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

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Measured performance of a 1.72 kW rooftop grid connected photovoltaic system in Ireland

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ABSTRACT

This paper presents results obtained from monitoring a 1.72 kW_p 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/m^2 in March, 29.5 °C and 46.9 °C in June respectively.

The annual total energy generated was 885.1 kW h/kW_p while the annual average daily final yield, reference yield and array yield were 2.41 kW h/kW_p/day, 2.85 kW h/kW_p/day and 2.62 kW h/kW_p/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/kW_p/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 improve Ireland's suitability.

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.

Electricity generation using photovoltaic (PV) systems is important, reliable and has the potential to play a significant role in CO_2 emissions mitigation [1]. It is widely accepted that PV will become one of the major future sources of electricity generation considering the potential for cost reduction of PV systems and grid-parity expected in Southern and Northern Europe around 2020 [2]. Global PV electricity generating technology has sustained an impressive annual growth rate compared with other renewable energy generating technologies. Total global installed capacity of grid connected solar PV was 3.5 GW_p, 5.1 GW_p, 7.5 GW_p and 13 GW_p in 2005, 2006, 2007 and 2008 respectively [3]. Despite this impressive growth, Ireland still lags with virtually little or no installations. In 2008, the cumulative installed PV capacity in Ireland was 0.4 MW_p made up of 0.1 MW_p and 0.3 MW_p of grid-connected and off-grid capacity respectively. The installed photovoltaic power per inhabitant in Ireland was 0.09 W_p/inhabitant while the EU 27 average was 19.2 W_p/inhabitant [4].

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Nomenclature

A_m	PV module area (m^2)
A_a	PV array area (m^2)
AC	alternating current (A)
CF	capacity factor (%)
DC	direct current (A)
E_{AC}	AC energy output (kW h)
$E_{DC,d}$	total daily total DC energy output (kW h)
$E_{AC,d}$	total daily total AC energy output (kW h)
$E_{AC,m}$	total monthly AC energy output (kW h)
$E_{AC,a}$	total annual AC energy output (kW h)
$\bar{E}_{AC,d}$	monthly average daily total AC output (kW h)
$\bar{E}_{DC,d}$	monthly average daily total DC output (kW h)
E_{ideal}	energy generated at rated power (kW h)
E_{real}	energy generated during operation (kW h)
G_{STC}	total solar radiation under standard test conditions (KW/m^2)
G_t	total in-plane solar radiation (W/m^2)
H_t	total in-plane solar insolation (kW h/m^2)
L_c	capture losses (h/day)
L_s	system losses (h/day)
L_T	cell temperature losses (h/day)
P_{AC}	AC power (kW)
P_{DC}	DC power (kW)
$P_{DC,STC}$	DC power under standard test conditions (kW)
$P_{PV,rated}$	PV rated power (kW$_p$)
PR	performance ratio (%)
Y_A	array yield (kW h/kW$_p$)
Y_F	final yield (kW h/kW$_p$)
Y_R	reference yield (kW h/kW$_p$)
η	efficiency (%)

Subscripts

deg	degradation
m	monthly
inv	inverter
PV	photovoltaic module
soil	soiling
sys	system
STC	standard test conditions
temp	temperature

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 kW$_p$ [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 m^2 with an installed capacity of 1.72 kW$_p$ within the range of typical domestic installations. The Sanyo HIP-215NHE5 modules were each of 215 W$_p$ 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 uncleaned 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/m^2. The PV module temperature sensor was a PT 100-M type with accuracy of ±0.5 °C while the ambient temperature sensor was a JUMO PT 100 U type with accuracy of ±0.5 °C. The ane-

Fig. 1. The PV system installation.

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Table 1
PV modules and array specifications.

PV module/array	Specification
Type	Mono-crystalline silicon
Cell efficiency	19.3%
Module efficiency	17.2%
Maximum power (P_{max})	215 W
Maximum power voltage (V_{pm})	42.0 V
Maximum power current (I_{pm})	5.13A
Open circuit voltage (V_{oc})	51.6 V
Short circuit current (I_{sc})	5.61 A
Warranted minimum power (P_{min})	204.3 W
Output power tolerance	+10/−5%
Maximum system voltage (V_{dc})	1000
Temperature coefficient of P_{max}	−0.3%/°C
Module area	1.25 m^2
No. of modules	8
NOCT	45 °C

