MONITORING OF DOMESTIC PV INSTALLATIONS

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MONITORING OF DOMESTIC PV INSTALLATIONS
EXECUTIVE SUMMARY

E.1 INTRODUCTION

The report describes the activities and results of the project “Monitoring of Domestic PV Installations” (Project Ref. S/P2/00319). Data obtained from the monitoring of photovoltaic installations can be used to determine operating factors such as typical system efficiencies, the reliability of components, the effectiveness of maintenance measures and the contribution of the energy supply in meeting the required loads. These factors can, in turn, be used to inform and improve the design and operation of future systems.

The project commenced in April 1999 and was completed in March 2003. The project objectives were as follows:

(a) the identification and selection of suitable PV systems installed on domestic properties in the UK;
(b) the establishment of agreements to monitor the selected systems and the installation of appropriate monitoring equipment;
(c) the collection of performance data over a period of two years for each system;
(d) the development of recommendations regarding design and operation of domestic PV installations as a result of analysis of the collected data.

There were delays in obtaining data from some sites, due to slippage of construction schedules, problems with grid connection and access restrictions due to the foot and mouth epidemic. However, performance data have been obtained for eight individual PV systems at locations around the country. Although it was not possible to obtain two years of data for all sites, a full data set has been obtained for most systems, together with substantial overlap of monitoring periods. In accordance with the requirements of the Department of Trade and Industry and the agreements with the system owners, the system locations and the commercial details of the system components are not identified in the report.

During the course of the project, the Department of Trade and Industry has commenced both the Domestic PV Systems Field Trial and the Major Demonstration Programme, which aim to promote the use of photovoltaics in the domestic sector. This project was a precursor to the Domestic Field Trial and will allow initial results on system performance to be fed back into that programme. In addition, issues identified in this project can be investigated further in the Field Trial projects. Thus, this report provides both information and recommendations on system design and performance in its own right, but also acts as a preliminary study in advance of results of the data analysis from the Field Trial.

E.2 SITE SELECTION

Ideally, the selected sites should include a variety of PV technologies, integration methods and locations, be of a suitable size for extrapolation to other domestic systems and represent the current technology at the time of inception of the project. There should also be sufficient common features to allow inter-comparisons to be made. Whilst this was difficult to achieve fully with a small number of systems, a target mix of systems was outlined. The following list indicates how the selected systems met the original criteria. Criteria 1-3 were considered the most important with the remainder used to refine the choice. The attitude of the owner and their willingness to co-operate with the monitoring programme were also taken into account in the site selection.

- **(i)** **Integration Methods:** The systems should include a mixture of full integration (i.e. replacement of a building component) and add-on systems. Of the final eight systems, 4 of each type were included.
- **(ii)** **Technology:** As far as possible, the systems should include all current cell technologies and a range of module construction. Due to the limited options, only one amorphous silicon system was included, with all other systems based on single crystal silicon cells. Two roof tile systems and one glass/glass module system were included and four manufacturers were represented (some with more than one module type).
- **(iii)** **Electrical System:** Seven of the final systems were conventional grid connected designs as originally intended. The eighth was adapted from a stand alone system and included battery storage, but was also grid connected throughout the monitoring period.
- **(iv)** **System Size:** The system size was required to be in the range 0.5kWp – 5kWp. The eight systems selected range in size from 1.02 to 3.43kWp.
- **(v)** **Time of Installation:** Systems should have been installed no earlier than 1996 and all complied with this requirement. One of the systems was installed during the course of the project.
- **(vi)** **Location:** A range of locations around the UK was desired. It proved difficult to find systems in northern UK locations which also met the other criteria. The most northerly system is located in Yorkshire and the most southerly in south west England.

Table E.1 summarises the details of the eight selected systems. The systems are presented in order of location, from south to north. Systems D, E and G were installed by housing associations and the remaining five were under private ownership.

Table E.1. System Details
(presentation order according to latitude starting with the most southerly location)

System Reference	Region	System Size (kWp)	Module details	System description
A	South West England	1.27	50Wp and 34Wp amorphous silicon laminates	Modules integrated into conservatory roof
B	West of England	3.43	12Wp crystalline silicon roof tiles	Roof integrated system
C	South East England	2.88	120Wp crystalline silicon modules	Roof integrated system
D	South East England	2.2	110Wp crystalline silicon modules	Roof mounted system
E	West of England	1.05	75Wp crystalline silicon modules	Roof mounted system
F	West Midlands	1.02	85Wp crystalline silicon modules	Roof mounted system
G	North West England	1.4	35Wp crystalline silicon roof tiles	Roof integrated system
H	North of England	0.68 (fixed) 0.85 (tracking)	85Wp crystalline silicon modules	Fixed array roof mounted, tracking array free standing

E.3 MONITORING SCHEME

The purpose of the monitoring was to obtain data on the performance of the PV system, including efficiency, performance ratio and total output, including any variations resulting from the specific design of the system. Data were also collected in regard to the energy consumption of the dwelling. The baseline for the specification of the monitoring requirements was the “Testing, Commissioning and Monitoring Guidelines” developed under contract for the DTI.

The requirements for the monitoring equipment can be summarised as follows:

- compliance with monitoring guidelines in terms of measurements to be made and sensor type and accuracy;
- minimum disruption to existing PV systems;
- minimum requirement for action by system owners during the course of the monitoring;
- reliability of data acquisition;
- accommodation of different system designs;

A data logger with modem connection was used to allow remote downloading of the data. As far as possible, the sensors were selected to minimise any disconnection or modification of existing wiring and the same make and type of sensor was used on all sites. Further details of the monitoring equipment are given in the main report.

E.4 PERFORMANCE ANALYSIS

The performance of each system was analysed with respect to the main performance parameters of system efficiency, performance ratio and annual yield. Consideration was also given to climatic data, reliability, loss mechanisms and contribution to building loads. During the course of the project, all system owners were provided with monthly summaries of the performance of their system. These consisted of a data sheet providing performance data for the month, notes on any operational issues, the total monitored output to date and a bar chart of daily output.

Table E.2 provides a summary of some of the calculated performance parameters and a brief discussion of each system is presented below the table. Further explanation of the values and performance issues are included in the main report together with detailed discussions for each system.

E.5 COMPARISON WITH SYSTEM SIMULATION

The performance parameters derived from the measured data for several systems were compared with the results of system simulation. In this case, average insolation values for the array planes were obtained from Meteonorm (Version 3) and system simulations were performed using PVSyst 3.1. Both these software packages are used extensively by the PV community in the design of systems and for output predictions. The comparison considered horizontal and in-plane insolation, annual yield, system efficiency and performance ratio.

Table E.2 Summary of performance parameters

System Reference	**Average system efficiency (%)**	**Average performance ratio**	**Annual yield for stated year (kWh/kWp)**	**Monitoring period (months)**
A	3.5	0.6	679 (2001) 668 (2002)	27 (after change of inverter)
B(1)	6.5	0.65	692 (2002)	21
C	8.3	0.68	639 (2002)	19
D	9.3	0.74	639 (2001) 534 (2002) (2)	25
E(3)	8.4	0.71	747 (2001)	22
F	10.4	0.77	857 (2001) 844 (2002)	25
G	6.5	0.73	n/a	1
H (fixed) H (tracking)	6.5 8.6	0.48 0.64	438 (2002) 606 (2002)(4)	12

(1) System B had an inverter failure in the summer of 2002 which reduced the performance values significantly. The efficiency and performance ratio averages discount this period and the yield is a predicted value, assuming operation of the inverter over this period (measured yield 423kWh/kWp).

(2) System D suffered a data storage problem in April 2002 so the yield figure for 2002 is reduced. Since insolation measurements were not available for this period, a predicted value has not been calculated.

(3) System E also suffered from inverter failures (see further discussion below) and, as for B, the performance parameters have been corrected to show the system performance when operating properly. The yield value is predicted. The measured values for the parameters were 6.9%, 0.58 and 555kWh/kWp.

(4)The annual yield is reduced due to a tracking fault for several months.

System simulations were carried out for Systems A, B, C (south facing array), D and F. System E experienced several problems with inverter trips and, whilst it is possible to predict the output values for these periods, it requires several assumptions to be made. Therefore, it was not felt to be suitable to include this system in the simulations. There is insufficient data for System G and System H is too complex to be simulated in a conventional package.

In general, PVSyst used lower values of horizontal insolation than Meteonorm and these were more consistent with the measured data. There was also considerable variation between selectable sites for Meteonorm, whereas the measured data showed a high level of consistency across the system sites.

Table E.3 Main results from performance simulation using PVSyst.

System	**A**	**B**	**C**	**D**	**F**
Measured annual yield (kWh/kWp)	668	733	639	538	844
PVSyst annual yield	755	812	835	800	846
Measured yield corrected to PVSyst insolation level	665	649	680	620	801
Measured system efficiency (%)	3.6	6.5	8.5	9.3	10.3
PVSyst system efficiency	4.1	8.2	9.7	10.0	10.5
Measured performance ratio	0.61	0.65	0.69	0.73	0.76
PVSyst performance ratio	0.68	0.79	0.79	0.79	0.78

Notes to Table 13:

- For System B, the measured annual yield has been calculated for May 2001 – Apr 2002 since the system was not operational in the summer of 2002.
- For System D, the measured annual yield has been calculated using a corrected output for April 2002 to allow for the low monitoring fraction in this month.

With the exception of System F, the measured values of system performance were significantly lower than those predicted by PVSyst. This implies that there are system losses that are not taken into account in the simulation as discussed below. PVSyst takes into account losses of around 3% for cabling and bypass diodes, 2% for module mismatch (assuming operation at maximum power point rather than fixed voltage) and 3% on module quality (i.e. modules being below the nominal rating although within the allowed tolerance range). The thermal model assumes a free-standing system.

Table E.4 shows the measured and predicted performance ratios (where available) and indicates the magnitude of the additional losses implied by these two values. The nature of those losses, both identified by analysis of the data and expected from consideration of the system design, are then presented for each system. Whilst it would be possible to quantify some of the identified inverter and shading losses, this would take a considerable amount of time since it is not easy to automate such a task. This was outside the scope of this project.

Data were also gathered on import and export of electricity to the properties in order to consider the contribution of the PV system to meeting the household loads. The contribution made will depend strongly on both the size of the PV system and the typical load levels. The latter depends in turn on the lifestyle of the occupants and the detail of the electrical equipment used. This project was not designed to assess the effects of lifestyle on the use of PV systems and so there is no load analysis presented. However, some comments can be made regarding the contribution of the PV system outputs for seven of the sites (excluding System G).

Table E.4 Summary of loss mechanisms for the monitored systems.

System	Measured PR	PVSyst PR	Additional measured losses (%)	Identified or expected losses
A	0.61	0.68	10	Higher temperature than free standing – integrated system (but low temperature coefficient of modules). Mismatch between modules. Reduced efficiency of maximum power point tracking. High inverter threshold.
B	0.65	0.79	18	Higher temperature than free standing Significant shading in summer Undersized inverter Saturation of inverter at high irradiance levels Inverter trip
C	0.69	0.79	13	Higher temperature than free standing Inverter trip Calculations based on horizontal so lower accuracy of measured PR
D	0.73	0.79	8	Higher temperature than free standing Inverter drop out in summer months Some shading in afternoon
E	0.58	n/a	n/a	Higher temperature than free standing Inverter trips (severe) Undersized inverter Saturation of inverter above 800W/m^2
F	0.76	0.78	3	Higher temperature than free standing Small amount of shading
G	0.73	n/a	n/a	Higher temperature than free standing Significant shading in afternoon. Very limited data set
H (fixed)	0.48	n/a	n/a	Operation at fixed voltage. Shading of system at low sun angles in morning. Higher temperature than free standing
H (tracking)	0.64	n/a	n/a	Operation at fixed voltage. Long cable lengths.

The Solar Fraction can be considered as the maximum contribution which the PV system could make to the building loads. Its value was, as expected, highest for the large PV systems (B, C and D) and low building loads (C, D). For System C, it exceeded 100% for one month in the monitoring period and was over 95% for four other months. The average Solar Fraction across all systems was 28%. All the systems use over 50% of the PV system output directly and System F as much as 80% on average. This is the smallest PV system in the survey with one of the highest average building loads. The average percentage of the load met directly from the PV system is generally in the 10-30% range. Two of the systems (B and C) export over 70kWh per month on average, whilst the remainder have values around 20-30kWh. The maximum export values are 2-3 times the average value.

E.5 SUMMARY AND RECOMMENDATIONS

Based on the project results and the preceding discussions, the following conclusions and recommendations can be made.

- The use of proprietary design software such as PVSyst, whilst very useful in the design of systems, consistently underestimates the actual losses for all except one of the systems monitored in this project. In order to obtain more accurate predictions, it is necessary to modify some of the default values, particularly thermal behaviour and shading issues.
- The measured insolation values showed a high degree of consistency between sites. This is not always the case with available solar databases and care should be taken when interpreting performance data based on these.
- Almost all the systems showed some problems with shading. In particular, care should be taken regarding self-shading by parts of the same building and shading due to trees. It is possible that both these shading effects will not be obvious during site inspections.
- Undersizing of the inverter can cause significant losses due to saturation of output. This was not observed for systems with inverter/array capacity ratios over 0.75.
- The largest loss factor was related to inverter outages and these are not always observed until a significant period has elapsed. The period would be expected to be longer if the system in not monitored.
- Users have problems in identifying both short and long term problems with the inverter performance and attention should be paid to providing some simple and cost effective means of identification.

Many of the issues identified in this project will be able to be addressed in more detail by the Domestic PV Field Trial. This will provide similar data for a larger number of systems, a wider range of technology and a wider range of locations. It is recommended that the Field Trial considers the issues of inverter reliability raised in this study and assesses the prevalence and effect of array shading.

CONTENTS

LIST OF FIGURES AND TABLES

Page

MONITORING OF DOMESTIC PV INSTALLATIONS
FINAL REPORT

1. INTRODUCTION

This report describes the activities and results of the project "Monitoring of Domestic PV Installations" (Project Ref. S/P2/00319). Data obtained from the monitoring of photovoltaic installations can be used to determine operating factors such as typical system efficiencies, the reliability of components, the effectiveness of maintenance measures and the contribution of the energy supply in meeting the required loads. These factors can, in turn, be used to inform and improve the design and operation of future systems. Effective monitoring and the dissemination of the results can significantly increase the rate at which design errors are eliminated and improvements are implemented.

Thus, the project objectives were as follows:
(a) the identification and selection of suitable PV systems installed on domestic properties in the UK;
(b) the establishment of agreements to monitor the selected systems and the installation of appropriate monitoring equipment;
(c) the collection of performance data over a period of two years for each system;
(d) the development of recommendations regarding design and operation of domestic PV installations as a result of analysis of the collected data.

The project commenced in April 1999 and was completed in March 2003, having been extended due to delays in obtaining data from some sites. These delays were for a variety of reasons, including slippage of construction schedules, problems with grid connection and access restrictions due to the foot and mouth epidemic, as discussed more fully in later sections. However, performance data have been obtained for various periods from eight individual PV systems at locations around the country. It has not been possible to meet objective (c) fully, in that not all systems have provided a full two years of data, but a full data set has been obtained for most systems, together with substantial overlap of monitoring periods. The results of the data analysis are presented in Section 4. System reliability and operational issues are also discussed in Section 5.

