PERFORMANCE MONITORING OF BIPV SYSTEMS ON A DEVELOPMENT OF ZERO CARBON HOMES IN SLOUGH, UK

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1. Introduction

We present a report on the performance of the photovoltaic systems installed on a development of ten zero carbon houses in Slough, UK. There are 11 separate PV systems ranging from 4.4 to 10.2 kW_p with a combined capacity of 62.9 kW_p. All systems use Solarcentury C21e photovoltaic roof tiles covering the major part of the roof. The homes were built over summer 2010 and the PV systems were commissioned in September 2010. The PV systems are oriented within ten degrees of due south. Figure 1 shows a graphic of the development. Houses 1-4 are built using timber frame construction while the other properties are masonry construction.

Figure 1 Greenwatt Way development. Houses are numbered clockwise from bottom left.

The PV systems at this development are one of a number installed by SSE on their sites across the UK to help reduce the company's greenhouse gas emissions. The UK PV industry has grown rapidly from a low base since the introduction of a feed-in tariff in 2010 and there is need for continued learning to maximize the effectiveness of PV in the UK.

The monitoring of this site is part of a project between SSE, Solarcentury and the University of Reading (UoR) to enhance the availability of information on the performance of PV across the UK. As part of this process we present performance records based on solar radiation measurements made at the UoR weather station 24 km from the site.

This paper presents a calculation of the performance ratio made using the NREL method (Marion et al. 2005) on the site using remote instrumentation to calculate on-site irradiance. The operational monitoring results are compared to predicted performance assessment made at the design stage. The use of the performance ratio as the main measure of performance allows for intercomparison among the systems at the site and will highlight any operational issues which may arise.

2. Methodology

The aim of this paper is to demonstrate that remotely gathered weather data can be used to monitor the performance of a PV system with a reasonable level of accuracy. There are several points at which errors may be introduced in this process. The key potential sources of error are instrument errors, interpolation errors, diffuse/direct decomposition errors, transposition errors and ground-reflected irradiance error. With the exception of performance prediction which was carried out with PVSyst 5.21, all calculations were performed in MS Excel 2007 or higher.

2.1 Performance prediction

Performance was modelled for a representative 5 kW_p system of the same module technology, layout and orientation as the systems at Chalvey using PVSyst v5.21 with the meteo data for London. Stringing of the systems was as per the PVSyst default settings. As a consequence of design changes prior to construction, some of the PV systems are subject to partial shading which has a strong impact on the performance over winter. These were captured by modelling the system with three near-shading regimes reflecting the shading which is experienced by the various systems on site. In Table 1, these are noted as three shading conditions: 0 for unshaded and 1 & 2 for the two different levels of shed type shading from adjacent properties.

2.2 Radiation data

In this paper, we will use diffuse and direct irradiance data from the weather station at the UoR as the remote data to assess the performance of the PV systems installed on a development of ten zero carbon homes. The homes form a wider research project allowing SSE to develop insight into the impact of UK zero carbon homes regulations on the utility industry, many elements of this research require meteorological data and global horizontal irradiance is measured on site for several purposes. This data has not been used for this assessment due to inconsistencies between the on-site radiation sensor (reference solarimeter) and the UoR instruments (Kipp & Zonen CMP11 pyranometers).

Separate diffuse radiation measurements are not regularly available for the majority of sites across the UK and so, as part of this project the global radiation data from UoR has also been split into diffuse and direct components to assess the performance of this approach for wider applications.

Data from the university was recorded on a sub-hourly basis and converted to hourly datasets before being used for performance analysis. Data points with non-physical values were removed as part of this process.

2.3 Radiation component separation

In order to successfully transpose irradiance from a horizontal plane to an inclined plane, the irradiance must first be split into diffuse and direct components which are transposed in very different ways. There are several well established methods for separating direct and diffuse irradiance based on the clearness index. These use the relationship between the clearness index (the ratio of surface irradiance to the extra-terrestrial irradiance) and the diffuse fraction of the global horizontal irradiance. In this investigation we have used the Reindl decomposition method (Reindl et al. 1990).

