it is necessary to evaluate these losses using detailed performance monitoring data. Prominent among these losses are: array capture losses, system losses, cell temperature losses, soiling and degradation. Soiling and degradation losses are more difficult to evaluate because they are small effects that occur over large fluctuations in operating conditions and are not be discussed here.

Under real operating conditions the following additional losses could be observed [18]:

- Optical reflection losses due to non-perpendicular irradiance.
- Losses due to low irradiance levels (reduction of form factor and voltage).
- Thermal losses as voltage reduction due to elevated cell temperatures.
- Reduction of output current for irradiance sun spectra with an air mass lower than AM 1.5.
- Shadowing: if a cell is shadowed in a serial string, the output current is limited by the reduced current of the shadowed cell.

- Power conditioning units are very often located in a small building some distance away from the generator. According to literature, the wiring losses from the PV panels to the converters are in the vicinity of 3% for most applications.
- The inverters often have high conversion efficiencies at the rated power input, but for low irradiance levels and low power input the conversion efficiency decreases. Therefore, the average conversion efficiency over a whole day could be considerably lower than the rated one.

5.10.1. Array capture losses

Array capture losses \( (L_c) \) are due to the PV array losses and are given as [8]:

\[
L_c = Y_R - Y_A \quad (14)
\]

5.10.2. System losses

System losses \( (L_s) \) are as a result of the inverter and are given as [8]:

\[
L_s = Y_A - Y_F \quad (15)
\]

5.10.3. Cell temperature losses

As a general rule of thumb, the PV module peak power \( (P_m) \) decreases by 0.3–0.4% for every 1 °C increase in the PV cell temperature above standard test conditions (STC). Losses resulting due to the operating cell temperature varying about the temperature at STC, \( L_t \), are calculated as [19]:

\[
L_t = E_{AT} - E_A \quad (16)
\]

where

\[
E_{AT} = \frac{E_A}{\eta_{item}}
\]

The temperature loss coefficient \( (\eta_{item}) \) is calculated as [8]:

\[
\eta_{item} = 1 - 0.003(T_c - 25)
\]

Fig. 13 shows the monthly average daily capture and system losses over the monitored period. The system losses varied between 0.12 h/day in December and January to 0.32 h/day in May. In November, December and January the PV modules experienced improvements in capture of 0.08 h/day, 0.21 h/day and 0.16 h/day respectively while capture losses varied between 0.12 h/day in December and January to 0.32 h/day in May. The maximum average daily loss due to temperature effect was 0.09 h/day which occurred in June. Due to low average daily module temperatures between November...
and April, there is a positive temperature effect on the PV modules' output. On average there was no net cell temperature loss over the monitored period.

### 5.1.1. Seasonal performance

The seasonal average daily in-plane solar insolation, ambient temperature, module temperature, wind speed, PV module efficiency, system efficiency and inverter efficiency over the monitored period are shown in Table 5. The results show that the maximum seasonal average in-plane solar insolation, ambient temperature, module temperature and inverter efficiency were 3.9 kW h/m²-day, 18.2 °C, 23.4 °C and 91.3% respectively in summer while the maximum wind speed, module efficiency and system efficiency were 4.4 m/s, 15.7% and 13.0% respectively in winter respectively. The minimum seasonal average in-plane solar insolation, ambient temperature, module temperature and inverter efficiency were 1.4 kW h/m²-day, 8.2 °C, 10.0 °C and 86.2% respectively in winter while the minimum module and system efficiency were 14.1% and 12.4% respectively in summer.

The seasonal energy generated, final yield, reference yield, array yield, capture losses, system losses, capacity factor and performance ratio over the monitored period are shown in Table 6. The results show that the maximum seasonal average energy generated, final yield, reference yield, array yield, capture losses, cell temperature losses and capacity factor were 288.8 kW h/kWp, 3.14 kW h/kWp/day, 3.89 kW h/kWp/day, 3.42 kW h/kWp/day, 0.48 kW h/kWp/day, 0.07 kW h/kWp/day and 13.1% respectively in summer while the minimum energy generated, final yield, reference yield, array yield, capture losses, cell temperature losses and capacity factor were 2.41 kW h/kWp, 2.85 kW h/kWp/day, 2.63 kW h/kWp/day, 0.23 kW h/kWp/day, 0.00 kW h/kWp/day, 10.1 kW h/kWp/day and 5.5% respectively in winter.

### 5.1.2. Performance parameters for different building mounted PV systems

Table 7 presents the performance parameters for different building mounted PV systems.

### Notes

- Values represent capture and cell temperature gains.