During the course of the project, the Department of Trade and Industry have commenced both the Domestic PV Systems Field Trial and the Major Demonstration Programme, which aim to promote the use of photovoltaics in the domestic sector. This project was a precursor to the Domestic Field Trial and will allow initial results on system performance to be fed back into that programme. In addition, operational issues identified in this project can be investigated further in the Field Trial projects. Thus, this report provides both information and recommendations on system design and performance in its own right, but also acts as a preliminary study in advance of results of the data analysis from the Field Trial.

For some of the systems, the measured data have been affected by faults or other problems with the system hardware or problems with data access. Although any system faults observed by analysis of the measured data were reported to the system owners as early as possible, it was not within the scope of the project to investigate the cause of such faults or to rectify them. Similarly, although the system owners generally provided information freely, they were not required to report the cause of any problem nor to rectify that problem solely for the purpose of this monitoring programme.

Where appropriate, predicted outputs and system parameters have been derived for certain periods and these values are clearly identified in the report.

In accordance with the requirements of the Department of Trade and Industry and the agreements with the system owners, the individual system locations and the commercial details of the system components are not identified in the report. The data are generally presented in the form of monthly averages or totals and annual values, except where it is necessary to illustrate the system behaviour on a shorter timescale.

The detailed measurement data have not been included in the report. The DTI recognises that the data from this study may be a valuable resource and is prepared to release some or all of the data under circumstances where a genuine research purpose can be demonstrated and conditions of confidentiality can be agreed. In the first instance, interested parties should contact the authors of this report for details on how to proceed with a request for access to the data.

The next section describes the criteria for site selection and the systems chosen for this project, whilst Section 3 discusses the monitoring scheme. In Section 4, the analysis of system performance is discussed, both individually for all systems and via comparisons between systems. Finally, some conclusions and recommendations are presented.

2. SITE SELECTION AND DESCRIPTIONS

The first task in the project was the selection of suitable sites with existing or planned PV systems for monitoring and then to secure the agreement of the owners of these systems to participate in the project. This section outlines the criteria for the original selection and discusses how well these were met, considers the agreements made with the system owners and provides information about the selected sites.

The original target was for ten systems to be monitored within the project and candidates were identified by a combination of existing information in both public and restricted data sets and regular contact with several system installers. However, it only proved possible to identify and establish an agreement for the monitoring of eight systems within the project period. This was mainly because systems did not meet the criteria for monitoring, particularly in regard to the age or usage of the system, or a suitable arrangement could not be made.

2.1 Site Selection Criteria

Since the results of this monitoring project were intended to gain information on typical performance and reliability aspects and to advise on best practice, it was necessary to consider the use of the PV system as a building component and its contribution to the electrical needs of the dwelling. It was agreed that, ideally, the selected sites should include a variety of PV technologies, integration methods and locations, be of a suitable size for extrapolation to other domestic systems and represent the current technology at the time of inception of the project. There should also be sufficient common features to allow assessment of the validity of any inter-comparisons being made. Whilst this was difficult to achieve fully with a maximum of ten systems in the study and limited control over the details of those which will be available for monitoring, a target mix of systems was outlined. The following list provides the original objectives for each criterion and indicates the actual situation for the completed project. Criteria (i)-(iii) were considered the most important with the remainder used to refine the choice. The attitude of the owner and their willingness to co-operate with the monitoring programme were also taken into account in the site selection.

(i) **Integration Methods:** It was intended that a mixture of full integration (i.e. replacement of a building component) and add-on systems would be monitored with a target of six for the former and four for the latter category. All systems should be applicable to a range of housing types. Of the final eight systems, four of each type were included.

(ii) **Technology:** As far as possible, the systems should include all current cell technologies (single crystal, multicrystalline and thin film silicon) and a range of manufacturers. It was suggested that cadmium telluride technology would also be included if a system became available within the project timescale. A range of module construction, to include at least one glass/glass and one roof tile construction, was also intended. This criterion proved to be the most difficult to achieve, due to the limited availability of all but monocrystalline silicon technology. Only one amorphous silicon system was finally included, with all other systems based on single crystal silicon cells. Initial negotiations regarding a second system using an amorphous silicon roof tile were not successful due to change of ownership. The system installers contacted could not offer further examples within the project period. Two roof tile systems and one glass/glass module system were included in the project and four manufacturers were represented (some with more than one module type).

(iii) **Electrical System:** It was expected that most of the systems would be grid connected since this represents the most appropriate electrical configuration. However, it was suggested that one or two stand alone systems may be considered if they provide important data in other respects. Seven of the final systems were conventional grid connected designs. The eighth was adapted from a stand alone system and included battery storage, but was also grid connected throughout the monitoring period.

(iv) **System Size:** To allow proper comparison of systems, it was suggested that the system size be restricted to the range 0.5kWp – 5kWp. The eight systems selected range in size from 1.02 to 3.43kWp.

(v) **Time of Installation:** In order to ensure that the technology was current, it was suggested that system should have been installed no earlier than 1996. All systems complied with this requirement. One of the systems was installed during the course of the project.

(vi) **Location:** As far as possible, it was intended that a range of locations around the UK would be selected, with, in some cases, two or three sites in a particular geographical location being chosen to provide additional possibilities for comparison of data. It proved difficult to find systems in northern UK locations and which also met the other criteria. Therefore, the most northerly system is located in Yorkshire. However, it was possible to include systems in the south west and to include two systems in the London area.

Table 1 summarises the details of the eight selected systems. The systems are presented in order of location, from south to north.

In addition to the above system details, it is useful to note that Systems D, E and G were installed by housing associations, with whom the monitoring agreements were made, and the remaining five were under private ownership. This has relevance when considering some of the issues arising from the study.

Table 1. System Details
(presentation order according to latitude starting with the most southerly location)

System Reference	Region	System Size (kWp)	Module details	Inverter size	System description
A	South West England	1.27	22 x 50 Wp and 5 x 34 Wp amorphous silicon laminates	1.1 kW	Modules are integrated into conservatory roof
B	West of England	3.43	286 x 12 Wp crystalline silicon roof tiles	2 x 1.1 kW	Roof integrated system
C	South East England	2.88	24 x 120 Wp crystalline silicon modules	2 x 1.1 kW	Roof integrated system
D	South East England	2.2	20 x 110 W crystalline silicon modules	2 x 0.85 kW	Roof mounted system
E	West of England	1.05	14 x 75Wp crystalline silicon modules	0.7 kW	Roof mounted system
F	West Midlands	1.02	12 x 85 Wp crystalline silicon modules	0.85 kW	Roof mounted system
G	North West England	1.4	40 x 35 Wp crystalline silicon roof tiles	2 x 0.7 kW	Roof integrated system
H	North of England	0.68 (fixed) 0.85 (tracking)	Total of 18 x 85 Wp crystalline silicon modules	Connected via 24 V battery bank	Fixed array roof mounted, tracking array free standing

2.2 Monitoring Agreement

In each case, after informal discussions with the system owners, a short document setting out the agreement for the monitoring was signed by both parties. This agreement included the arrangements for access to the property to install and, where agreed, remove the monitoring equipment, access for downloading data (by modem where possible), the monitoring period, the ownership of the data and liability for damage caused during access to the property.

3. MONITORING SCHEME AND DATA COLLECTION

This section describes the selection of the monitoring equipment, the installation of the monitoring system and the data collection activity. The purpose of the monitoring was to obtain data on the performance of the PV system, including efficiency, performance ratio and total output, including any variations resulting from the specific design of the system. Data were also collected in regard to the energy consumption of the dwelling. The baseline for the specification of the monitoring requirements was the "Testing, Commissioning and Monitoring Guidelines" developed under contract for the DTI [1].

The measured parameters were as follows:

- Irradiance in-plane with the array
- Horizontal irradiance
- Ambient temperature
- PV module temperature (via a sensor attached to rear surface of module)
- Array DC current
- Array DC voltage
- System AC power
- System AC energy output
- Imported energy from the grid

In order to reduce the number of data channels and hence improve the storage time before access was needed, the DC power was not measured directly, but calculated from the voltage and current values. For some of the properties, the module temperature and the horizontal irradiance could not be measured due to access difficulties. Finally, where the system consisted of more than one sub-array, the system parameters were measured for one of the sub-arrays, together with the overall AC output.

The requirements for the monitoring equipment can be summarised as follows:

- compliance with monitoring guidelines in terms of measurements to be made and sensor type and accuracy;
- minimum disruption to existing PV systems;
- minimum requirement for action by system owners during the course of the monitoring;
- reliability of data acquisition;
- accommodation of different system designs;

A data logger with modem connection was used to allow remote downloading of the data. It was intended that the system owner should not have to be responsible for any collection or downloading of data under normal circumstances. (Although some problems were encountered early in the project, only System E required manual downloading on a regular basis, since the quality of the telephone line would not allow reliable data transfer.) Local computer control was not considered, due to the additional requirement for space and power and because of the lower level of security against tampering. The storage capacity of the data logger, the number of channels being measured and the measurement frequency was chosen so as to allow a reasonable schedule for the downloading of data. As far as possible, the sensors were selected to minimise any disconnection or modification of existing wiring and the same make and type of sensor was used on all sites.

For all systems, Time Electronics HLog data loggers with external modems were used. These have an internal memory card and the option to download data manually, in case of problems with remote data access. The loggers each have 24 analogue channels (0-5V input) and eight digital channels and 10-bit resolution on the analogue signal. The suppliers also provided amplifiers for platinum resistance thermometers and thermistors, together with signal conditioning components.

Irradiance was measured by Kipp and Zonen SP-Lite silicon pyranometers. These sensors are quite low in cost and robust, which was important for this monitoring programme where action from the system owners was not desirable. They also have a better temperature stability than a conventional pyranometer. All the sensors were supplied with their own calibration certificate. The stability is quoted as ±2% and the spectral error range as ±5%. The sensors are more suited to measurement of crystalline silicon arrays than amorphous silicon arrays, due to the different spectral response characteristics of the latter technology. However, since it was felt to be important to have continuity of measurements between sites and there is no equivalent sensor designed for use with amorphous silicon (in terms of reliability and robustness), it was decided to use these sensors on all sites. There is only one amorphous silicon system in the study.

The measurement of ambient temperature was performed using a shielded thermistor (supplied by Vector Instruments) with a stated accuracy of less than ±0.3% over the temperature range required. The array temperature was measured by a platinum resistance thermometer (supplied by Rhopoint) fixed with thermally conductive adhesive to the rear of one of the modules and beneath a cell in each case. The PRT has a stated accuracy of ±0.5%.

The DC measurements were carried out using LEM current and voltage transducers, both with a measurement accuracy of ±1%. The AC measurements used power transducers from Willow Electronics. For the AC output of the PV system, a dual signal transducer was used, giving a frequency output representing the instantaneous power level and a pulse output for cumulative energy production. A pulsed output was used for export and import values and, in these cases, clamp-on meters were used to avoid the need to disconnect the cabling to install the monitoring system. Due to the limited availability of sizes for meters of this design, the transducers for the export measurement were rated for current values up to 100A. This is higher than would be needed and therefore the export measurements are not as accurate as the other AC measurements on the system. All the transducers provided an output of 1000 pulses per kWh, with the exception of the import and export meters on System A which gave 750 pulses per kWh.

Before installation, all the energy sensors were calibrated in the laboratory using a power analyser and the amplifiers were calibrated using a controlled current-voltage source or signal generator. This determined their linearity of response and allowed the construction of look-up tables for each site, so as to facilitate conversion of the sensor signals to the numerical value of the quantity being measured. The sensors were checked again on site during the installation process in order to allow for modification due to the sensor cabling.

4. ANALYSIS OF SYSTEM PERFORMANCE

Section 4 is divided into two main parts. In Section 4.1, several of the main performance parameters are discussed to provide the background for the subsequent discussions of measured performance. In Sections 4.2 – 4.9, the eight systems are discussed individually, with specific performance parameters and details of any operational issues provided. These sections include system efficiency, performance ratio and annual yield values for the systems, together with relevant climatic data. The comparison of various aspects of performance for the group of systems is discussed in Section 5, where the considerations of temperature effects, comparative yields and contribution to building loads are included.

During the course of the project, all system owners were provided with monthly summaries of the performance of their system. These consisted of a data sheet divided into four sections. The first part provided information about any anomalies, modifications or system outages for that month and the monitoring fraction (the amount of data collected as a percentage of the maximum possible in that period). The second part detailed the climatic data, providing monthly averages for insolation and temperature. The third part provided the system performance details for the month, including total AC output, system efficiency, performance ratio and information on the electrical load. The total measured output to date is also provided. Finally, there is a bar chart showing the daily output of the system for the month, to illustrate the variation seen. A sample of the summary report is provided in Appendix A.

4.1 Performance Parameters

Whilst there are several performance parameters that can be derived from the measured data, the most important in terms of describing the overall performance of the system are the system efficiency, the performance ratio and the annual yield. A short description of each of these parameters and how they can be used to assess system performance is provided here, in order to aid interpretation of the data presented in the remainder of Section 4 and in Section 5.

4.1.1 System Efficiency

This is the most commonly quoted performance parameter. It is the ratio of the energy output of the system, in the form of electricity, to the energy input to the system, in the form of sunlight, and is usually expressed as a percentage. It is calculated directly from the AC output of the system and from the sunlight level in the plane of the array. It is also possible to calculate efficiencies for parts of the system, in particular in relation to the DC output of the array (i.e. before conversion to AC by the inverter) and, where this is considered in the report, it is clearly stated as the “DC system efficiency”. In all other cases, the system efficiency quoted is related to the AC output of the complete system.

The system efficiency is generally lower than the module efficiency quoted by the manufacturers since the system output is affected by a number of factors. The main factors affecting the system efficiency are listed below:

- Temperature, reducing with increasing temperature due to the effect on the operation of the PV cells.
- Light level, reducing under poor light conditions due to the behaviour of both the modules and the inverter. Efficiency can also be reduced when the light is incident at high angles (usually early or late in the day).

- Conversion from DC to AC power by the inverter, which is typically 90-95% at reasonable power levels but is usually reduced substantially at low power levels (below around 10% of rated capacity).
- Mismatch between the module outputs (i.e. they do not all have exactly the same electrical behaviour), leading to some or all modules operating off their maximum power point.
- Voltage drops within the cabling (especially if the cable routes are long).
- Dirt accumulation on the modules
- Shading of the array.

4.1.2 Performance Ratio

The performance ratio is a parameter that allows an assessment of the system losses and, since it takes into account the solar input to the system, also allows direct comparison of systems at different sites. It is calculated by comparing the AC output of the system over a given period to the output that would be expected by an ideal system at the same location. The ideal output is calculated from the system rating and the solar input and the performance ratio can be expressed by:

$$PR = \frac{\text{AC Output of System}}{\text{System Rating x Solar Input}}$$

where the AC output is expressed in kWh, the system rating in kW and the solar input in kWh/m^2 (usually calculated by multiplying the daily average solar input in the period by the number of days in the period). Due to the definition of the system rating, the product of the system rating and solar input provides the electrical output of the ideal system. The performance ratio can be expressed as a percentage or as a number between 0 and 1. To reduce confusion with the values presented for system efficiency, the latter format is used throughout this report.