2.4 Transposition into an inclined plane

The transposition of the direct and diffuse components must be performed separately before they are recombined with an estimate of ground-reflected irradiance to give the global inclined irradiance. Transposition of the direct component is a simple geometric exercise. For the diffuse component, a number of models exist with the Perez model (Perez et al. 1990) being recognised as performing well, particularly when observed diffuse and direct irradiance values are available. This model treats the diffuse radiation as comprising three elements, an isotropic background with a horizon/zenith brightening term (resulting from Rayleigh scattering effects) and a circumsolar brightening term (from Mie scattering). Ground-reflected irradiance in the plane of the modules has been calculated using a simple isotropic model assuming a fixed albedo value of 0.2.

2.5 Solar production data

Each system has Fronius electronics which are monitored centrally via a Fronius Datalogger.Web. AC energy production is measured on a 15 minute basis and later aggregated to hourly kWh for ease of comparison with weather data. The fiscal meters (Elstar A100) for each system are also read manually on a monthly basis. This is used to calibrate the values recorded by the datalogger and apply correction factors where necessary.

Table 1 System details

System	Capacity (kW_p)	Inverter(s)	Shading condition
House 1	6.2	IG+50, IG15	0
House 2	5.0	IG+50	1
House 3	4.4	IG+50	2
House 4	4.4	IG+50	2
House 5	4.4	IG+50	0
House 6	4.4	IG+50	0
House 7	5.8	IG60	2
House 8	5.8	IG60	2
House 9	6.2	IG+50, IG15	1
House 10	6.2	IG+50, IG15	0
Meeting room	10.2	IG+ 35, IG+ 35, IG 20	0
Overall	62.9		

The specific yield of the systems at Chalvey have been calculated on a monthly basis by aggregating the hourly generation and radiation figures. These specific yields are then divided by the calculated in-plane irradiance (in kW/m^2) to give the performance ratios. As expected, the partially shaded systems perform less well than the unshaded systems and as a consequence have been omitted from some of the results presented in this paper for the sake of clarity.

3. Results

3.1 Performance prediction

All systems on the development have the same basic geometry (oriented south with a tilt of 18°). As there is moderate variation in system size and an associated variation in the inverters, a simplified model representing all the household systems at the development was created with a capacity of 5.1 kW_p. As noted in section 2.4 there are three different shading regimes at the site with a slightly larger gap from house 1-2 and house 10-9 than between houses 2-3-4 and 9-8-7. Three variants of the predictive model were developed to cover these three situations.

Figures 2 & 3 show the monthly predicted and actual irradiance, electricity production and performance ratios. Figure 3 shows the performance ratios predicted on a monthly basis using the representative PVSyst model and the average performance ratio of the unshaded systems. Since April, monthly PR has been close to that which was expected from predictions.