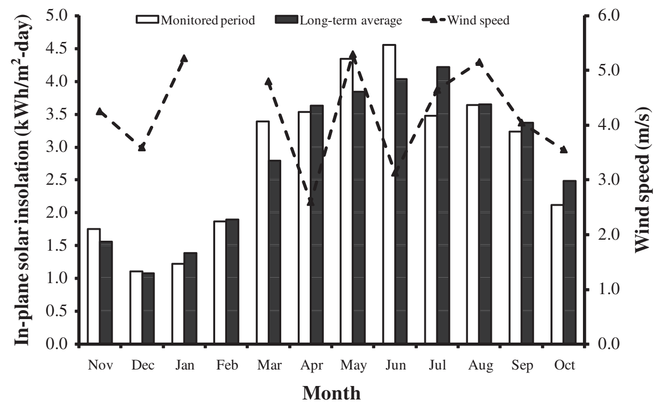

Fig. 3. Monthly average daily total in-plane solar insolation, long-term in-plane average for Dublin and wind speed.

Table 2
Sunny Boy 1700 inverter specifications.

Inverter	Specification
Input	
Maximum dc power	1850 W
Maximum dc voltage	400 V
PV – voltage range at MPPT	139–400 V
Output	
Maximum ac power	1700 W
Nominal ac power	1550 W
Efficiency	
Maximum efficiency	93.5%
Euro-eta	91.8%
Weight	25 kg

mometer was a Thies small wind transmitter with accuracy of ±5%. 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 on the PV modules measured from November 2008 to October 2009. The monthly average daily total solar insolation varied from 1.11 kW h/m^2/day in December to 4.56 kW h/m^2/day in June. These values were slightly higher than the corresponding minimum and maximum long-term monthly average daily values of 1.08 kW h/m^2/day and 4.22 kW h/m^2/day in December and July respectively. The annual total measured and long-term in-plane solar insolations were 1043.1 kW h/m^2 and 1034.5 kW h/m^2 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 temperature and temperature at the back of one of the PV modules over the monitored period. The monthly average ambient temperature varied between 7.4 °C in January and 18.9 °C in August while the PV module temperature varied between 9.9 °C in January and 24.1 °C in June. Wind speed and PV module temperature data for February were not available due to a problem with the SensorBox.

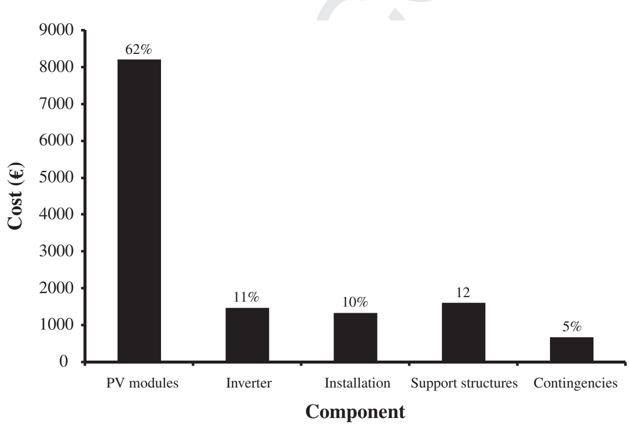

Fig. 2. Cost breakdown of the PV system.

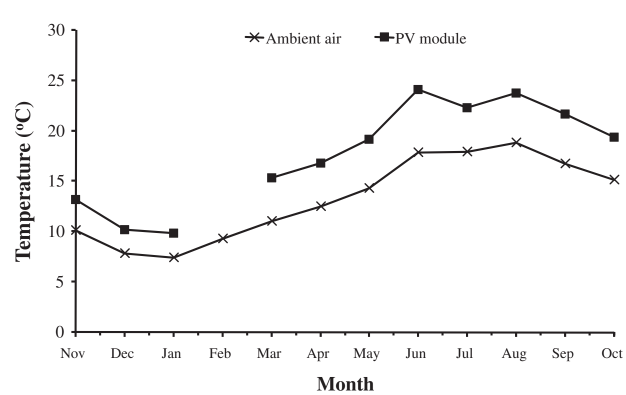

Fig. 4. Monthly average daily ambient air and PV module temperature over the monitored period.

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Table 3
Average ambient air temperature, PV module temperature and wind speed for different levels of solar radiation.