The PR value is reduced by the various system losses and, if some of these can be quantified, can be used to estimate the effect of the remaining losses. A PR value of 0.8 is considered to represent a well-designed system, with the main losses being those relating to DC to AC conversion and operating temperature.

4.1.3 System Yield

The system yield describes the ratio of the electrical output of the system to the rated system capacity over a defined period, usually one year (in which case, it is referred to as Annual Yield). This parameter is often used in the design of systems to describe the predicted annual output and, in this case, the average solar input at the site is used to determine the expected electrical output. In this report, we consider the measured yield in comparison with typical design values, taking into account the variation between the measured and average insolation values. It should be recognised that whilst the system efficiency and performance ratios are expected to be reasonably consistent regardless of the period of operation considered, the measured annual yield will vary from year to year because it depends directly on the insolation values for the year in question.

4.1.4 Monitoring Fraction

Finally, whilst not a system parameter, the monitoring fraction (MF) for any monitoring scheme has an important influence on the weight that can be assigned to the measured data. The monitoring fraction is the ratio of the number of measurements obtained in a given period to the maximum number of measurements that could be obtained in the same period. For example, if we consider measurements of a quantity at intervals of 1 minute over a period of 10 days, then we should obtain 14,400 readings. If data collection does not occur for a total of 6 hours at some time in this period, then we would have lost 360 data points and the monitoring fraction would be 97.5%.

Some data loss is usual even for the best monitoring systems and values of MF below 100% are accounted for by including the MF value in the denominator for the calculation of system efficiency and performance ratio. This is based on the assumption that the system performance parameters for the period for which data are not available are equivalent to the average of the parameters for the period for which data are available. In the case of a PV system, one of the most important and uncontrolled variables is the insolation value. It is clear that the climatic conditions are not predictable over long periods of time and so the assumption can only be used for cases where the loss of measured data is small. Based on experience, it is recommended that caution is exercised in interpreting PV system data where the MF value is less than 85%.

The average MF for each system is provided in the discussion of the system performance and, as indicated in the detail of the report, some monthly parameters have been excluded from the overall analysis where the MF value was considered too low. In general, the month in which the monitoring was commenced for each system is omitted for this reason. However, it should be noted that the MF values were generally high throughout the programme.

4.2 Performance of System A

System A is the only one using a technology other than monocrystalline silicon cells for the PV array. The original system consisted of 27 amorphous silicon laminates, each rated at 50Wp, integrated into the conservatory roof. These were arranged in three series strings, each of 9 modules connected in parallel. At around the time of commencement of the monitoring, five of the modules had to be replaced. The replacement modules were the same physical size, but each rated at 34Wp. The owner was unable to advise of the exact position of these modules in the electrical circuit, but it is believed that they are distributed across all three strings. This will result in some mismatch losses, both within the strings and as a result of the series connection of dissimilar strings. Since amorphous silicon also has a period at the beginning of operation when the output reduces to a stabilised level, it is possible that the five newly installed modules had not reached their stable value when the monitoring commenced, whereas the original modules had been installed for over a year.

The array rating is 1.27kWp and the total array area is 21.65m^2. The array is connected to a 1.1kW inverter. This system was the first to commence data collection in July 2000 and an overall monitoring period of 30 months was possible. The monitoring system was generally well behaved and an average monitoring fraction of over 98% was obtained. Due to the lack of a suitable location for the sensor, it was not possible to include measurement of the horizontal irradiance at this site.

The initial data sets indicated that the original inverter in the system was cutting out regularly, mainly when the irradiance level changed rapidly, and was then remaining off for periods of several minutes. On some days, this resulted in large losses in output. The problem had been identified previously by the system owner, who arranged to change the inverter to a model from a different manufacturer towards the end of September 2000. Unless otherwise stated, all the subsequent performance analysis relates to the system configuration with the replacement inverter.

The problem is illustrated in Figures 1(a) and (b), which show system output compared with insolation level for typical days with the first and second inverters respectively. In both cases, the heavier line indicates the electrical output. In Figure 1(a), it can be seen that the inverter repeatedly drops out both in the morning period when there are some noticeable changes in insolation and in the afternoon when there is no apparent major change in insolation level. After drop out, the inverter remains off for several minutes before attempting to locate the optimum operating point of the array. By contrast, Figure 1(b) shows the second inverter following the change of insolation well, even for major variations in the period between 3:00 and 4:30 pm. The inverter shows evidence of needing to adjust its maximum power point tracking at this stage, as would be expected, but soon recovers to a reasonable operating point.

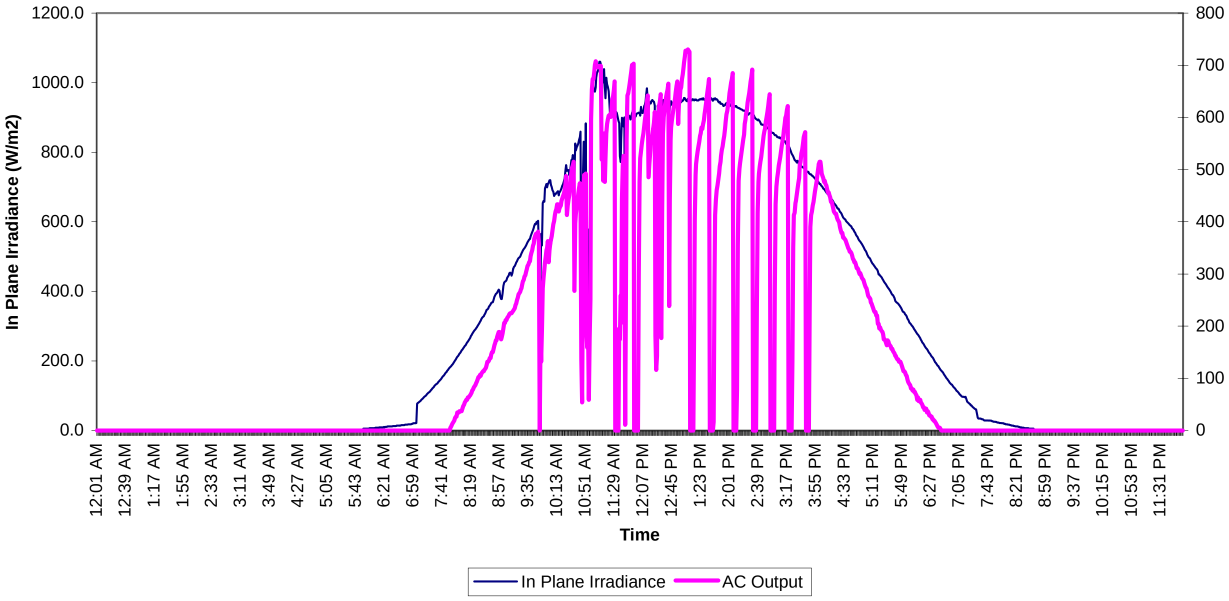

Figure 1(a). Output of System A for 11/08/00 in comparison with the irradiance level. This illustrates the behaviour of the first inverter for which the output falls to zero repeatedly during the day.

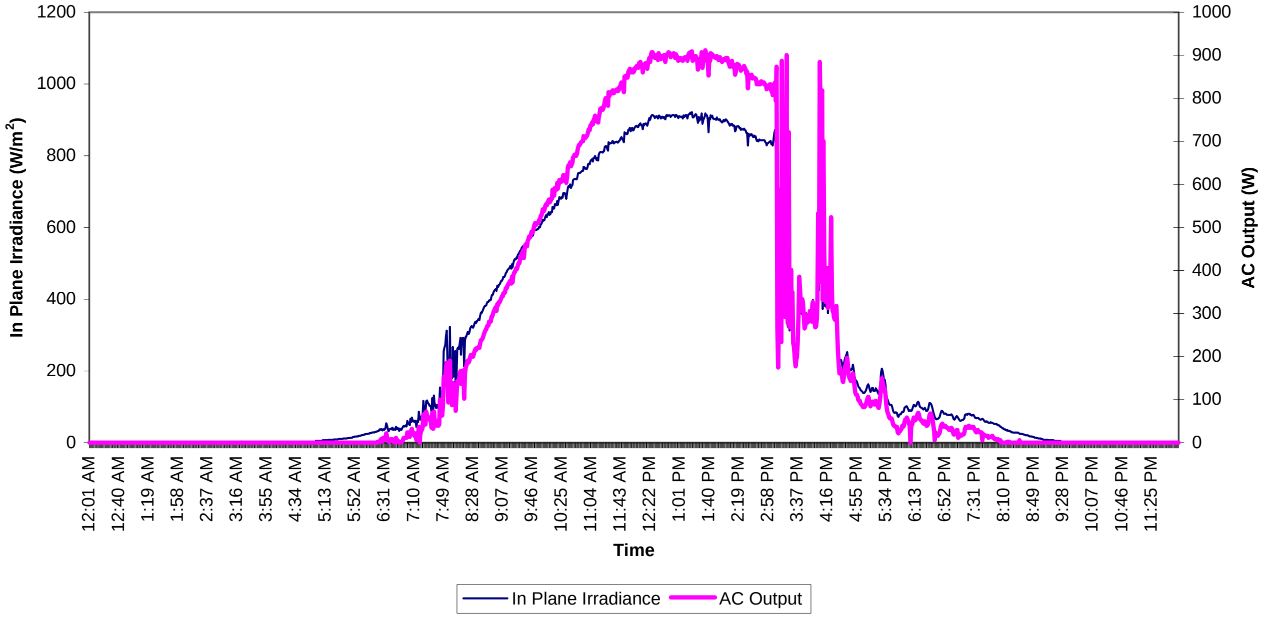

Figure 1(b). Output of System A for 20/06/01 in comparison with the irradiance level. This illustrates the behaviour of the second inverter in tracking the sunlight level.

It has been observed previously that inverters designed for use with crystalline silicon arrays can have problems with tracking the maximum power point for amorphous silicon arrays, due to the difference in shape of the current-voltage characteristic. The amorphous silicon I-V curve is much flatter with a less obvious maximum power point. For those trackers which rely on identifying changes in power level whilst oscillating the voltage around the maximum power point, the difference in the power level change between the two technologies can result in the inverter being unable to follow the maximum power point during rapid changes in the insolation level. If the inverter proceeds with voltage change in the wrong direction, it can sometimes lead to drop out. There is not enough data from the first system to confirm that this effect is the cause in this case, but it is likely to have contributed to the problem.

It is worth noting that the performance problems of the first inverter may not have been noticed by an owner with less interest in the detailed operation of the system. Although it was clear from the monitored data, this would only be available if the system was included in a project such as the one reported here. If unresolved, the problem could lead to a substantial loss of output from the system. Based on monthly system efficiency values calculated both before and after the change of inverter, it appears that up to 40% of the system output could have been lost due to the drop outs of the first inverter.

Table 2 summarises the main system parameters determined for System A over the monitoring period between October 2000 and December 2002. The overall monitoring fraction for this period was 98.7%. The nominal module efficiency for the system is 6.3% based on the manufacturer’s rating.

From the data in the table, the following values can be obtained:

- Average daily in-plane insolation for 2001 = 3.09kWh/m^2
- Average daily in-plane insolation for 2002 = 2.95kWh/m^2
- Average system efficiency for whole period = 3.5%
- Average performance ratio for whole period = 0.60
- Annual yield for 2001 = 679kWh/kWp
- Annual yield for 2002 = 668kWh/kWp

Some of the data given in Table 2 are also presented graphically in Figure 2. It can be seen that the monthly electrical output follows the average insolation value closely as would be expected. The efficiency is essentially constant apart from a small decrease in the winter months, which is common for most systems. The only remarkable aspect is the more marked decrease observed in the first February and March and it is not clear why this should be greater than in later years.

Table 2. Summary of system parameters for System A (operation with second inverter only).

Month	**Average daily in-plane irradiance (kWh/m^2)**	**Average ambient temperature (^oC)**	**Monthly AC output of system (kWh)**	**System efficiency (%)**	**Performance ratio**
Oct ‘00	2.2	10.9	55	3.6	0.62
Nov ‘00	1.9	7.7	57	3.1	0.52
Dec ‘00	0.8	7.1	18	3.4	0.58
Jan ‘01	1.4	5.5	32	3.5	0.6
Feb ‘01	2.4	6.2	42	2.9	0.5
Mar ‘01	1.9	6.7	32	2.5	0.43
Apr ‘01	3.7	8.7	84	3.5	0.59
May ‘01	5.3	12.7	116	3.7	0.62
Jun ‘01	5.1	14.6	123	3.7	0.64
Jul ‘01	4.5	16.5	115	3.8	0.65
Aug ‘01	3.9	16.3	102	3.9	0.66
Sep ‘01	3.7	14.3	93	3.9	0.66
Oct ‘01	2	13.6	49	3.7	0.63
Nov ‘01	1.8	8.3	43	3.8	0.64
Dec ‘01	1.4	5.4	33	3.5	0.6
Jan ‘02	0.7	7.7	16	3.2	0.54
Feb ‘02	2	8	44	3.6	0.62
Mar ‘02	2.5	8.3	60	3.6	0.61
Apr ‘02	4.4	9.3	106	3.7	0.63
May ‘02	4.3	11.3	106	3.7	0.64
Jun ‘02	4.4	13.7	102	3.6	0.61
Jul ‘02	4.9	15.9	122	3.7	0.63
Aug ‘02	4.1	16.5	100	3.7	0.63
Sep ‘02	4.1	14.6	101	3.8	0.65
Oct ‘02	2.1	11.7	53	3.7	0.64
Nov ‘02	1.3	10.3	30	3.6	0.61
Dec ‘02	0.6	6.7	10	3.2	0.55

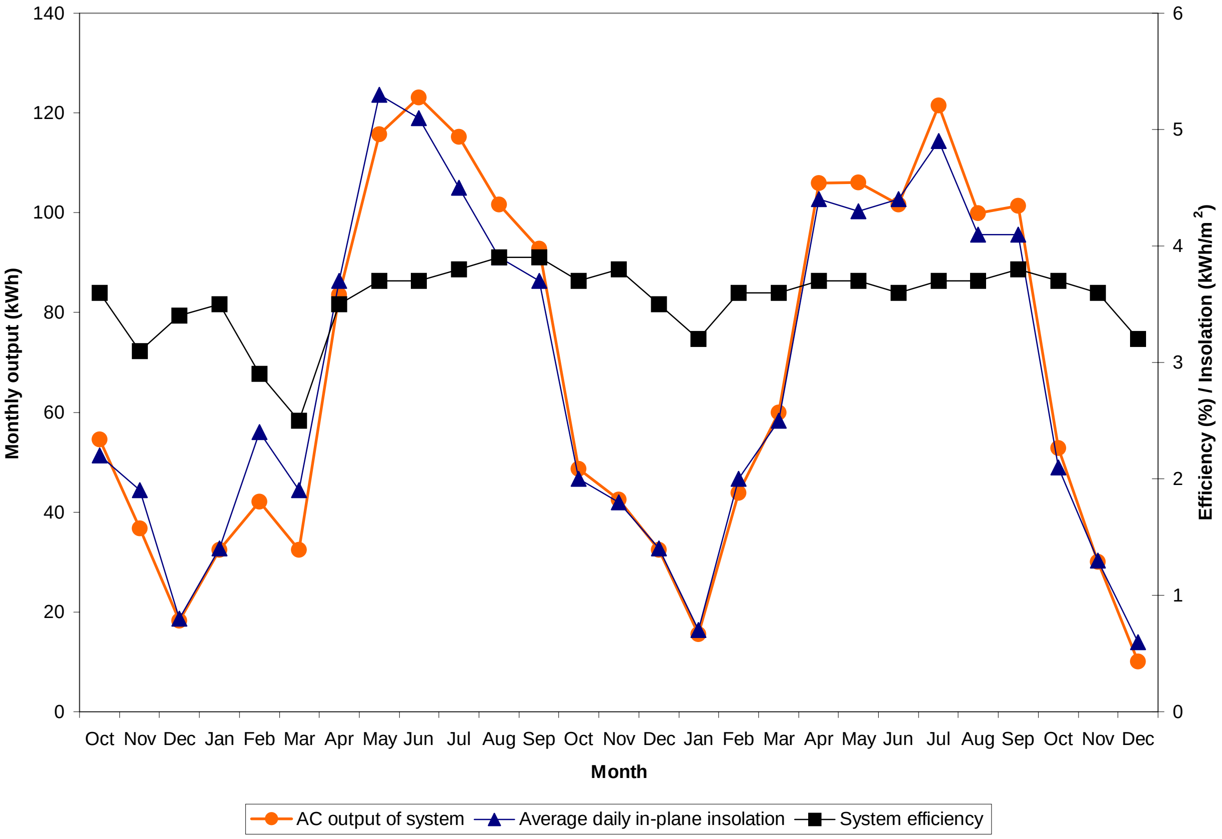

Figure 2. Variation of main system parameters with month for System A.