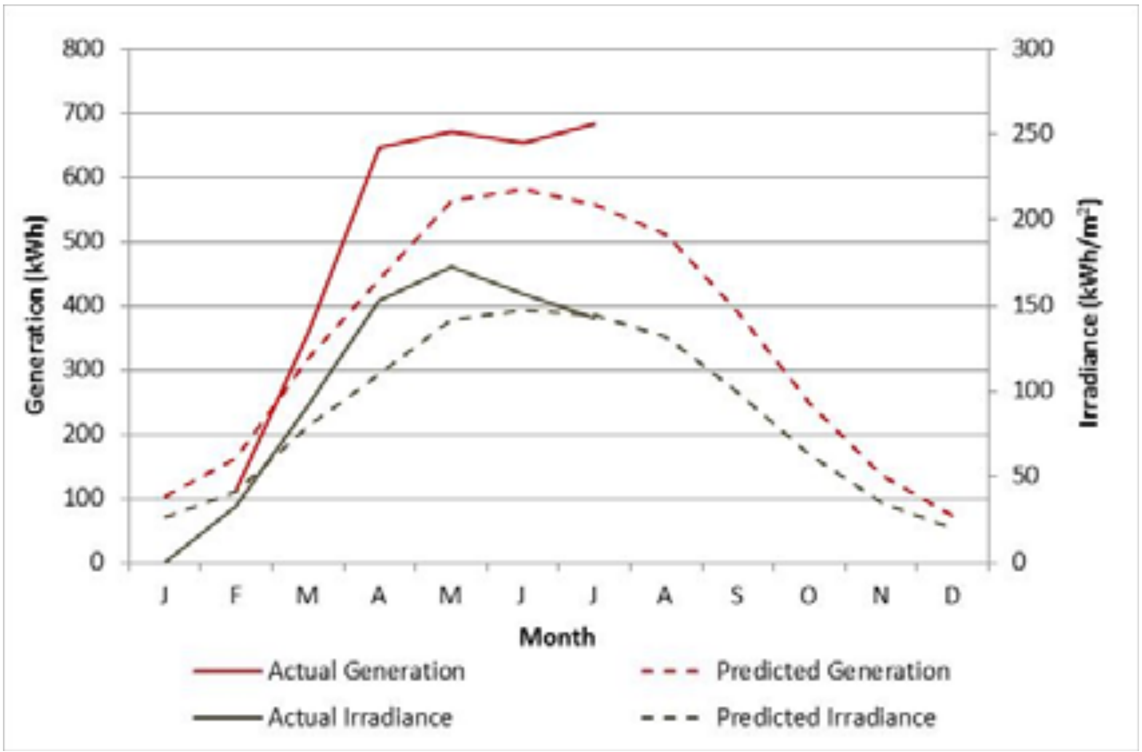

Figure 2 Predicted and observed irradiance and generation for unshaded systems

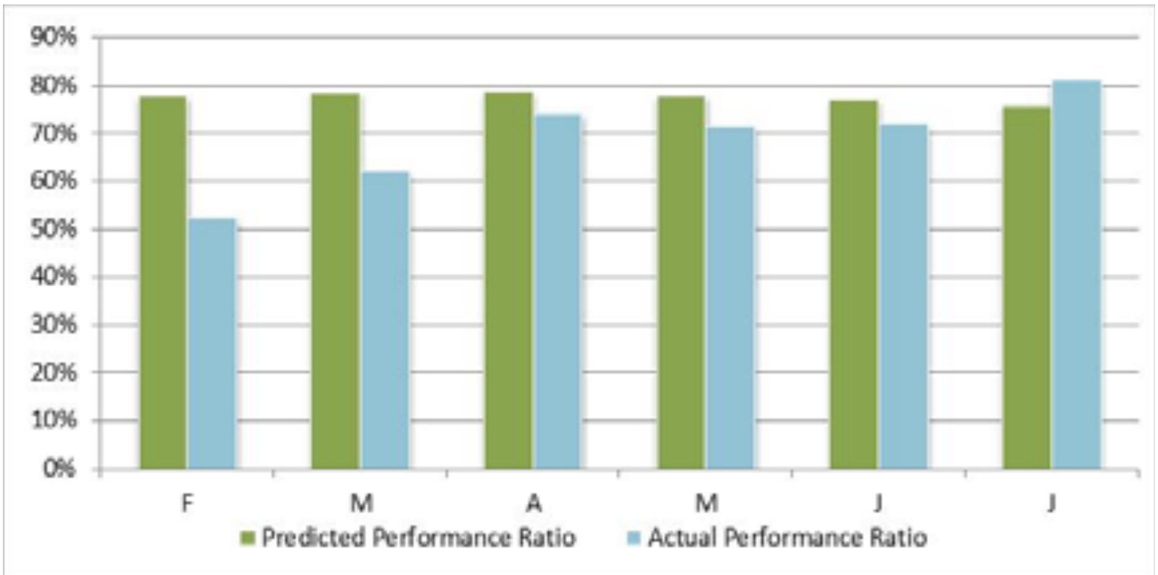

Figure 3 Predicted and actual monthly performance ratios of unshaded systems

3.2 Diffuse radiation component separation and Transposition

As outlined in section 2.2, while the UoR weather station is instrumented to take readings of diffuse radiation as well as global and direct radiation, often this quality of data will not be available. Consequently, it has been deemed necessary to test the accuracy of using a component separation model to allow for similar performance assessment of sites where instrumentation is not available or would be unreasonably costly. Figure 4 shows the relationship between the diffuse fraction of the global horizontal irradiance and the clearness