In-plane solar radiation (W/m^2)	Fraction of solar radiation (%)	Ambient temperature (°C)	PV module temperature (°C)	Wind speed (m/s)
0–99	30.3	13.9	14.3	3.6
100–199	22.6	15.4	17.9	4.1
200–299	12.8	16.0	20.6	4.3
300–399	7.9	16.0	22.1	4.5
400–499	5.9	16.0	23.7	4.7
500–599	4.9	16.2	25.5	4.7
600–699	4.2	16.5	27.5	4.8
700–799	3.8	17.5	30.2	4.7
800–899	3.8	18.1	33.3	4.4
900–999	3.0	18.3	34.8	4.6
1000–1099	0.8	16.8	30.9	5.9
1100–1199	0.1	16.8	29.6	5.8
1200–1299	0.0	12.1	29.0	5.8

Table 3 shows the fraction of solar radiation, average ambient air temperature, PV module temperature, and wind speed for different levels of solar radiation between November 2008 and October 2009. The average ambient air temperature varied between 12.1 °C at 1200–1299 W/m^2 and 18.0 °C at 900–999 W/m^2. The average PV module temperature varied between 14.3 °C at 0–99 W/m^2 and 34.8 °C at 900–999 W/m^2. 92.3% of total in-plane solar radiation was below 800 W/m^2 with a maximum average PV module temperature of 22.7 °C in this solar radiation range. This indicates low influence of high PV module temperature on the PV system's performance. Low average ambient temperatures and high wind speeds provided good operating conditions for the PV system by keeping the average PV module operating temperature lower than the standard operating condition temperature.

4.2. PV module temperature

A PT 100 M-type temperature sensor was used to measure the temperature at the back surface of one of the PV modules. Fig. 5 shows the variation of average wind speed, ambient air and PV module temperature against different levels of solar radiation. The ambient air and PV module temperatures are seen to generally increase as the level of solar radiation increases. The PV module temperature experienced a higher increase at solar radiation levels between 600 and 999 W/m^2 as a result of lower average wind speeds at these radiation levels. However, higher average wind speeds at solar radiation levels between 1000 and 1299 W/m^2 caused a drop in PV module temperature.

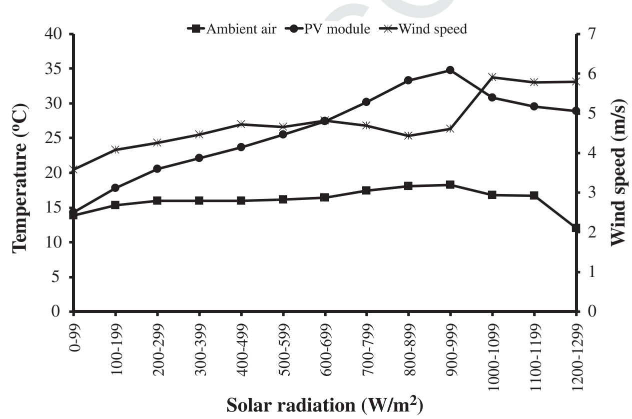

Fig. 5. Average wind speed, ambient air and PV module temperature against different levels of solar radiation over the monitored period.

Table 4 shows monthly ranges variation of solar radiation, PV module temperature, ambient temperature, and the linear correlation coefficient (R^2) between the PV module temperature and the ambient temperature. The average annual R^2 value of 0.67 however, indicated a fairly wide scatter between the values. This scatter band arises from delayed transient temperature responses to insolation changes and variations in wind speed [7]. High wind speeds, low ambient temperatures, the height of the building (over 12 m) on which the PV modules are installed as well as not being roof integrated contributed to lowering the PV module temperature. The maximum temperature difference between the PV module and ambient was 26 °C and occurred at a solar radiation intensity of 791 W/m^2. The maximum PV module temperature recorded was 46.9 °C which occurred when the solar radiation intensity, ambient temperature and wind speed were 977.8 W/m^2, 23.6 °C and 0.92 m/s respectively.

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:

$$E_{AC,d} = \sum_{t=1}^{t=24} E_{AC,t} \quad \text{and } E_{AC,m} = \sum_{d=1}^{N} E_{AC,d}$$

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/kW$_p$ in December and 111.7 kW h/kW$_p$ in June. The annual total energy generated by the PV system was 885.1 kW h/kW$_p$. 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]:

$$Y_A = \frac{E_{DC}}{P_{PV,rated}} \qquad (1)$$

The daily array yield ($Y_{A,d}$) and monthly average daily array yield ($Y_{A,m}$) are given as [2,9]:

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

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

Table 4
Monthly variation of solar radiation, PV module temperature, ambient temperature.