The most influential factor in the winter efficiency reduction is a decrease in the average inverter efficiency due to a higher proportion of operation at low power (ie low light) levels. Unfortunately, there were problems with the DC voltage measurement in the initial months of operation of the second inverter and so we do not have a direct measurement of inverter efficiency for the period of interest. In the second year, the average inverter efficiency does show a small decrease in the winter, consistent with the change in system efficiency.

It is possible that part of the decrease can be attributed to temperature effects. Since the temperature coefficient of efficiency is negative, the module conversion efficiency should actually rise in the winter months when the average ambient temperature is reduced. However, in terms of overall system efficiency, this effect is usually offset by the reduced inverter efficiency and so a decrease in system efficiency is observed. Since amorphous silicon cells have a lower temperature coefficient of efficiency than crystalline silicon cells, the temperature effect would be expected to be lower in this case anyway.

However, amorphous silicon has been observed to have another temperature effect that may be relevant. It is well known that the amorphous silicon module exhibits an initial efficiency loss on exposure to sunlight. After a period, it achieves an equilibrium value, but this value is temperature dependent with lower levels at lower temperatures. If the output of a single module is monitored, it generally shows a cyclic behaviour with higher efficiencies in the summer months and lower efficiencies in winter (ie the opposite effect of that resulting from the temperature dependence of the photovoltaic effect).

For this system, the lowest efficiency is obtained for March 2001, rather than the traditional winter months of December – February. In terms of the climatic data presented in Table 2, March 2001 is unusual in two regards. Firstly, the average insolation value is substantially reduced from the value in the previous month and in March of the following year. This would be expected to reduce the inverter efficiency because of low power operation. Secondly, the average ambient temperature in the period January-March was only 6.1°C compared to 8°C for the same period the following year. Thus, periods of cold weather may also have reduced the stabilised efficiency level at this time.

It is noticeable that the performance ratio values are quite low for this system, averaging 0.60 for the monitoring period. This is discussed in more detail in Sections 5.3 and 5.4. The variation of the array operating temperature is discussed in Section 5.2.

4.3 Performance of System B

System B is comprised of 286 roof tiles incorporating crystalline silicon cells and integrated into the roof structure of the house. The total array area is 34.32m^2. The system has a total rating of 3.43kWp and is divided into 2 subsystems, each connected to a 1.1kW inverter. The output of one subsystem was monitored fully, together with the total AC output of the whole system. In the data presented, system efficiencies and performance ratios are calculated for the measured subsystem, whilst the monthly output values are provided for the whole system. The data indicate that both subsystems were operating in a very similar manner throughout the operating period. Since this system was already installed when the monitoring agreement was reached, it was not possible to gain access to the rear of the tiles to install an array temperature sensor.

Table 3 summarises the main system parameters determined for System B over the monitoring period between April 2001 and December 2002. The overall monitoring fraction for this period was 99.5%. The nominal module efficiency for this system was 10% based on the manufacturer's rating.

In Table 3, some of the boxes for the period June – September 2002 are shaded to indicate that these values were obtained at a time when the system was not fully operational. Both inverters were off from 09/06/02 to 11/09/02, resulting in zero values during July and August and reduced values for June and September. However, since the monitoring fractions for all four months remained at 100%, the values for insolation and ambient temperature are valid. These can be used to produce a predicted annual yield for the system. The problem appears to have been caused by an inverter trip and this is usually a result of a fluctuation in grid voltage. The owners had not noticed this problem and were advised by the project team after inspection of the monitoring data. It was then possible to restart the inverter. As discussed later, other systems have also experienced inverter trips that were only identified as a result of the monitoring being undertaken on this project.

From the data in Table 3, the following values can be obtained:

- Average daily in-plane insolation for 2002 = 2.89kWh/m^2
- Average system efficiency for whole period = 6.1%
- Average system efficiency discounting June-September 2002 = 6.5%
- Average performance ratio for whole period = 0.60
- Average performance ratio discounting June-September 2002 = 0.65
- Annual yield for 2002 = 423kWh/kWp
- Predicted annual yield for 2002 = 692kWh/kWp

The predicted annual yield was obtained by correcting the monthly outputs for June – September inclusive, using the measured in-plane irradiance and assuming a system efficiency of 6.5%.

Table 3. Summary of system parameters for System B.

Month	Average daily in-plane irradiance (kWh/m^2)	Average ambient temperature (°C)	Monthly AC output of system (kWh)	System efficiency (%)	Performance ratio
Apr '01	3.8	8.8	264	6.8	0.68
May '01	4.9	13.1	332	6.4	0.64
Jun '01	5.5	14.8	369	6.5	0.65
Jul '01	4.9	16.7	331	6.4	0.64
Aug '01	4.1	16.4	289	6.6	0.65
Sep '01	3.2	14.4	210	6.4	0.64
Oct '01	2.1	13.9	142	6.5	0.65
Nov '01	1.4	8.1	93	6.5	0.65
Dec '01	1.2	4.3	77	6	0.6
Jan '02	0.8	7.1	52	6.3	0.63
Feb '02	1.5	8.2	94	7	0.7
Mar '02	2.6	8.3	188	6.8	0.68
Apr '02	4.5	10	314	6.9	0.69
May '02	4.5	12	325	7.1	0.71
Jun '02	4.7	14.1	71	1.5	0.15
Jul '02	4.4	15.8			
Aug '02	4.1	16.7			
Sep '02	3.6	14.4	150	4.1	0.41
Oct '02	2.1	10.9	133	6	0.6
Nov '02	1.2	9.6	83	6.6	0.66
Dec '02	0.7	6.8	43	5.9	0.59

The main parameters are presented in graphical form in Figure 3. It can be seen that the system is well behaved, with the exception of the period between June and September 2002 that has already been discussed. System output follows the in-plane insolation closely and the system efficiency shows little variation.

Again, the performance ratio for this system is quite low and the behaviour of the system was investigated in more detail in an attempt to identify the problem. This is discussed, in comparison with other systems, in Section 5.4. The operating temperature of this system was not directly measured, but can be partially inferred from comparison with other systems as discussed in Section 5.2.

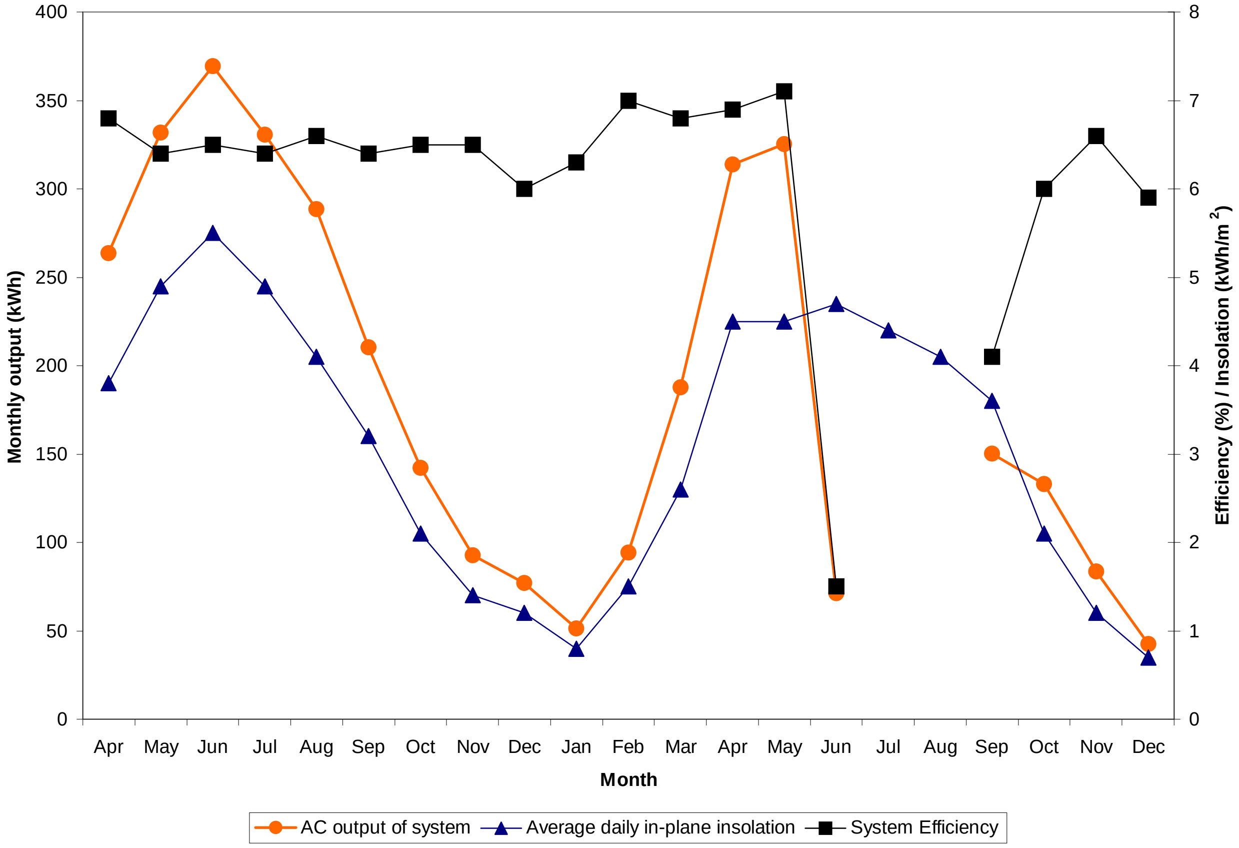

Figure 3. Variation of main system parameters with month for System B.

4.4 Performance of System C

System C consists of two similar subsystems, both comprising 12 crystalline silicon modules integrated into the roof and connected to a 1.1kW inverter. Each module is rated at 120W. The total array area is 23.4m^2 with a total system rating of 2.88kWp. As in the previous system, the fact that the modules were sealed into the roof structure prevented the direct measurement of module temperature.

The two subsystems, whilst identical in specification, have different orientations with one facing south and the other facing north. The arrays have a low tilt angle of 11 degrees to the horizontal, so the north-facing array should still receive a fairly high level of insolation (the Meteonorm solar data base suggests 867kWh/m^2 per year compared to 1029kWh/m^2 for the south facing surface). However, since the orientations differ, the use of data from both subsystems modifies the parameters calculated and makes comparison with other systems difficult. Therefore, full analysis has been completed only for the south facing system.

Table 4 summarises the main system parameters determined for System C over the monitoring period between June 2001 and December 2002. The overall monitoring fraction for this period was 98.5%. The nominal module efficiency for this system was 12.4% based on the manufacturer's rating.

Table 4. Summary of system parameters for System C.

Month	Average daily horizontal irradiance (kWh/m^2)	Average ambient temperature (°C)	Monthly AC output of system (kWh)	System efficiency (%)	Performance ratio
Jun '01	4.9	16.6	255	8.2	0.66
Jul '01	4.4	19.3	241	8.3	0.67
Aug '01	3.8	18.7	217	8.6	0.7
Sep '01	2.6	14.8	142	8.7	0.71
Oct '01	1.6	14.6	88	8.6	0.7
Nov '01	0.9	22.3	36	6.5	0.53
Dec '01	0.6	5.8	24	8.1	0.66
Jan '02	0.6	8.1	22	8.6	0.69
Feb '02	1.3	8.7	66	8.9	0.72
Mar '02	2.3	9.7	134	9	0.73
Apr '02	3.9	11.4	225	8.8	0.71
May '02	4.2	13.5	241	8.6	0.69
Jun '02	4.6	16.2	254	8.3	0.67
Jul '02	4.3	18.1	246	8.2	0.67
Aug '02	3.7	19	210	8.2	0.67
Sep '02	3.1	16.2	173	8.8	0.72
Oct '02	1.6	12.1	86	8.7	0.71
Nov '02	0.8	10.3	37	8	0.65
Dec '02	0.4	7.8	15	7.4	0.6

The monitoring system had a single in-plane insolation sensor for the south-facing array. Early in the monitoring period, this sensor began to give high readings and was replaced. However, the second sensor only operated for a short period before it also failed. It is believed that this is due to moisture ingress to the amplifier due to the position of the sensor. Due to the low tilt angle of the system, it has been possible to use the horizontal insolation sensor to calculate the system parameters. This introduces an error in the efficiency values which would be expected to be small in the summer months (2-3%) but could be over 20% in the winter months, based on Meteonorm predictions. It is difficult to correct for this because it depends on the mix of direct and diffuse irradiance received, but should be taken into account when assessing the results.

From the data in Table 4, the following values can be obtained:
- Average daily horizontal insolation for 2002 = 2.57kWh/m^2
- Average system efficiency for whole period = 8.3%
- Average performance ratio for whole period = 0.68
- Annual yield for south facing system for 2002 = 639kWh/kWp

From the measured data set, it is also possible to calculate:
- Annual yield for north facing system for 2002 = 549kWh/kWp

The main parameters of Table 4 are presented graphically in Figure 4. This again shows a well-behaved system with no significant operational problems. There is a marked reduction in system efficiency for November 2001. This was due to an outage of the south facing system during the period 20-27 November that reduced the overall output. The owner did not advise the cause.