index using measured diffuse irradiance and calculated diffuse irradiance derived using the Reindl model. The falling away of the diffuse fraction for the observed data at low clearness indices is a well-understood artefact of data points corresponding to low sun angles. While the observed data shows much broader variability than the modelled data, the overall shape of the distributions are well matched. Similarly in Figure 5, there is good correlation between the predicted irradiance in PVSyst and the transposed irradiance (data is for 2010) using either the measured or modelled components. The disparities for April, June and August are linked to strong deviations from the typical weather patterns for those months.

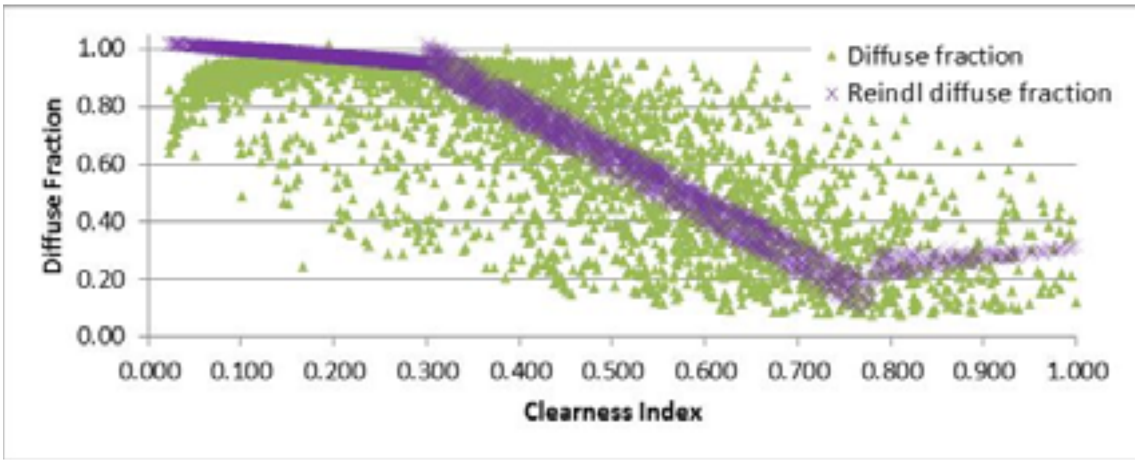

Figure 4 Measured and Modelled diffuse fraction of horizontal radiation (UoR)