Month	Solar radiation (W/m^2)		PV module temperature (°C)			Ambient temperature (°C)	
	Min	Max	R^2	Min	Max	Min	Max
January	2.5	744.9	0.64	−1.4	27.6	1.0	14.1
February	0.4	1023.4				1.4	15.6
March	4.8	1241.9	0.57	0.4	40.7	2.7	20.7
April	6.6	1184.5	0.76	2.0	41.6	6.0	21.3
May	5.8	1173.1	0.66	4.5	44.6	6.8	23.2
June	6.5	1105.9	0.72	9.0	46.9	10.8	29.5
July	6.6	1104.4	0.69	11.5	41.9	11.9	24.4
August	5.5	1153.0	0.64	10.5	46.4	12.4	27.9
September	4.6	1119.6	0.77	6.7	46.6	9.2	24.0
October	6.1	979.7	0.71	3.5	43.2	6.1	20.9
November	5.6	834.1	0.60	−1.7	37.4	0.6	16.6
December	3.6	643.8	0.66	−3.5	28.0	0.0	13.9

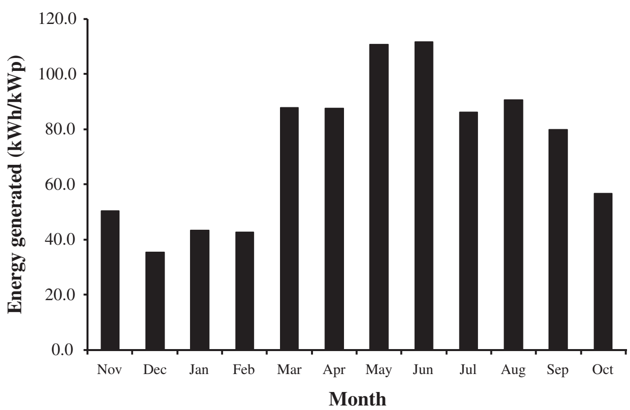

Fig. 6. Monthly total energy generated over the monitored period.

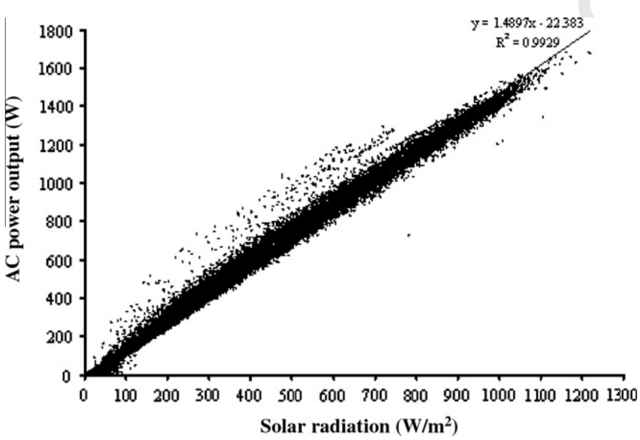

Fig. 7. AC power output against solar radiation.

power of the installed PV array at standard test conditions (STC) of 1 kW/m^2 solar irradiance and 25 °C cell temperature. This is a representative figure that enables comparison of similar PV systems in a specific geographic region. It is dependent on the type of mounting, vertical on a façade or inclined on a roof and also on the location [9]. The annual final yield is given as [8,10]:

$$Y_{F,a} = \frac{E_{AC,a}}{P_{PV,rated}} \tag{2}$$

The daily final yield ($Y_{F,d}$) and the monthly average daily final yield ($Y_{F,m}$) are given as:

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

5.4. Reference yield

The reference yield is the total in-plane solar insolation H_t (kW h/m^2) divided by the array reference irradiance (1 kW/m^2). It is the number of peak sun-hours and is given as [8]:

$$Y_R = \frac{H_t(\text{kW h/m}^2)}{1(\text{kW/m}^2)} \tag{3}$$

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/kW$_p$/day, 1.1–4.6 kW h/kW$_p$/day and 1.3–4.0 kW h/kW$_p$/day in December and June respectively. The annual average daily final, reference and array yields were 2.41 kW h/kW$_p$/day, 2.85 kW h/kW$_p$/day and 2.62 kW h/kW$_p$/day respectively.