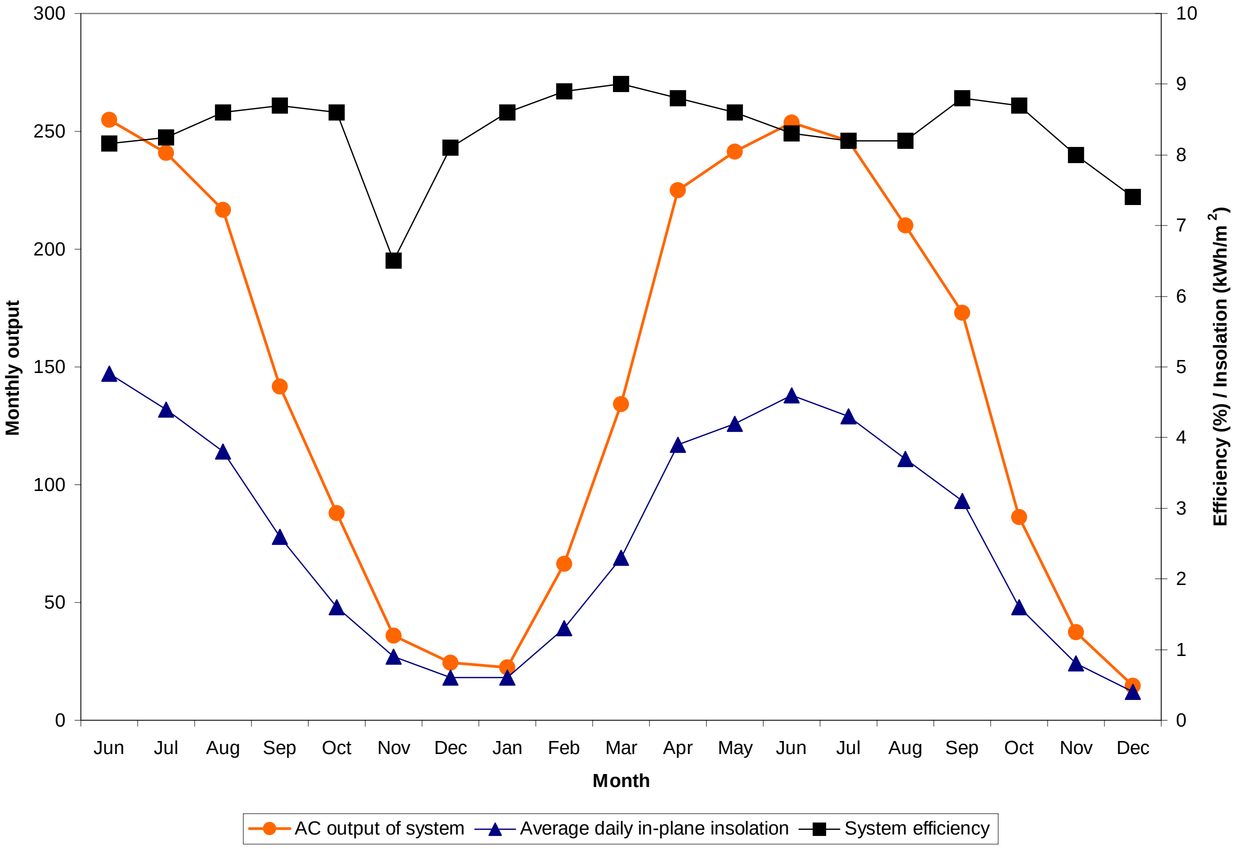

Figure 4. Variation of main system parameters with month for System C.

The performance values, including yield, performance ratio and operating temperature are discussed in comparison with the other systems in Sections 5.2-5.4 inclusive.

4.5 Performance of System D

The array for this system is composed of 20 crystalline silicon modules, each rated at 110Wp. The array area is 17.4m^2 and the array rating is 2.2kWp. As for Systems B and C, the system is divided into two similar subsystems. In this case, each half of the array is connected to its own inverter of 0.85kW capacity. The PV modules are mounted on the roof of the property in their own support structure. This is sometimes referred to as a stand-off system since there is usually an air gap between the array and the roof to provide some air flow around the modules.

This system is installed on a housing association property, in contrast to the three systems already discussed which are all privately owned. During the course of this programme, it has been observed that any problems with the system operation or the monitoring took much longer to address than for privately owned systems. This has some implications for ensuring reliable system operation in tenanted properties and this is discussed further in Section 5.

As with the other divided PV systems, only one subsystem was monitored fully, together with the total output from the whole system. Table 5 summarises the main system parameters determined for System D over the monitoring period between December 2000 and December 2002. The overall monitoring fraction for this period was 96.6%. The nominal module efficiency for this system was 12.6% based on the manufacturer’s rating.

Table 5. Summary of system parameters for System D.

Month	Average daily in-plane irradiance (kWh/m^2)	Average ambient temperature (^{o}C)	Monthly AC output of system (kWh)	System efficiency (%)	Performance ratio
Dec ‘00	0.57	8.2	30	9.6	0.76
Jan ‘01	1.04	5.9	56	10.01	0.79
Feb ‘01	1.49	7.4	73	10.12	0.8
Mar ‘01	1.58	7.9	80	10.01	0.79
Apr ‘01	2.81	10.3	123	8.4	0.66
May ‘01	4.48	14.8	186	7.7	0.61
Jun ‘01	4.55	17.1	187	7.91	0.62
Jul ‘01	3.93	20.1	190	8.98	0.71
Aug ‘01	3.6	19.4	181	9.36	0.74
Sep ‘01	2.47	15.5	126	9.78	0.77
Oct ‘01	1.78	15.7	96	9.96	0.79
Nov ‘01	1.12	9.8	58	10.01	0.78
Dec ‘01	0.87	5.9	48	10.2	0.81
Jan ‘02	0.7	8.4	36	9.6	0.76
Feb ‘02	1.4	9.6	69	10.1	0.8
Mar ‘02	1.7	10.1	64	10.1	0.8
Apr ‘02	3.1	7.5	36	10.3	0.81
May ‘02	4	12.6	198	9.3	0.73
Jun ‘02	3.9	16.8	170	8.4	0.66
Jul ‘02	3.9	18.3	157	7.5	0.6
Aug ‘02	3.4	19.6	158	8.6	0.68
Sep ‘02	2.9	16.8	138	9.1	0.71
Oct ‘02	1.6	12.7	84	9.8	0.77
Nov ‘02	0.9	11	45	9.6	0.76
Dec ‘02	0.4	8.2	21	9.2	0.72

As for most of the other systems in the study, the measured data were downloaded on a weekly basis by modem link. This worked best when a dedicated telephone line was provided by the system owner. In this case, the housing association arranged for an additional line to be installed in the loft of the house, with responsibility for payment being taken by the association rather than the tenant. This caused problems on two occasions, firstly as a result of the telephone company disconnecting the line when the tenant indicated that it was not part of their requirement and, secondly, when the annual rental was not paid in due time by the housing association as a result of personnel changes in the organisation. In the first case, this did not lead to a loss of data because of the high storage capacity of the logger, but in the second case the logger capacity was exceeded resulting in a reduced monitoring fraction for April 2002. The value of the measured output for this month is much lower than the actual system performance.

It was also observed that the ambient temperature sensor began to give erratic readings during April 2002 and the average for that month is lower than would be expected. Although the values for later months are generally consistent with values from System C, the nearest of the other sites, the boxes have been shaded in Table 5 to indicate that there may be a higher error than usual on these values.

From the data in Table 5, the following values can be obtained:

- Average daily in-plane insolation for 2001 = 2.48kWh/m^2
- Average daily in-plane insolation for 2002 = 2.33kWh/m^2
- Average system efficiency for whole period = 9.3%
- Average performance ratio for whole period = 0.74
- Annual yield for 2001 = 639kWh/kWp
- Annual yield for 2002 = 534kWh/kWp (includes reduced output for April)

The main parameters from Table 5 are presented graphically in Figure 5. Inspection of the system efficiency shows a reduction in the summer months for both years of monitoring. This is unusual since most systems show a winter reduction due to lower average inverter efficiency. Although higher summer temperatures causes a reduction in array efficiency, the magnitude of the reduction observed in this case is much greater than would be expected. Inspection of the daily system data was required to determine the cause.

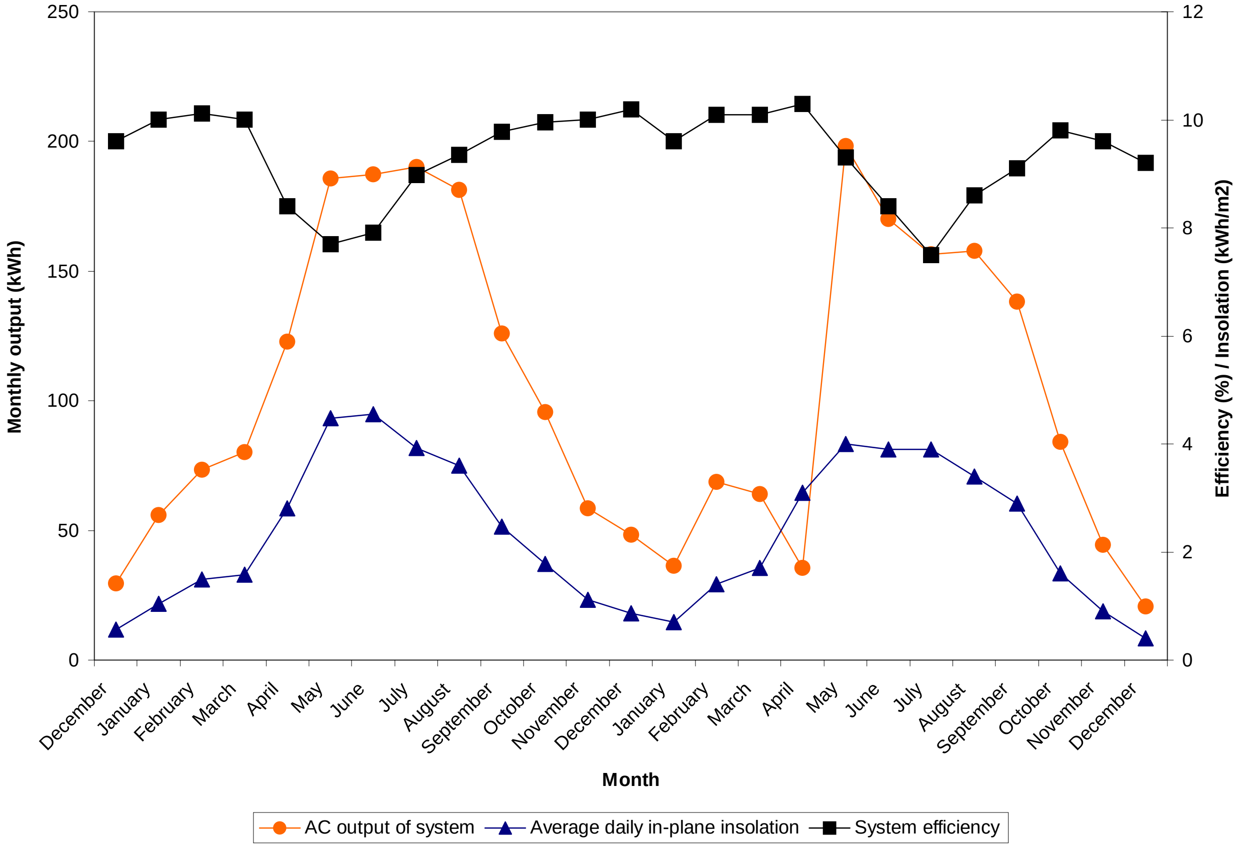

Figure 5. Variation of main system parameters with month for System D.

Figures 6(a) and (b) show the behaviour typically observed during the summer months. The data points in Figure 6(a) are output values taken at intervals of one minute throughout the day and plotted as a function of the irradiance level. Generally, these would be expected to follow a single line (or two closely spaced lines if operating temperature is a significant effect). Section 5.4 provides some more illustrations of this type of plot for other systems. In this case, there are two distinct sets of data and a trendline has been fitted through each set for illustrative purposes. The lower set of points is at about half of the value of the upper set for an equivalent irradiance value. This indicates that, for these points, only one of the inverters is operating.

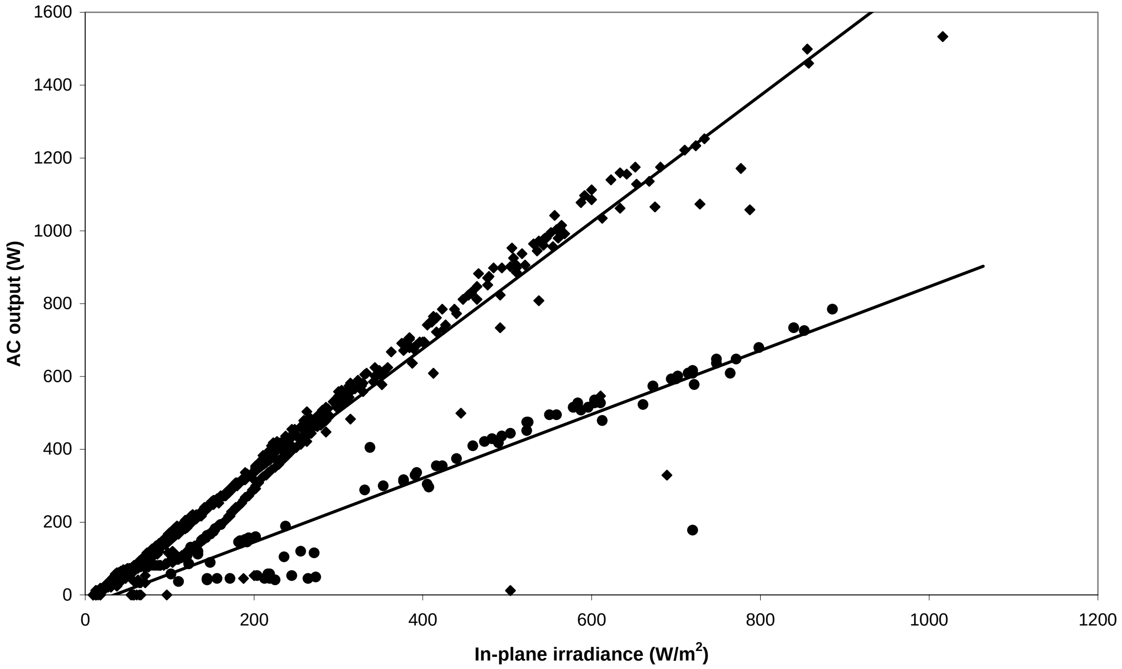

Figure 6(a). Comparison of AC output with irradiance level for System D on 9th June 2001.