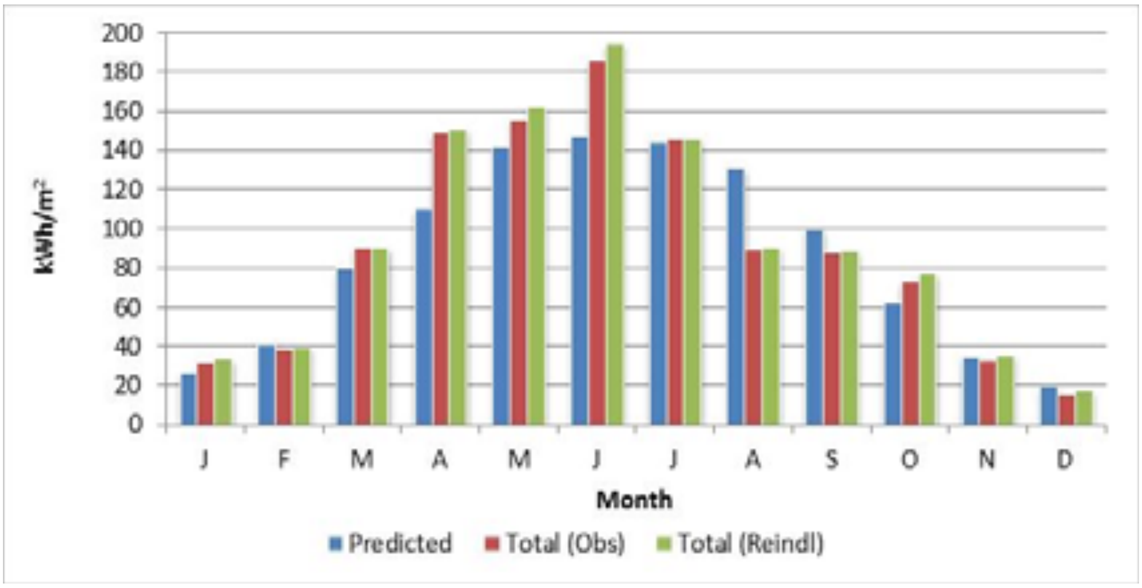

Figure 5 PVSyst prediction and transposed horizontal irradiance for 2010

3.3 Energy Production & Performance Ratios

Over a period of close to a complete year (October 2010 to end July 2011), the eleven systems on site have together generated 38,268 kWh which equates to 608 kWh/kW$_p$. This is less than the 632 kWh/kW$_p$ that was predicted using PVSyst, primarily due to more severe performance impediment over winter months due to shading of systems by adjacent properties. Specific yields for the unshaded systems are presented in Figure 6. The unshaded systems have a specific yield which is within 1% of what was predicted by PVSyst though given the higher than usual irradiance on the site, this reflects a lower performance ratio over the period to date although over the past four months, the observed performance ratio has improved to close to the expected values (Figure 3).