5.5. PV module efficiency

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

$$\eta_{PV} = \frac{P_{DC}}{G_t A_m} \tag{4}$$

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

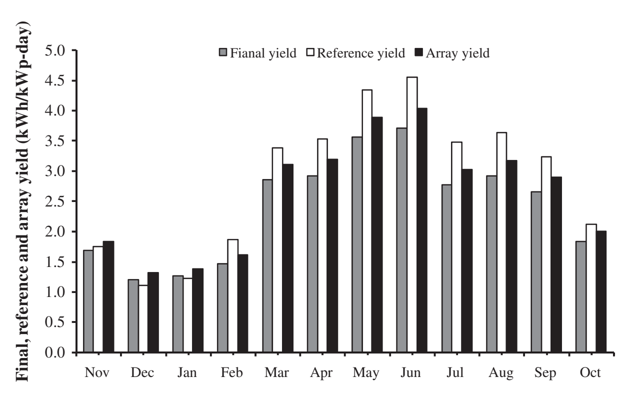

Fig. 8. Monthly average daily PV system's final yield, reference yield and array yield over the monitored period.

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$$\eta_{\mathrm{PV,m}} = \left(\frac{\bar{E}_{\mathrm{DC,d}}}{G_{\mathrm{t}}A_{\mathrm{m}}}\right) \times 100\% \quad (5)$$

5.6. System efficiency

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

$$\eta_{\mathrm{PV}} = \frac{P_{\mathrm{AC}}}{G_{\mathrm{t}}A_{\mathrm{a}}} \quad (6)$$

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

$$\eta_{\mathrm{sys,m}} = \left(\frac{\bar{E}_{\mathrm{AC,d}}}{G_{\mathrm{t}}A_{\mathrm{a}}}\right) \times 100\% \quad (7)$$

5.7. Inverter efficiency

The instantaneous inverter efficiency is calculated as:

$$\eta_{\mathrm{PV}} = \frac{P_{\mathrm{AC}}}{P_{\mathrm{DC}}} \quad (8)$$

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

$$\eta_{\mathrm{inv,m}} = \left(\frac{\bar{E}_{\mathrm{AC,d}}}{\bar{E}_{\mathrm{DC,d}}}\right) \times 100\% \quad (9)$$

Fig. 9 shows the monthly average daily PV module, system and inverter efficiency over the monitored period. The PV module and system efficiency 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 PV module, system and inverter efficiencies were 14.9%, 12.6% and 89.2% respectively.

Fig. 10 shows daily variation of PV module and inverter efficiencies during three days characterized by heavily overcast (10/03/09), clear (20/03/09) and intermittent cloud covered (21/03/09) skies. During the clear sky day, the PV module and inverter efficiency peak during the early hours after sunrise and late hours during sunset. The lowest efficiency occurs at the peak of solar radiation showing the effect of PV cell temperature increase on cell efficiency. During days with heavily overcast sky and intermittent cloud covered sky the PV module and inverter efficiencies show an irregular profile.

Fig. 11 shows variation of inverter efficiency with in-plane solar radiation. The inverter efficiency is seen to increase as the level of solar radiation increases from 0 to 200 W/m^2 and then remains

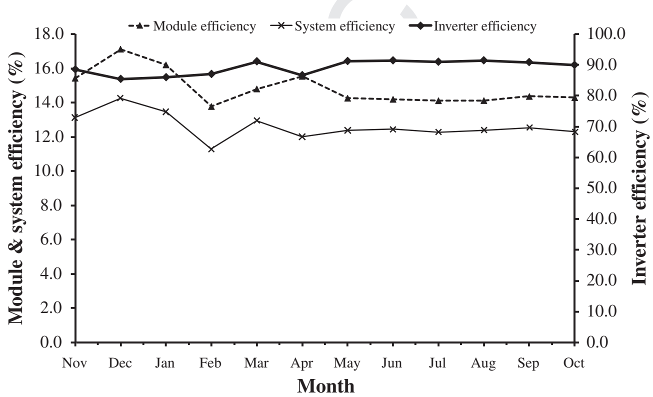

Fig. 9. Monthly average daily PV module, system and inverter efficiency over the monitored period.