This is confirmed by Figure 6(b), which shows the ratio of the system output to the irradiance value plotted as a function of irradiance for the central portion of the day. Under normal circumstances, the ratio would be expected to be roughly constant. In this graph, it can be seen that there are a few instances when both inverters are not operating (eg 10:42 and 12:00-12:12) and a significant number of instances when only one inverter is operating (eg 10:18-10:24, 12:30-12:42). This could not be seen directly from the measured data since the inverter that was dropping out was not the one being monitored.

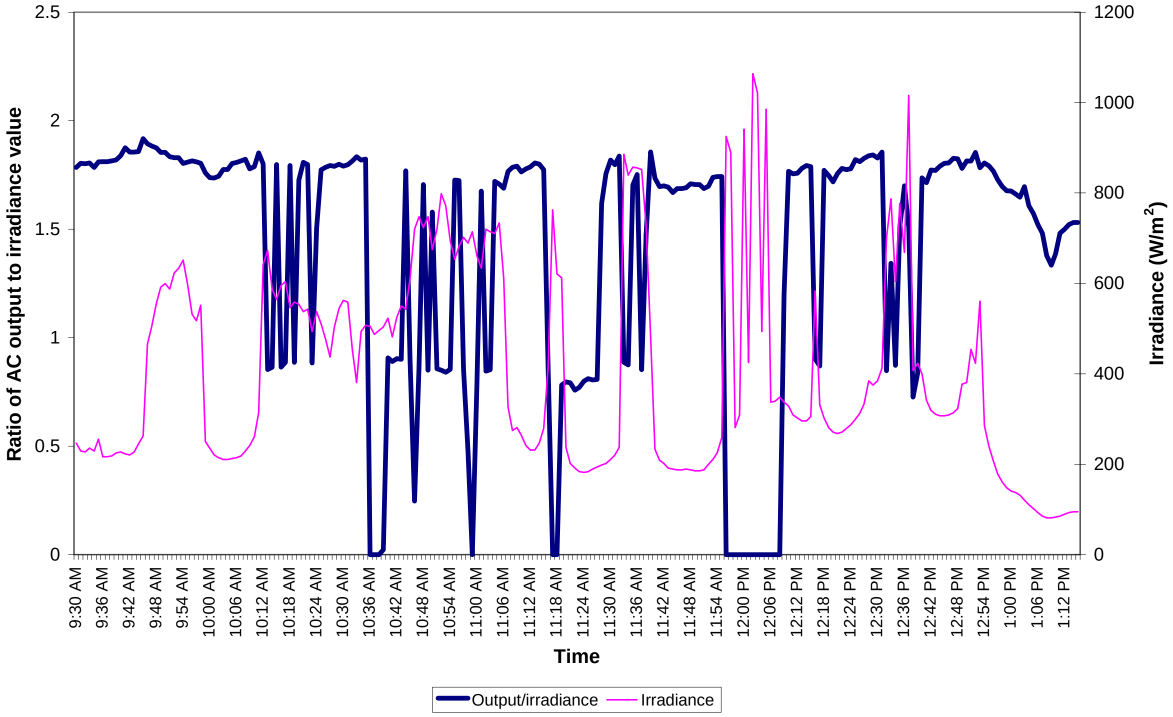

Figure 6(b). Illustration of inverter behaviour for System D, 09:30 - 13:30, 9th June 2001.

This behaviour looks similar to that observed for the first inverter on System A, but closer inspection of the data shows that a different trend is exhibited. The effect tends to happen at high irradiance values, but is not consistently linked with changes in irradiance. Also, it only occurs in the summer months (May to September), which is not consistent with the cause being a tracking problem since this would be expected to be present all year. It was felt that the most likely cause was high grid voltages at times of low load in the summer months. This could result in the inverter closing down due to the grid voltage being outside the allowable limits for operation. An external cause such as the grid voltage would explain the fact that the drop out of the inverter could not be correlated with specific sunlight conditions, but rather showed a seasonal effect.

Most inverters currently used in UK systems are manufactured in mainland Europe and the original settings relate to a 220-230V grid voltage. It is usual for a factory or field adjustment to be made to the inverter settings to allow operation up to 250V (generally the upper end of the range available from the inverter). It is not clear whether the problem observed for System D is a result of the adjustment not being made to the required extent or a particularly high grid voltage at the site, but it seems likely that it is a combination of both aspects.

The behaviour was reported to both the housing association and, at their request, the system installers, in early 2002 after the first year of monitoring data had been analysed. It was suggested that the inverter should be checked during the spring months, when the effect would be expected to recur. Neither party has advised that this check had taken place and inspection of the data for summer 2002 indicates that the problem remains unresolved.

This is not a trivial problem in terms of energy production from the system. For example, if we assume that the system should operate during the April – September 2001 period at the average system efficiency of the remainder of the year (calculated at10.05%), then the predicted annual yield becomes 716kWh/kWp. This indicates that 11% of the annual energy output was lost as a result of the inverter drop out. A similar calculation predicts an annual yield of 642kWh/kWp for 2002.

It should be recognised that this problem was not necessarily identifiable at the time of installation and, with the exception of the issue of adjustment for UK grid voltage, does not necessarily represent a design or installation fault. If it relates, as thought, to a high grid voltage that only occurs under certain load conditions, it may not have been possible to measure this during the installation of the system. The installation was carried out during the autumn of 2001, at which time the data indicates the problem is not experienced.

However, the user would also be unlikely to observe the problem even if a display of system output is provided. Unless they paid diligent attention to the system output and had a good understanding of the level of performance expected, the intermittent drop out of one inverter would not be observed. At most times, the display would show an output from the other half of the system and no error would be indicated.

The comparative performance of this system with the others included in this project is discussed in Sections 5.2 – 5.4.

4.6 Performance of System E

System E is another housing association property with a stand-off PV array mounted on the roof. The array consists of 14 crystalline silicon PV modules, each rated at 75Wp, connected to a single 0.7kW inverter. The nominal array rating is 1.05kWp and the array area is 8.9m^2.

Table 6 summarises the main system parameters determined for System E over the monitoring period between December 2000 and September 2002. The overall monitoring fraction for this period was 97.3%. The nominal module efficiency for this system was 11.7% based on the manufacturer’s rating.

Table 6. Summary of system parameters for System E.

Month	**Average daily in-plane irradiance (kWh/m^2)**	**Average ambient temperature (^{o}C)**	**Monthly AC output of system (kWh)**	**System efficiency (%)**	**Performance ratio**
Dec ‘00	0.8	6.7	19	8	0.68
Jan ‘01	1.2	4.3	29	8.4	0.71
Feb ‘01	1.8	5.4	29	7.5	0.64
Mar ‘01	2.1	6.2	0	0	
Apr ‘01	3.6	8.8	0	0	
May ‘01	4.8	13.3	64	4.8	0.41
Jun ‘01	5.1	15.8	115	8.4	0.71
Jul ‘01	4.6	17.9	107	8.4	0.71
Aug ‘01	3.9	17.3	89	8.4	0.71
Sep ‘01	2.9	14.1	65	8.4	0.71
Oct ‘01	2.1	13.8	33	5.8	0.49
Nov ‘01	1.3	8.2	28	8.4	0.72
Dec ‘01	1.1	4.3	26	8.7	0.73
Jan ‘02	0.7	6.9	2	1	0.08
Feb ‘02	1.6	7.9	0	0	0
Mar ‘02	2.7	8.5	59	7.9	0.67
Apr ‘02	4.4	9.9	37	3.1	0.27
May ‘02	4.4	12.4	59	4.9	0.41
Jun ‘02	4.8	15.1	109	8.5	0.72
Jul ‘02	4.6	16.6	104	8.3	0.7
Aug ‘02	3.9	17.4	90	8.3	0.7
Sep ‘02	3.7	15	83	8.4	0.71

Although it was originally intended to use a modem link to download data from this system, the available telephone line was not of sufficient quality to facilitate this. As a result, all data were downloaded manually by a representative from the housing association and forwarded be e-mail or disk as appropriate. This proved to be satisfactory for the majority of the monitoring period and a high monitoring fraction was generally obtained. However, there was a longer delay between measurement and inspection of the data than for other systems and system faults were not identified until several weeks after their occurrence.

This can be observed in the data given in the table. The shaded sections represent periods when the inverter was shut down. This occurred between 24/02/01 and 15/05/01, 7-17/10/01, 03/01/02-02/03/02, 12/04/02 – 01/05/02 and 20-29/05/02. In the first instance, the tenants were unaware that the inverter was not working until this was identified as a result of analysing the measured data in April 2001. It appears that the inverter was turned off during fitting of a new electricity meter at the property and was not turned on again by the engineer from the electricity company. Since there is no display indicating the performance of the system and the inverter is located in the roof space, the tenant would have had to deliberately check the system to observe the problem. Subsequent shutdowns of the inverter were similarly identified from the measured data although it has not been possible to establish the cause.

From the data in Table 6, the following values can be obtained:

- Average daily in-plane insolation for 2001 = 2.88kWh/m^2
- Average system efficiency for whole period = 6.9%
- Average performance ratio for whole period = 0.58
- Annual yield for 2001 = 555kWh/kWp

Clearly, the periods of shut down of the inverter have severely affected the average system efficiency and PR values and the annual yield. Inspection of the efficiency values shows very consistent performance in those months that exhibited no operational problems with a typical value of 8.4% and a corresponding PR value of 0.71. If we assume this efficiency for the other months and correct the monthly AC output accordingly, then the predicted yield is as follows:

- Predicted annual yield for 2001 = 747kWh/kWp

The main parameters in Table 6 are presented graphically in Figure 7. The effects of the inverter trips on the monthly output and the system efficiency can be clearly seen.

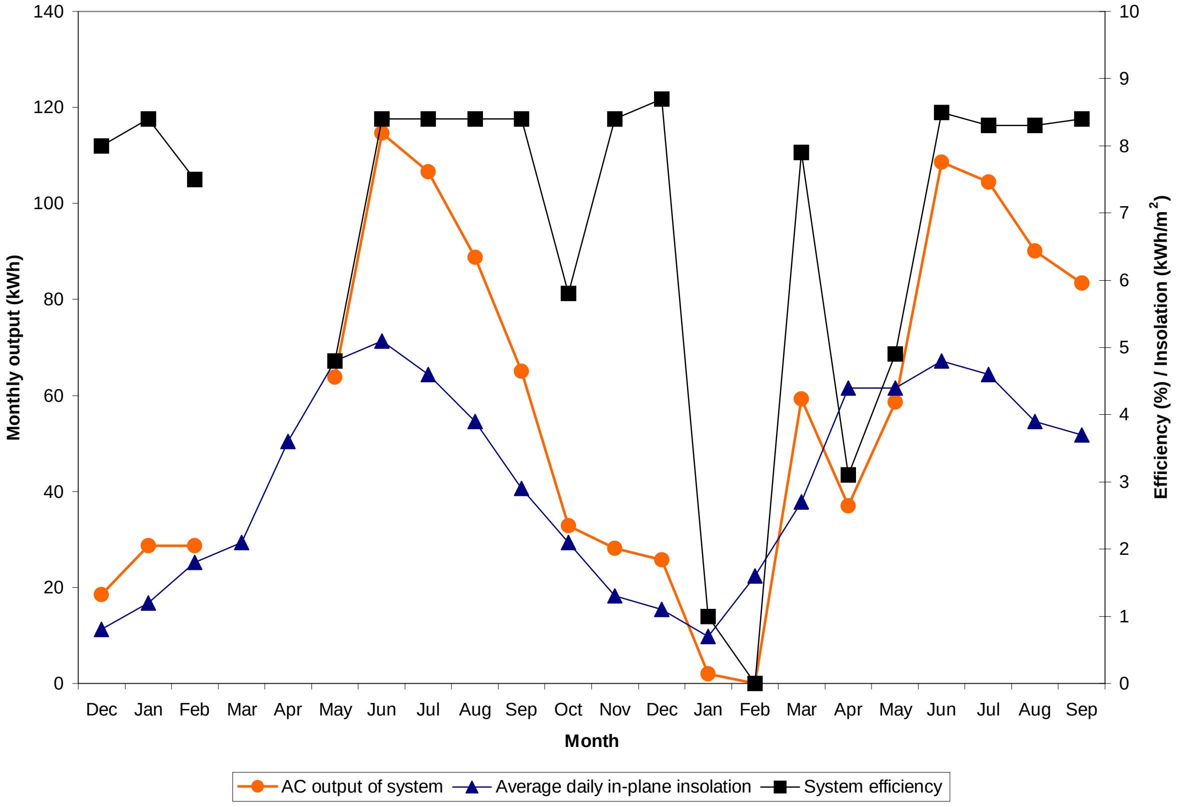

Figure 7. Variation of main system parameters with month for System E.

Other than the problems with the inverter, no other significant operational issues have been identified for this system.

4.7 Performance of System F

System F is a privately owned system, again in a stand-off configuration mounted on the house roof. It consists of 12 crystalline silicon modules each rated at 85Wp, to give a nominal array rating of 1.02kWp. The inverter is rated at 0.85kW and the array area is 7.56m^2.

Table 7 summarises the main system parameters determined for System F over the monitoring period between December 2000 and December 2002. The overall monitoring fraction for this period was 99.8%. The nominal module efficiency for this system was 13.5% based on the manufacturer's rating.

Table 7. Summary of system parameters for System F.

Month	Average daily in-plane irradiance (kWh/m^2)	Average ambient temperature (^{o}C)	Monthly AC output of system (kWh)	System efficiency (%)	Performance ratio
Dec '00	1.1	5.9	22	8.9	0.66
Jan '01	1.6	4	41	10.6	0.78
Feb '01	2.2	5.2	50	10.9	0.81
Mar '01	2.4	5.9	61	10.9	0.81
Apr '01	3.4	8.4	83	10.8	0.8
May '01	4.9	14.1	120	10.5	0.78
Jun '01	4.8	15.6	118	10.7	0.8
Jul '01	4.3	18.3	106	10.6	0.78
Aug '01	4.1	17.5	102	10.6	0.79
Sep '01	2.8	13.9	68	10.8	0.8
Oct '01	2.2	13.4	57	11	0.82
Nov '01	1.6	7.8	38	10.6	0.79
Dec '01	1.5	4.3	32	9.5	0.7
Jan '02	1	6.3	22	9.7	0.72
Feb '02	1.9	7.5	42	10.6	0.78
Mar '02	2.9	8.3	73	10.7	0.79
Apr '02	4.8	10.2	112	10.3	0.78
May '02	4.5	12.6	108	10.4	0.77
Jun '02	4.6	15.1	108	10.3	0.76
Jul '02	4.6	17.1	112	10.5	0.77
Aug '02	3.9	18	94	10.4	0.77
Sep '02	3.7	15.6	89	10.5	0.78
Oct '02	2.3	10.5	56	10.6	0.78
Nov '02	1.3	8.7	29	10	0.74
Dec '02	0.8	6.2	16	9.2	0.68

From the data in Table 7, the following values can be obtained:

- Average daily in-plane insolation for 2001 = 2.98kWh/m^2
- Average daily in-plane insolation for 2002 = 3.0kWh/m^2
- Average system efficiency for whole period = 10.4%
- Average performance ratio for whole period = 0.77
- Annual yield for 2001 = 857kWh/kWp
- Annual yield for 2002 = 844kWh/kWp

This system was very reliable and well behaved showing consistent system efficiency throughout. There were no observed problems with the inverter. The main parameters in Table 7 are presented graphically in Figure 8. As expected, a small reduction in efficiency is seen in the winter months.