---

**Table 5**

<table>
<thead>
<tr>
<th>Season</th>
<th>In-plane solar insolation (kW h/m²-day)</th>
<th>Ambient temperature (°C)</th>
<th>PV module temperature (°C)</th>
<th>Wind speed (m/s)</th>
<th>PV module efficiency (%)</th>
<th>System efficiency (%)</th>
<th>Inverter efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1.4</td>
<td>8.2</td>
<td>10.0</td>
<td>4.4</td>
<td>15.7</td>
<td>13.0</td>
<td>86.2</td>
</tr>
<tr>
<td>Spring</td>
<td>3.8</td>
<td>12.6</td>
<td>17.1</td>
<td>4.2</td>
<td>14.9</td>
<td>12.5</td>
<td>89.7</td>
</tr>
<tr>
<td>Summer</td>
<td>3.9</td>
<td>18.2</td>
<td>23.4</td>
<td>4.3</td>
<td>14.1</td>
<td>12.4</td>
<td>91.3</td>
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<tr>
<td>Autumn</td>
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<td>14.0</td>
<td>18.1</td>
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<td>12.7</td>
<td>89.8</td>
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**Table 6**

<table>
<thead>
<tr>
<th>Season</th>
<th>Energy generated (kW h/kWp)</th>
<th>Final yield (kW h/kWp/day)</th>
<th>Reference yield (kW h/kWp/day)</th>
<th>Array yield (kW h/kWp/day)</th>
<th>Capture losses (kW h/day)</th>
<th>System losses (kW h/day)</th>
<th>Cell temp. losses (kW h/day)</th>
<th>Capacity factor (%)</th>
<th>Performance ratio (%)</th>
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<tbody>
<tr>
<td>Winter</td>
<td>122.0</td>
<td>1.31</td>
<td>1.40</td>
<td>1.44</td>
<td>-0.04</td>
<td>-0.05</td>
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<td>84.4</td>
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<tr>
<td>Spring</td>
<td>286.7</td>
<td>3.12</td>
<td>3.75</td>
<td>3.40</td>
<td>0.36</td>
<td>0.28</td>
<td>-0.01</td>
<td>13.0</td>
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<td>Summer</td>
<td>288.8</td>
<td>3.14</td>
<td>3.89</td>
<td>3.42</td>
<td>0.48</td>
<td>0.28</td>
<td>0.07</td>
<td>13.1</td>
<td>79.3</td>
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<tr>
<td>Autumn</td>
<td>187.6</td>
<td>2.06</td>
<td>2.37</td>
<td>2.24</td>
<td>0.12</td>
<td>0.19</td>
<td>0.00</td>
<td>8.6</td>
<td>82.1</td>
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<tr>
<td>Average</td>
<td>2.41</td>
<td>2.85</td>
<td>2.63</td>
<td>0.23</td>
<td>0.22</td>
<td>0.00</td>
<td>10.1</td>
<td>81.5</td>
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**Table 7**

<table>
<thead>
<tr>
<th>Location</th>
<th>PV type</th>
<th>Energy output (kW h/kWp)</th>
<th>Final yield (kW h/kWp/day)</th>
<th>PV module efficiency (%)</th>
<th>System efficiency (%)</th>
<th>Inverter efficiency (%)</th>
<th>Performance ratio (%)</th>
<th>Reference</th>
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<tr>
<td>Crete, Greece</td>
<td>PC-Si</td>
<td>1336.4</td>
<td>2.0–5.1</td>
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<td>67.4</td>
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<td>–</td>
<td>66.5</td>
<td>[13]</td>
</tr>
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<td>Málaga, Spain</td>
<td>1339</td>
<td>3.7</td>
<td>8.8–10.3</td>
<td>6.1–8.0</td>
<td>85–88</td>
<td>64.5</td>
<td>[21]</td>
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<tr>
<td>Jaén, Spain</td>
<td>892.1</td>
<td>2.4</td>
<td>7.8</td>
<td>88.1</td>
<td>62.7</td>
<td>–</td>
<td>[22]</td>
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<td>Algeria</td>
<td>PC-Si</td>
<td>1230</td>
<td>3.4</td>
<td>7.6</td>
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<td>84.8</td>
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<td>[24]</td>
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<td>Calabria, Italy</td>
<td>PC-Si</td>
<td>700–1000</td>
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<td>Ballymena, Northern Ireland</td>
<td>616.9</td>
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<td>7.5–10.0</td>
<td>6.0–9.0</td>
<td>87</td>
<td>60–62</td>
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<td>Warsaw, Poland</td>
<td>A-Si</td>
<td>830</td>
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<td>4.3–5.5</td>
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<td>92–93</td>
<td>60–80</td>
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<tr>
<td>Castile &amp; Leon, Spain</td>
<td>MC-Si</td>
<td>1180</td>
<td>1.4–4.8</td>
<td>13.7</td>
<td>12.2</td>
<td>89.5</td>
<td>69.8</td>
<td>[26]</td>
</tr>
<tr>
<td>Umbertide, Italy</td>
<td>PC-Si</td>
<td>–</td>
<td>–</td>
<td>6.2–6.7</td>
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<tr>
<td>UK</td>
<td>744</td>
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<td>–</td>
<td>–</td>
<td>–</td>
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<td>Livermore, UK</td>
<td>Tiles</td>
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<td>–</td>
<td>72</td>
<td>–</td>
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<tr>
<td>Dublin, Ireland</td>
<td>MC-Si</td>
<td>885.1</td>
<td>2.4</td>
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<td>Present study</td>
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<tr>
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<td>3.2</td>
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<tr>
<td>UK</td>
<td>PC-Si</td>
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<td>–</td>
<td>7.5</td>
<td>–</td>
<td>68.0</td>
<td>–</td>
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<tr>
<td>UK</td>
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<td>–</td>
<td>–</td>
<td>8.4</td>
<td>90–91</td>
<td>59–61</td>
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<td>Italy</td>
<td>A-Si</td>
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<td>–</td>
<td>–</td>
<td>66</td>
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</tr>
<tr>
<td>Germany</td>
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<td>–</td>
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<td>–</td>
<td>–</td>
<td>50–81</td>
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<tr>
<td>Brazil</td>
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<td>–</td>
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<td>Thailand</td>
<td>–</td>
<td>–</td>
<td>2.9–4.0</td>
<td>–</td>
<td>2.9–98</td>
<td>70–90</td>
<td>–</td>
<td>[28]</td>
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**PC-Si**: poly-crystalline silicon, **MC-Si**: mono-crystalline silicon, **A-Si**: amorphous silicon.
The performance ratio varied between 72.3% in February and 91.6% in December and the annual average performance ratio was 81.5%. The monthly average daily capacity factor varied between 5.0% in December and 15.5% in June with an annual average of 10.1%. The system losses varied between 0.12 h/day in December and January and 0.32 h/day in May. In November, December and January the PV modules experienced improvements in capture of 0.08, 0.21 and 0.16 h/day respectively while capture losses varied between 0.12 h/day in October and 0.51 h/day in June. The maximum average daily loss due to temperature effect was 0.09 h/day and occurred in June. The system losses varied between 0.12 h/day in December and January and 0.32 h/day in May. In November, December and January the PV modules experienced improvements in capture of 0.08, 0.21 and 0.16 h/day respectively while capture losses varied between 0.12 h/day in October and 0.51 h/day in June. The maximum average daily loss due to temperature effect was 0.09 h/day and occurred in June.