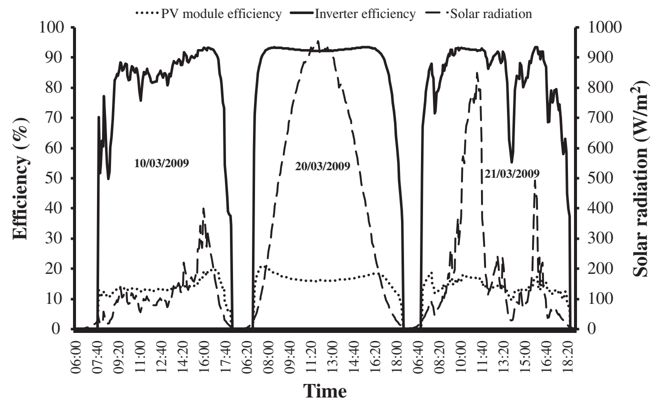

Fig. 10. Daily variation of PV module and inverter efficiency.

fairly constant between 91% and 93%. The maximum inverter efficiency was 94.9% when the solar radiation value was 634.6 W/m^2.

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]:

$$\mathrm{PR} = \frac{\eta_{\mathrm{sys}}}{\eta_{\mathrm{STC}}} = \frac{E_{\mathrm{AC}}}{G_{\mathrm{t}}}\frac{G_{\mathrm{STC}}}{P_{\mathrm{DC,STC}}} = \frac{E_{\mathrm{AC}}}{G_{\mathrm{t}}\eta_{\mathrm{STC}}} \quad (10)$$

where

$$\eta_{\mathrm{sys}} = \frac{E_{\mathrm{AC}}}{A_{\mathrm{a}}G_{\mathrm{t}}} \quad \text{and} \quad \eta_{\mathrm{STC}} = \frac{P_{\mathrm{DC,STC}}}{A_{\mathrm{a}}G_{\mathrm{STC}}}$$

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]:

$$\mathrm{PR} = \frac{Y_{\mathrm{F}}}{Y_{\mathrm{R}}} = \frac{E_{\mathrm{real}}}{E_{\mathrm{ideal}}} = \eta_{\mathrm{deg}}\eta_{\mathrm{tem}}\eta_{\mathrm{soil}}\eta_{\mathrm{inv}} \quad (11)$$

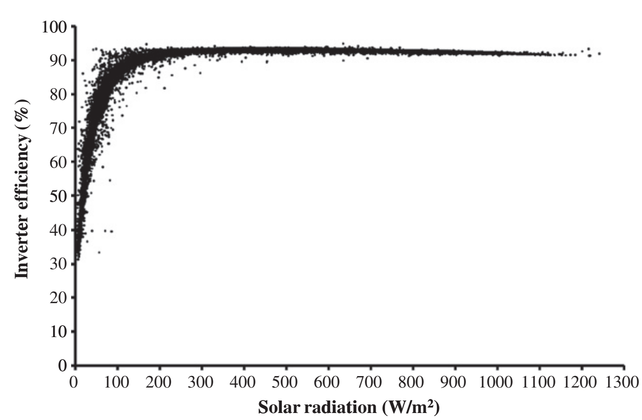

Fig. 11. Inverter efficiency against solar radiation over the monitored period.

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 ($P_{PV,rated}$) for 24 h per day for a year and is given as [8]:

$$CF = \frac{Y_{F,a}}{24 \times 365} = \frac{E_{AC,a}}{P_{PV,rated} \times 8760} = \frac{H_t \times PR}{P_{PV,rated} \times 8760} \quad (12)$$

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

$$E_{AT} = \frac{E_A}{\eta_{tem}}$$

The temperature loss coefficient (η_{tem}) is calculated as [8]:

$$\eta_{tem} = 1 - \beta(T_c - 25)$$

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 October and 0.51 h/day in June. 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

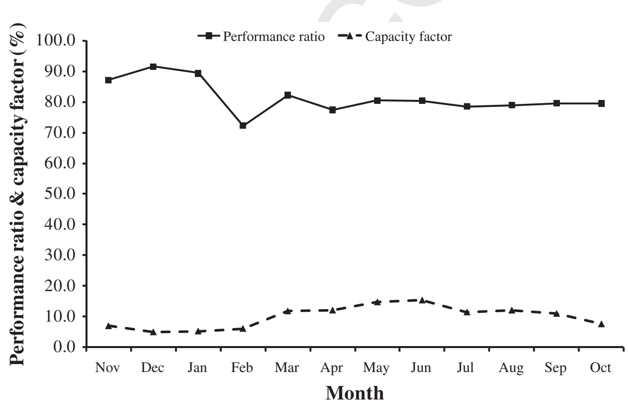

Fig. 12. Monthly average daily performance ratio and capacity factor over the monitored period.