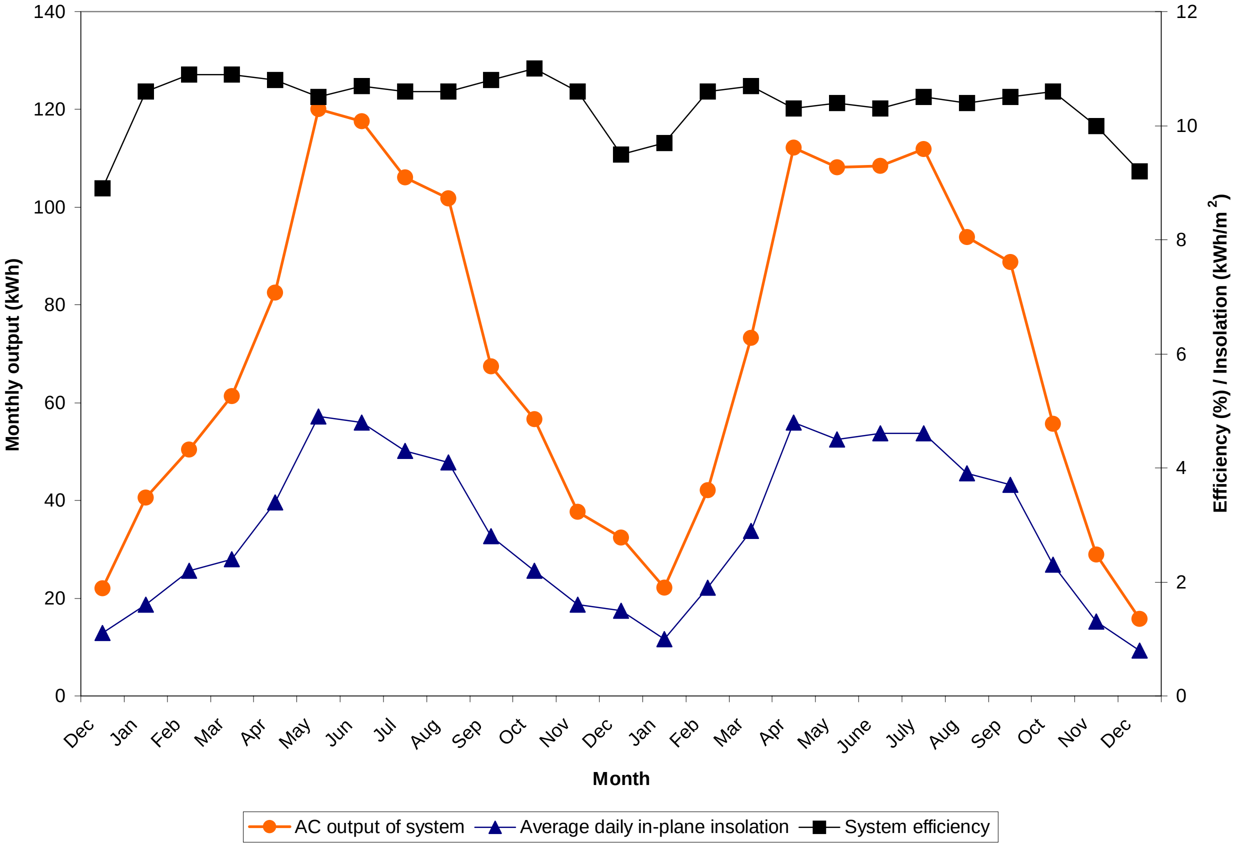

Figure 8. Variation of main system parameters with month for System F.

In July 2002, the owner installed a second system of the same rating using the same module and inverter types, supported under the Major Demonstration Programme. This did not affect the monitoring of the existing system except in respect of the import and export values for the electricity supply.

It was decided that the values should be corrected to represent the situation with a single system so as to allow the monitoring period to be completed. The owner assisted in this by providing the daily totals from the second system as provided by the inverter display. These values were then used to calculate the ratio of the outputs of the first and second systems. Assuming that this ratio was constant throughout the day, it was then possible to reconstruct the import and export data. This assumption does introduce an error, since it is known that the second array has some shading in the morning and late evening. This is supported by the fact that the daily totals are slightly lower for second system. However, it is the only method that can be implemented with the present data set to allow account to be taken of the second system. A discussion of the contribution of the PV system to meeting the building load is provided in Section 5.5.

4.8 Performance of System G

System G is rated at 1.4kWp and consists of 40 crystalline silicon roof tiles, each rated at 35Wp each. The system is integrated into the roof of the house and the array area is 15.8m^2. The array is divided into two sub-arrays, each connected to a 0.7kW inverter. The system is installed on a housing association property.

Although this system was one of the first sites to be identified and agreed within the project, the commencement of the monitoring was delayed by long negotiations regarding the grid connection of the system. Since the participation in this project was voluntary, there was no obligation for the housing association to complete the connection in direct relationship to the monitoring, although they were, of course, keen to conclude the work to allow the PV system to operate. Although the installation of the monitoring system took place in February 2001, it was not until April 2002 that the monitoring could be commenced.

Unfortunately, shortly after the monitoring period started, there was a problem with the system and as a result it was not possible to download data. It is believed that the problem was caused by the installation of a new card meter that was unsuitable for use with the PV system. It has already been noted in the installation phase of the Domestic PV Field Trial that certain electrical prepayment meters are incompatible with PV systems because they are permanently damaged by export of electricity and, although it has not been confirmed, this may have been a contribution in this case.

After reconnection of the PV system, checking of the monitoring system by the housing association staff failed to locate any fault but the downloading was still not operational. It was decided that, given the short time before the end of the project, the effort involved in repairing this system was not justified. Thus, the data analysis for this system concerns only a period of nine days in April and May 2002. Whilst it was not possible to perform the detailed analysis carried out for the other systems, some comparisons can be made. Systems using similar modules are included in the Domestic PV Field Trial, so further data on this system design should be available from this programme in the near future.

Table 8. Summary of system parameters for System G.

Day	Average in-plane irradiance (kWh/m^2)	Average ambient temperature (^{o}C)	AC output of system (kWh)	System efficiency (%)	Performance ratio
24 April 02	5.70	13.19	5.8	6.38	0.72
25 April 02	5.38	12.38	5.6	6.55	0.74
26 April 02	2.89	9.85	3.0	6.46	0.73
27 April 02	3.85	9.39	4.1	6.71	0.75
28 April 02	2.89	9.29	2.9	6.27	0.70
29 April 02	3.05	9.18	3.1	6.41	0.72
30 April 02	3.51	10.13	3.7	6.59	0.74
1 May 02	3.92	9.51	4.1	6.46	0.73
2 May 02	5.62	10.80	5.7	6.42	0.72

From the table, the following values can be calculated.

- Average system efficiency = 6.5%
- Average performance ratio = 0.73

Clearly, it is not possible to extract as much information about this system as for the others in the study. The consistency of efficiency values in the few days for which the system was operational is encouraging and the performance ratio value is reasonable for an integrated array. Where possible, results from System G will be included in the discussions of comparative performance in later sections.

4.9 Performance of System H

System H is the most complex of the eight systems in the project. It consists of two arrays, one fixed and one tracking. Both arrays use crystalline silicon modules rated at 85Wp each and they are rated at 0.68 and 0.85kWp respectively. The fixed array is a stand off system mounted on the roof, whereas the tracking system is ground mounted on a metal support frame. In addition, the system has a battery storage system connected between the arrays and the inverter. It was originally a stand alone system, but was adapted to a grid connected system shortly before the planned commencement of the monitoring.

The monitoring system was originally scheduled to be installed in March 2001, but was delayed by the outbreak of foot and mouth disease in the North East. This system is located in a rural farming area and access to the site was restricted so as to prevent spread of the disease. A second installation date in early June also had to be rescheduled due to a second outbreak in the region of the site in the previous month. The system was finally installed in October 2001 and data collection commenced the following month.

The system configuration is significantly different from the other systems included in the study. For most of the time, it is used in grid-connected mode, with the batteries kept fully charged, and the output of the PV arrays fed to the inverter. However, it is possible to use it in a stand-alone mode, with either the PV array or the battery system as the energy source. If the batteries are discharged, the output of the PV array will first recharge them and then feed excess power to the inverter. The batteries can also be charged directly from the grid, via the inverter.

This has a number of implications for the operation of the PV system. Firstly, the array operates at a fixed voltage of between 26.5 and 27V rather than in maximum power point tracking mode. Secondly, the system voltage is low, in order to be appropriate for the battery charging activity. Thirdly, the inverter is sized at 2.5kVA in order to meet the requirements in stand-alone operation when the battery bank is acting as the power supply. Thus the inverter is significantly oversized in comparison to the PV array (total rating of 1.53kWp) and will be operating at the lower end of its power range for most of the time. Finally, because the outputs of the two arrays are combined before feeding into the batteries, it is only possible to measure the DC performance of the arrays separately.

In early May 2002, the tracking mechanism on the tracking array developed a fault and this was not rectified until August 2002. Whilst this does not affect the system efficiencies calculated for this array, it did reduce the array output significantly and so affects yield values. In addition, there are no comparative values between the fixed and tracking arrays for the main summer months when the benefits of tracking would be expected to be greater in terms of output values. It was not felt that attempting to predict the system output with tracking was justifiable in these circumstances.

Tables 9 and 10 show the system parameters for the fixed and tracking arrays respectively. In both cases, the output values, system efficiency and performance ratio are for the DC system and do not include the inverter efficiency. For both arrays, the rated module efficiency is 13.5%. There were some problems with downloading of the data from this site at the beginning of the monitoring period and the monitoring fraction fell well below the limits discussed in Section 4.1.4. Thus the tabulated data commences from January 2002.

Table 9. Summary of system parameters for System H, fixed array.

Month	**Average daily in-plane irradiance (kWh/m^2)**	**Average ambient temperature (^oC)**	**Monthly DC output of system (kWh)**	**DC system efficiency (%)**	**DC performance ratio**
Jan '02	0.6	3.6	3	5	0.37
Feb '02	1.2	4.6	9.4	5.7	0.43
Mar '02	2.4	5.4	21	7	0.52
Apr '02	3.8	7.2	41.6	7.3	0.54
May '02	3.9	9.9	44.8	7.5	0.55
Jun '02	3.9	12.2	41.1	6.9	0.51
Jul '02	3.5	13.7	39.6	7.2	0.53
Aug '02	3.3	15.2	37.8	7.2	0.54
Sep '02	3.1	12.7	31.3	6.9	0.51
Oct '02	1.6	7.8	16.7	6.6	0.49
Nov '02	0.9	6.6	7.7	5.9	0.44
Dec '02	0.5	3.6	3.9	5	0.37

Table 10. Summary of system parameters for System H, tracking array.

Month	**Average daily in-plane irradiance (kWh/m^2)**	**Average ambient temperature (^oC)**	**Monthly DC output of system (kWh)**	**DC system efficiency (%)**	**DC performance ratio**
Jan '02	1.1	3.6	9.3	6.9	0.51
Feb '02	1.8	4.6	27	8.7	0.64
Mar '02	3.4	5.4	50.1	9.5	0.71
Apr '02	4.8	7.2	81.9	9.1	0.68
May '02	3.2	9.9	55	8.9	0.68
Jun '02	3.5	12.2	57.1	8.7	0.65
Jul '02	3.1	13.7	51.7	8.6	0.64
Aug '02	3.4	15.2	56.7	8.7	0.64
Sep '02	3.2	12.7	52.8	8.9	0.66
Oct '02	2.2	7.8	39.8	9.3	0.69
Nov '02	1.3	6.6	21.7	8.6	0.64
Dec '02	0.8	3.6	12	7.4	0.55

From Tables 9 and 10, the following parameters can be calculated.

- Average daily in-plane insolation, fixed array = $2.4kWh/m^2$
- Average DC system efficiency, fixed array = 6.5%

- Average DC system efficiency, tracking array = 8.6%
- Average DC performance ratio, fixed array = 0.48
- Average DC performance ratio, tracking array = 0.64
- DC annual yield, fixed array = 438kWh/kWp
- DC annual yield, tracking array = 606kWh/kWp (note that this is reduced because of the fault in the tracking system)

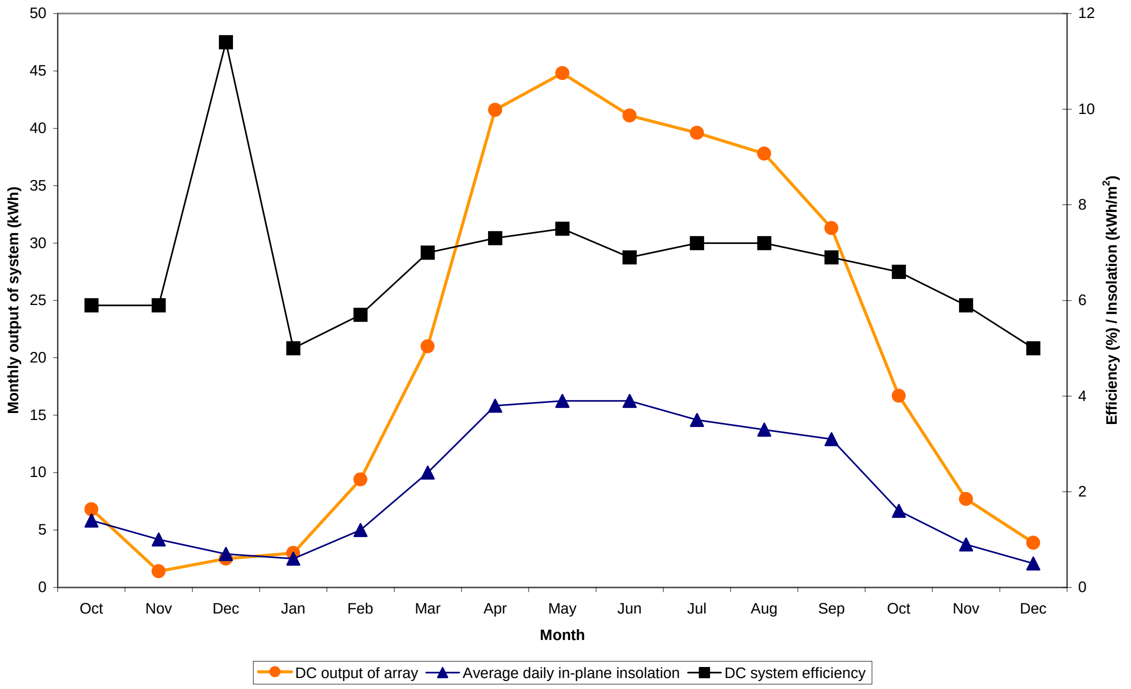

Figure 9. Variation of main system parameters for System H, fixed array.