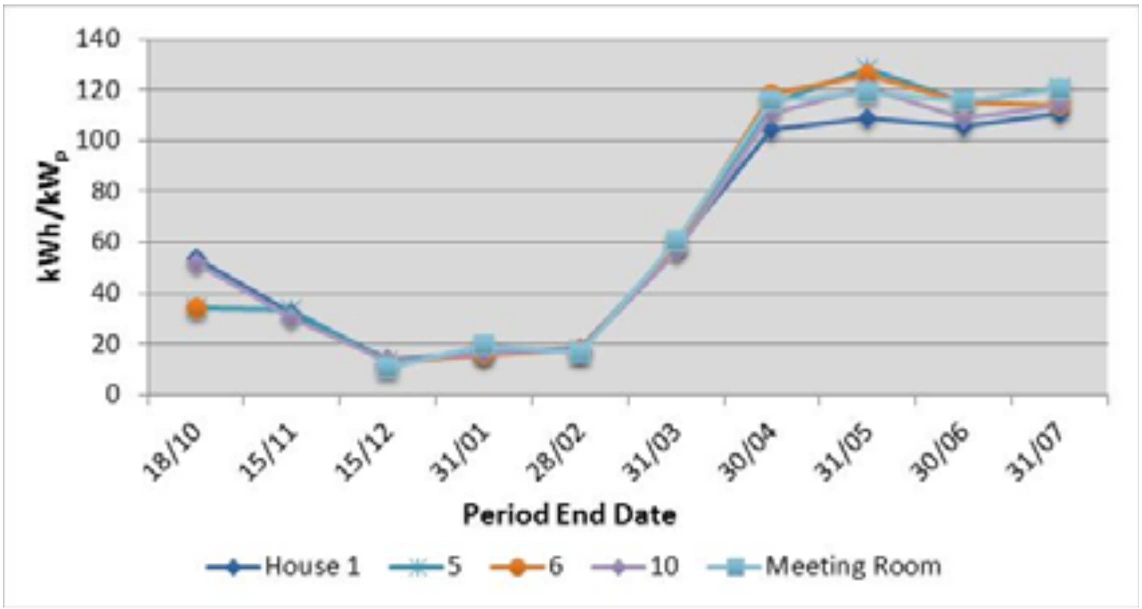

Figure 6 Specific Yield for each unshaded system

As is expected, the systems at the development produced only modest amounts of energy over winter with a substantial increase in generation coming from March onwards. All systems are now attaining performance ratios of over 60% systems and all but two have a PR of over 70%. The data (including the shaded systems) suggests that houses 1 – 4 may have slightly lower performance ratios than their counterparts in houses 7-10. Table 2 shows that no system has an overall PR of more than 71% overall although the evolution of the performance ratio suggests this has improved in recent months with the average PR of the unshaded systems since April being 74.5%. All systems recorded poorer performance ratios over winter. In part, this may result from the lack of correction to the data for days when snow was lying, this may have amounted to approximately one sixth of the period from 15 December 2010 to 31 January 2011. The performance ratio results are only reported here for the calculations based on the measured diffuse dataset from UoR. The Reindl modelled data gave very similar results (overall inclined radiation over the analysis period was 945 kWh/m^2 for the measured diffuse irradiance data versus 959 kWh/m^2 using the Reindl model).

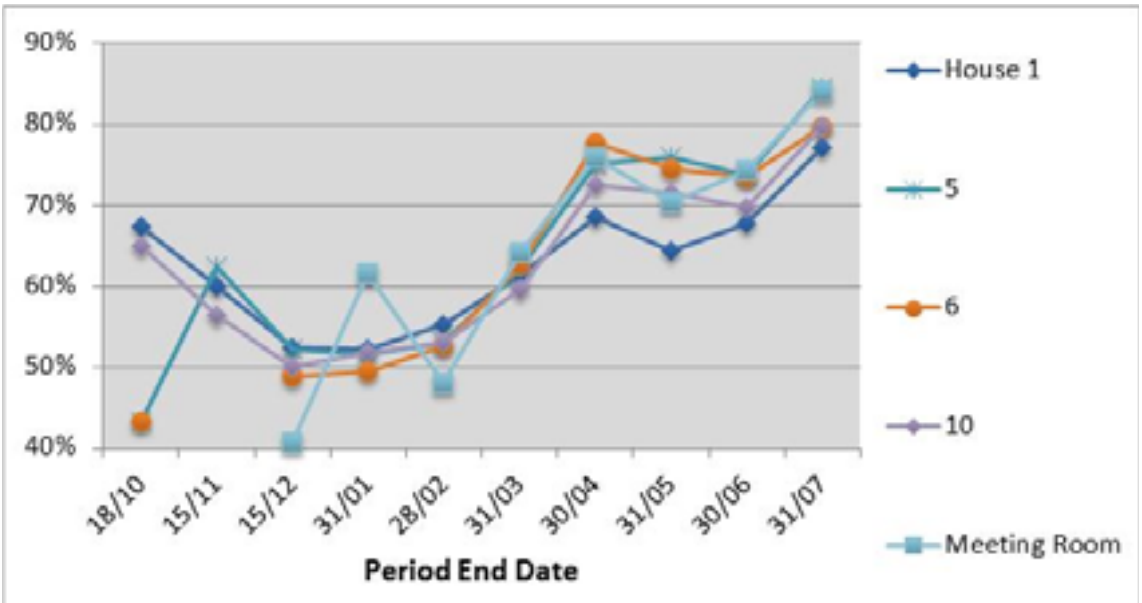

Figure 7 Performance ratio of systems (using UoR Met Data, observed diffuse)

Table 2 Overall unshaded system performance ratios

System	Performance Ratio
House 1	66%
House 5	70%
House 6	65%
House 10	68%
Meeting Room	62%
Average (All unshaded)	66%