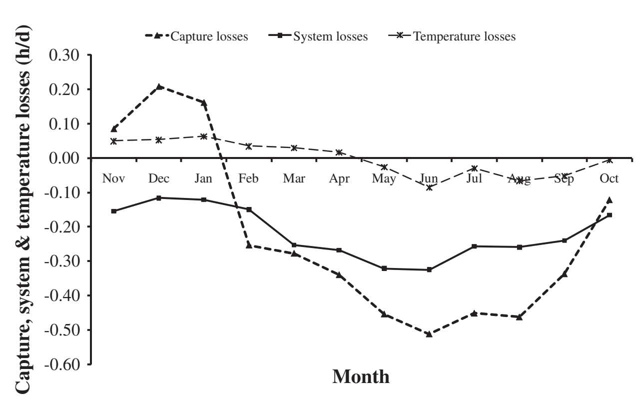

Fig. 13. Monthly daily average capture, system and temperature losses over the monitored period.

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Table 5
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.

Season	In-plane solar insolation (kW h/m^2-day)	Ambient temperature (°C)	PV module temperature (°C)	Wind speed (m/s)	PV module efficiency (%)	System efficiency (%)	Inverter efficiency (%)
Winter	1.4	8.2	10.0	4.4	15.7	13.0	86.2
Spring	3.8	12.6	17.1	4.2	14.9	12.5	89.7
Summer	3.9	18.2	23.4	4.3	14.1	12.4	91.3
Autumn	2.4	14.0	18.1	4.0	14.7	12.7	89.8

Table 6
Seasonal energy generated, final yield, reference yield, array yield, capture losses, system losses, capacity factor and performance ratio over the monitored period.

Season	Energy generated (kW h/kW$_p$)	Final yield (KW h/kW$_p$/day)	Reference yield (KW h/kW$_p$/day)	Array yield (KW h/kW$_p$/day)	Capture losses (h/day)	System losses (h/day)	Cell temp. losses (h/day)	Capacity factor (%)	Performance ratio (%)
Winter	122.0	1.31	1.40	1.44	−0.04*	0.13	−0.05*	5.5	84.4
Spring	286.7	3.12	3.75	3.40	0.36	0.28	−0.01*	13.0	80.1
Summer	288.8	3.14	3.89	3.42	0.48	0.28	0.07	13.1	79.3
Autumn	187.6	2.06	2.37	2.24	0.12	0.19	0.00	8.6	82.1
Average		2.41	2.85	2.63	0.23	0.22	0.00	10.1	81.5

* Values represent capture and cell temperature gains.

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.

5.11. 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/m^2-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% in winter respectively. The minimum seasonal average in-plane solar insolation, ambient temperature, module temperature and inverter efficiency were 1.4 kW h/m^2-day, 8.2 °C, 10.0 °C and 86.2% respectively in winter while the minimum wind speed was 4.0 m/s in autumn and 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/kW$_p$, 3.14 kW h/kW$_p$/day, 3.89 kW h/kW$_p$/day, 3.42 kW h/kW$_p$/day,

Table 7
Performance parameters for different building mounted PV systems.

Location	PV type	Energy output (kW h/kW$_p$)	Final yield (kW h/kW$_p$-day)	PV module efficiency (%)	System efficiency (%)	Inverter efficiency (%)	Performance ratio (%)	Reference
Crete, Greece	PC-Si	1336.4	2.0–5.1	–	–	–	67.4	[8]
Germany		680	1.9	–	–	–	66.5	[13]
Málaga, Spain		1339	3.7	8.8–10.3	6.1–8.0	85–88	64.5	[21]
Jaén, Spain		892.1	2.4	8.9	7.8	88.1	62.7	[22]
Algeria	MC-Si			10.1	9.3	80.7	–	[23]
Calabria, Italy	PC-Si	1230	3.4	7.6	–	84.8	–	[24]
Germany		700–1000	1.9–2.7	–	–	–	–	[15]
Ballymena, Northern Ireland	MC-Si	616.9	1.7	7.5–10.0	6.0–9.0	87	60–62	[10]
Warsaw, Poland	A-Si	830	2.3	4.5–5.5	4.0–5.0	92–93	60–80	[25]
Castile & Leon, Spain	MC-Si	1180	1.4–4.8	13.7	12.2	89.5	69.8	[26]
Umbertide, Italy	PC-Si	–	–	4.0–7.0	6.2–6.7	–	–	[27]
UK		744	–	–	–	–	69	[9]
Liverpool, UK	Tiles	777	–	–	–	–	72	[9]
Dublin, Ireland	**MC-Si**	**885.1**	**2.4**	**14.9**	**12.6**	**89.2**	**81.5**	**Present study**
UK	A-Si	–	–	3.7	3.2	64.5	42.0	[10]
UK	PC-Si	–	–	–	7.5	–	68.0	[10]
UK	–	–	–	–	8.4	90–91	59–61	[10]
Italy	A-Si	–	–	–	–	–	66	[10]
Germany	–	–	–	–	–	–	50–81	[10]
Brazil	A-Si	–	–	–	5	91	–	[10]
Thailand	–	–	2.9–4.0	–	–	92–98	70–90	[28]