Comparison of results from this study with those obtained from other studies internationally revealed that the PV system’s annual average daily final yield of 2.4 kW h/kWp/day is higher than those reported in Germany, Poland and Northern Ireland. It is comparable to results from some parts of Spain but it is lower than the reported yields in most parts of Italy and Spain. The PV system has the highest PV module efficiency, system efficiency and performance ratio compared to the other reported systems. Despite low insolation levels, high average wind speeds and low ambient temperature improve Ireland’s suitability.

7. Conclusion

A 1.72 kWp grid connected PV system installed in Dublin, Ireland was monitored between November 2008 and October 2009 and its performance parameters were evaluated on monthly, seasonal and annual basis. Site data during the monitored period showed that annual average daily PV module in-plane solar insolation, ambient temperature, PV module temperature and wind speed were 2.9 kW h/m²/day, 13.3 °C, 17.2 °C and 4.2 m/s respectively.

The monthly total energy generated varied between 35.6 kW h/kWp in December and 111.7 kW h/kWp in June while the annual total energy generated was 885.1 kW h/kWp. The monthly average daily final, reference and array yields varied between 1.2 kW h/kWp/day and 3.7 kW h/kWp/day, 1.1 kW h/kWp/day and 4.6 kW h/kWp/day and 1.3 kW h/kWp/day and 4.0 kW h/kWp/day in December and June respectively. The annual average daily final yield, reference yield and array yield were 2.41 kW h/kWp/day, 2.85 kW h/kWp/day and 2.62 kW h/kWp/day respectively. Low levels of solar insolation during winter resulted in low final yield, the PV module and system efficiencies varied between 13.8% in February and 17.1% in December and 11.3% in February and 14.3% in December respectively. The monthly average daily inverter efficiency varied between 85.4% in December and 91.5% in June and August. The annual average daily module, system and inverter efficiencies were 14.9%, 12.6% and 89.2% respectively.

The performance ratio varied between 72.3% in February and 91.6% in December and the annual average performance ratio was 81.5%. The monthly average daily capacity factor varied between 5.0% in December and 15.5% in June with an annual average of 10.1%. The system losses varied between 0.12 h/day in December and January and 0.32 h/day in May. In November, December and January the PV modules experienced improvements in capture of 0.08, 0.21 and 0.16 h/day respectively while capture losses varied between 0.12 h/day in October and 0.51 h/day in June. The maximum average daily loss due to temperature effect was 0.09 h/day and occurred in June. The system losses varied between 0.12 h/day in December and January and 0.32 h/day in May. In November, December and January the PV modules experienced improvements in capture of 0.08, 0.21 and 0.16 h/day respectively while capture losses varied between 0.12 h/day in October and 0.51 h/day in June. The maximum average daily loss due to temperature effect was 0.09 h/day and occurred in June.