4. Discussion

In general, the PV systems at the site have been performing within the range that could be expected. The systems are connected in strings running up and down the roof in keeping with standard practice rather than across the roof which would have been more appropriate for systems which experience the shed type shading seen at this site. This discrepancy was not factored in to the modelling. A second issue which was not addressed by modelling was the possibility that the shaded systems run at higher module temperatures due to lower levels of forced convection as these systems are also sheltered from the wind by the adjacent buildings. Quantifying the size of this effect in a predictive model would require knowledge of the wind conditions at the site and careful CFD modelling which was not available. If these factors were included in the PVSyst model, the difference between the predicted and observed shading impacts may be lessened.

There is a modest performance difference between houses 1-4 and their counterparts in houses 7-10. As a research project, the two banks of houses are of different construction types with houses 1-4 built of a timber frame construction with the remainder of traditional masonry construction. While the homes have slightly different numbers of modules and inverter provision, there may be some environmental element to this discrepancy such as differing levels of thermal mass in the building fabric which merits further investigation to determine if there is any module temperature difference between the roof spaces and modules which can be linked to the structure of the buildings.

Performance ratios of the systems are lower over winter. For the shaded systems it is clear that much of this is a consequence of the shading at low sun angles which make up a greater proportion of the daylight hours over winter than over the summer. A second factor which would affect all systems is the possibility that the Perez transposition model is producing overestimates of the inclined diffuse radiation at low sun angles which would lead to lower PRs, particularly over winter however this effect should be mitigated as the calculations are based exclusively on data points for zenith angles of 80° or less. If an in-plane pyranometer could be installed at the site this would allow both a direct measurement of the radiation received by the systems and also a means of checking the accuracy of the Perez transposition. An alternative radiation issue may be the disparity between the typical meteorological year for London used in the PVSyst model and the irradiation experienced by the systems to date. As monitoring continues in future, should any systems have performance ratios which are consistently lower than predicted on an annual basis, further investigation of the possible causes should be undertaken and where possible remedial action taken.

The results found using both the measured diffuse irradiance and the Reindl modelled diffuse irradiance data as the input to the Perez model produced very similar monthly results however, without an in-plane irradiance meter available at the site, it is not possible to verify the accuracy of the Perez transposition.

5. Conclusions

Performance assessment of the first ten months data for eleven PV systems on a development of zero carbon homes in Slough, UK has been conducted using off-site irradiation data. Performance is similar to what could have been expected based on modelling using PVSyst with unshaded systems having monthly performance ratios in line with expectations since April. The monitoring of this site is ongoing and the findings presented in this paper are based on a short timescale, as the available data increases over time the level of uncertainty in these results will diminish.

The PVSyst model of the systems on the development featured numerous simplifications. It would be worthwhile to repeat this modelling and capture the slight differences between each of the eleven systems and incorporate the string arrangement in order to provide a more representative baseline against which to compare the performance of the systems.

There are several groups of systems which bear identical array layouts and inverters, differing only in building construction type and shading conditions. These sub groups of systems may provide a better means of identifying the differences in performance as nearly all variables are held constant. An example of such a sub-group of identical systems are those on houses 1, 9 and 10 which allows for investigations into the effect of shading between 9 & 10 which will consequently allow for an investigation into the effect of the different system size and inverter provision between houses 2 & 9 which share the same shading regime.

Further work requiring additional pyranometry, temperature and electrical data recording is needed to:

1. confirm the accuracy of the results presented in this paper, particularly the use of the Perez transposition model
2. verify that the use of off-site horizontal radiation data as an input to the performance ratio is a valid approach
3. investigate the influence of construction type and possible temperature consequences on the differences in performance of homes 1 to 4 and 7 to 10.

Another aspect which should be investigated is the relationship of performance differences between systems and wind direction to establish the impact of systems being sheltered by adjacent buildings.

6. References

Marion, B. et al., 2005. Performance Parameters for Grid-Connected PV Systems. In *31st IEEE Photovoltaics Specialists Conference and Exhibition*.

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