PC-Si: poly-crystalline silicon, MC-Si: mono-crystalline silicon, A-Si: amorphous silicon.

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0.48 h/day, 0.07 h/day and 13.1% respectively in summer while the maximum system losses were 0.28 kW h/kW$_p$/day in spring and summer and the maximum performance ratio was 84.4% in winter. The minimum energy generated, final yield, reference yield, array yield, capture losses, system losses, cell temperature losses and capacity factor were 122.0 kW h/kW$_p$, 1.31 kW h/kW$_p$/day, 1.40 kW h/kW$_p$/day, 1.44 kW h/kW$_p$/day, −0.04 h/day, 0.13 h/day, −0.05 h/day and 5.5% respectively in winter while the minimum performance ratio was 79.3% in summer. The negative capture loss in winter represents improvement in capture. The system performance parameters in spring were close to those in summer since both periods had almost the same level of average daily solar insolation. The annual average daily final yield, reference yield, array yield, capture losses, system losses, cell temperature losses, capacity factor and performance ratio were 2.41 kW h/kW$_p$/day, 2.85 kW h/kW$_p$/day, 2.63 kW h/kW$_p$/day, 0.23 h/day, 0.22 h/day, 0.00 h/day, 10.1% and 81.5% respectively.

6. Comparative PV system performance

To be able to compare operating results from different PV systems, the specific yield in kW h/kW$_p$/year is calculated as well as the performance ratio. The full-load hours or the final yield (Y_F) is also a very important factor for comparing PV systems. The full-load hours is the ratio of the yield over a particular time period to the nominal power of the generator. The reference time-frame can be a day, week, month or year and is given as [16]:

$$Y_F = \frac{E_{real}}{P_{PV,rated}} \tag{17}$$

The annual average daily final yield of other monitored PV systems previously reported include: Germany, 1.8 kW h/kW$_p$/day; The Netherlands, 1.8 kW h/kW$_p$/day; Italy, 2.0 kW h/kW$_p$/day; Japan, 2.7 kW h/kW$_p$/day and Israel, 3.5 kW h/kW$_p$/day [20]. Table 7 shows performance parameters for different building mounted PV systems. The annual average daily final yield of the PV system in this study was 2.4 kW h/kW$_p$/day which was higher than those reported in Germany, Poland and Northern Ireland. It is comparable to results from some parts of Spain but it was lower than the reported yields in Italy and southern parts of Spain. The PV system had the highest PV module efficiency, system efficiency and performance ratio compared to the other systems. High wind speeds and low ambient temperature at the test location provided suitable conditions for PV systems.

7. Conclusion

A 1.72 kW$_p$ 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/m^2/day, 13.3 °C, 17.2 °C and 4.2 m/s respectively.

The monthly total energy generated varied between 35.6 kW h/kW$_p$ in December and 111.7 kW h/kW$_p$ in June while the annual total energy generated was 885.1 kW h/kW$_p$. The monthly average daily final, reference and array yields varied between 1.2 kW h/kW$_p$/day and 3.7 kW h/kW$_p$/day, 1.1 kW h/kW$_p$/day and 4.6 kW h/kW$_p$/day and 1.3 kW h/kW$_p$/day and 4.0 kW h/kW$_p$/day in December and June respectively. The annual average daily final yield, reference yield and array yield were 2.41 kW h/kW$_p$/day, 2.85 kW h/kW$_p$/day and 2.62 kW h/kW$_p$/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.

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/kW$_p$/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.

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