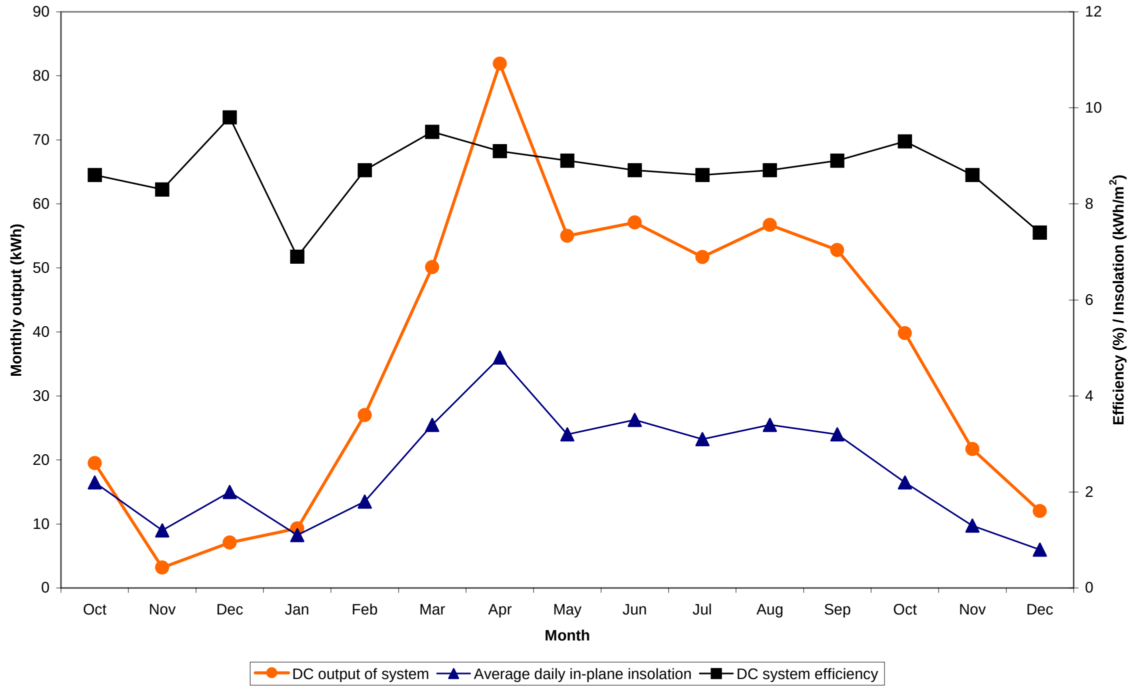

Figure 10. Variation of main system parameters for System H, tracking array. Note that in-plane insolation is not corrected for the tracking fault in the May-August period.

It is clear that the performance ratios of this system are substantially lower than the other systems and this is will be discussed in more detail in Section 5.4.

5. COMPARISONS OF SYSTEM PERFORMANCE

In this section, the results from individual systems are collated and compared to extract general conclusions about the performance of systems. In addition, the agreement between performance prediction using widely available design software and the measured data is discussed. The contribution of the PV systems towards the electrical loads of the dwellings is also considered.

5.1 Horizontal Insolation Levels

One of the benefits of monitoring several sites simultaneously is that it is possible to consider the variation of insolation levels across a range of locations. Horizontal insolation values have been measured at seven of the sites, although the limited data set from System G means that this has not been included in the comparison.

In Figure 11, the values from the different sites are compared on a bar chart. The figure is split into two parts representing values for 2001 (Figure 11a) and 2002 (Figure 11b) for clarity. The values for each month are presented in system order, starting with the most southerly at the left-hand side.

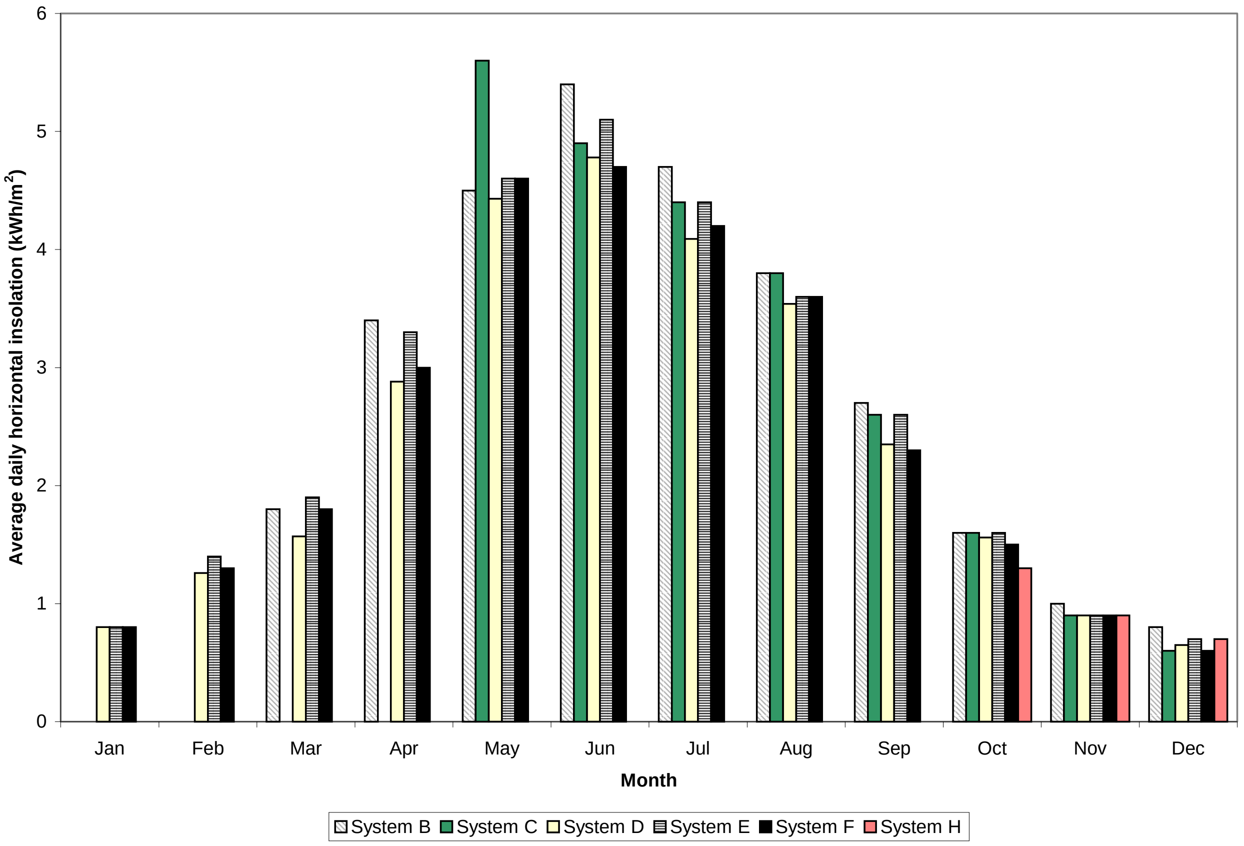

Figure 11a. Comparison of measured horizontal insolation values for 2001 at six sites. Note that sites began monitoring at different times.

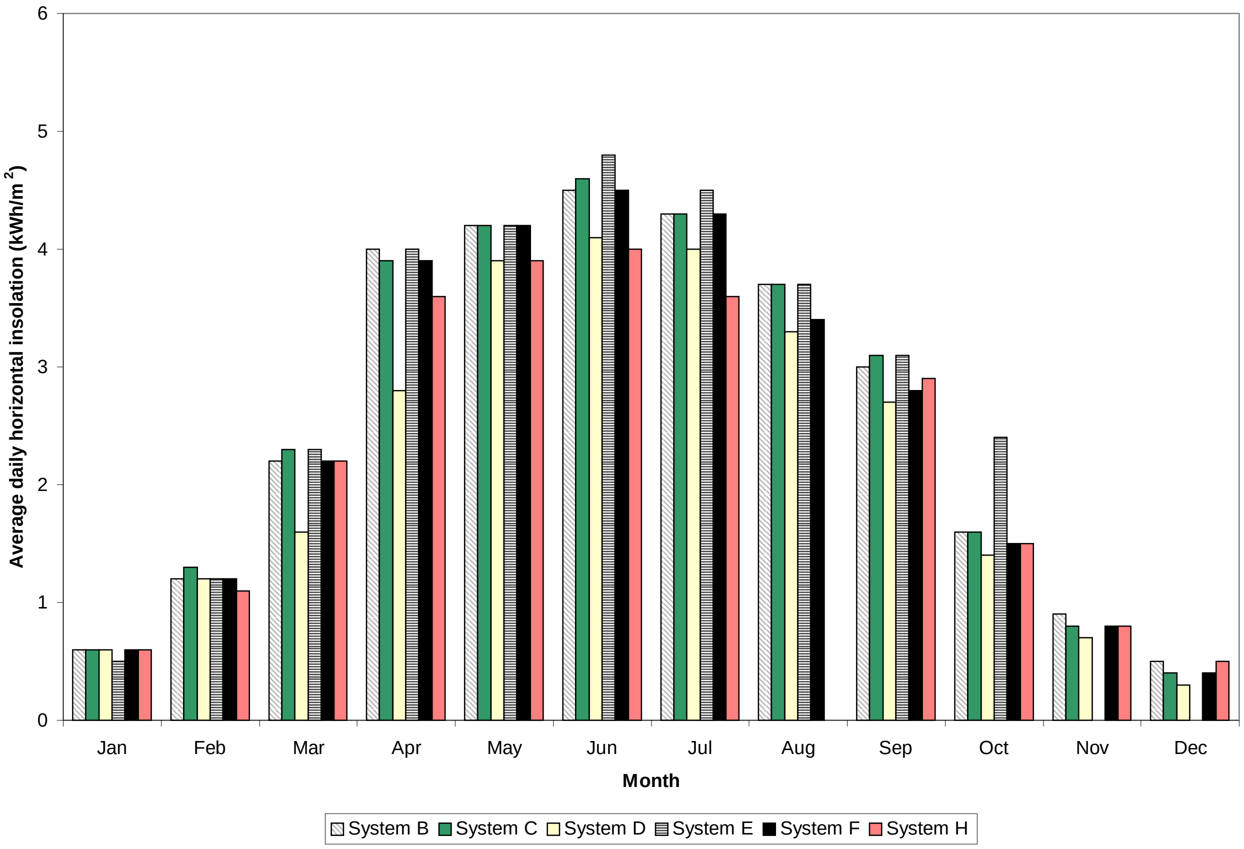

Figure 11b. Comparison of measured horizontal insolation values for 2002 at six sites.

The first observation is that the values from all sites are very consistent, apart from a couple of instances where high values are obtained. The high values for System C in May 2001 and for System E in October 2002 are the result of low monitoring fractions for these months, as is the low value for System D in April 2002. Comparison of the horizontal values for Systems C and D over the restricted period available for System C in May 2001 showed good agreement in support of this conclusion.

There is a small indication of reducing values from south to north, but it is not pronounced. This confirms that it is acceptable to use solar data from nearby sites for design and prediction purposes and that there is no significant shift in insolation levels over the geographical area considered here. This comparison can be extended to the Domestic Field Trial data, which will provide a greater spread of locations than was possible in this project.

5.2 Temperature Effects

The effect of temperature on system performance is significant and it is useful to establish the typical operating temperatures experienced by UK systems. Ambient temperature was measured at all sites and array temperature at six of the eight sites. For the two remaining systems (B and C), the installation of the sensors would have required removal of tiles or modules and this was considered to be an unacceptable risk to the project. The thermal behaviour of these two systems is inferred from comparison with the other sites.

Figures 12 (a) and (b) show the variation of average ambient temperature by month for seven sites for 2001 and 2002 respectively. It can be seen that there is a high degree of consistency across the sites but with some clear trends. As might be expected, the two Greater London sites generally show higher averages by 0.5-1 degree Celsius due to the urban location. Also, System H shows a generally lower temperature by 2-3 degrees Celsius. This is both further north and an exposed rural location. The high value for System C in May 2001 is again the result of the low monitoring fraction for this month.

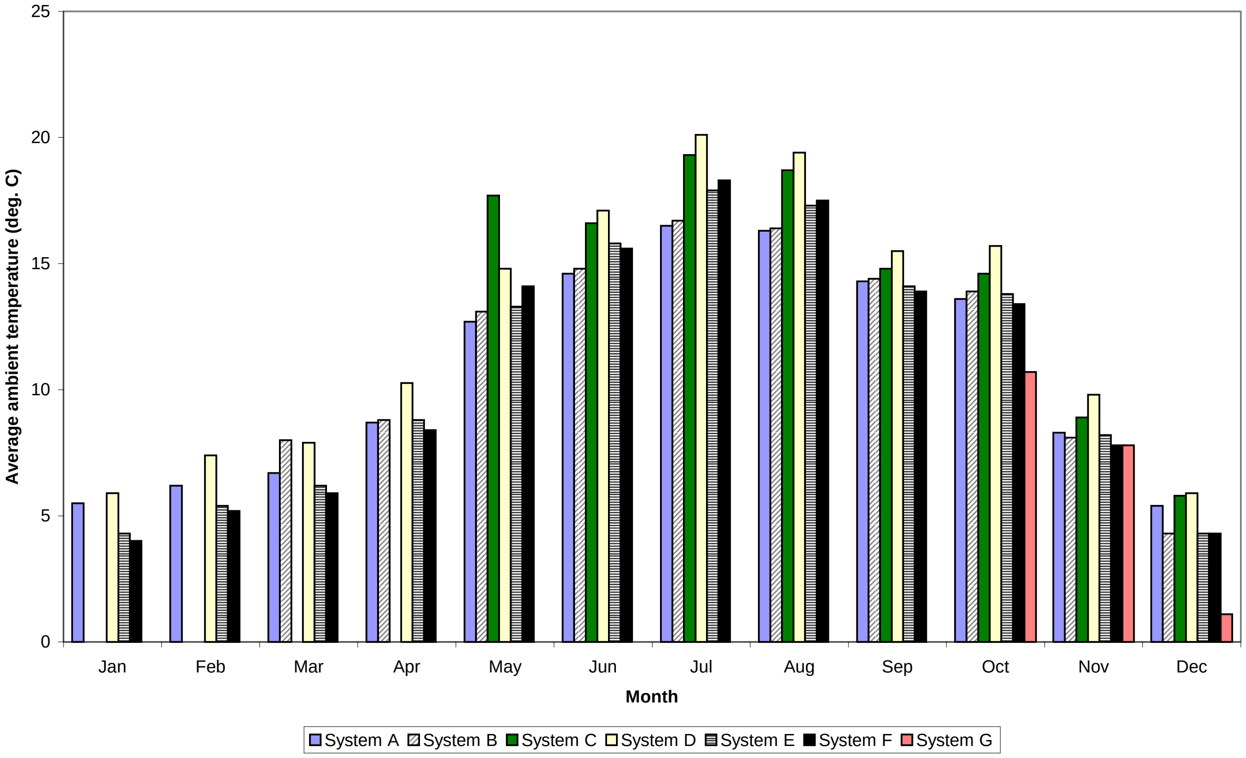

Figure 12a. Variation of ambient temperature with month for 2001.

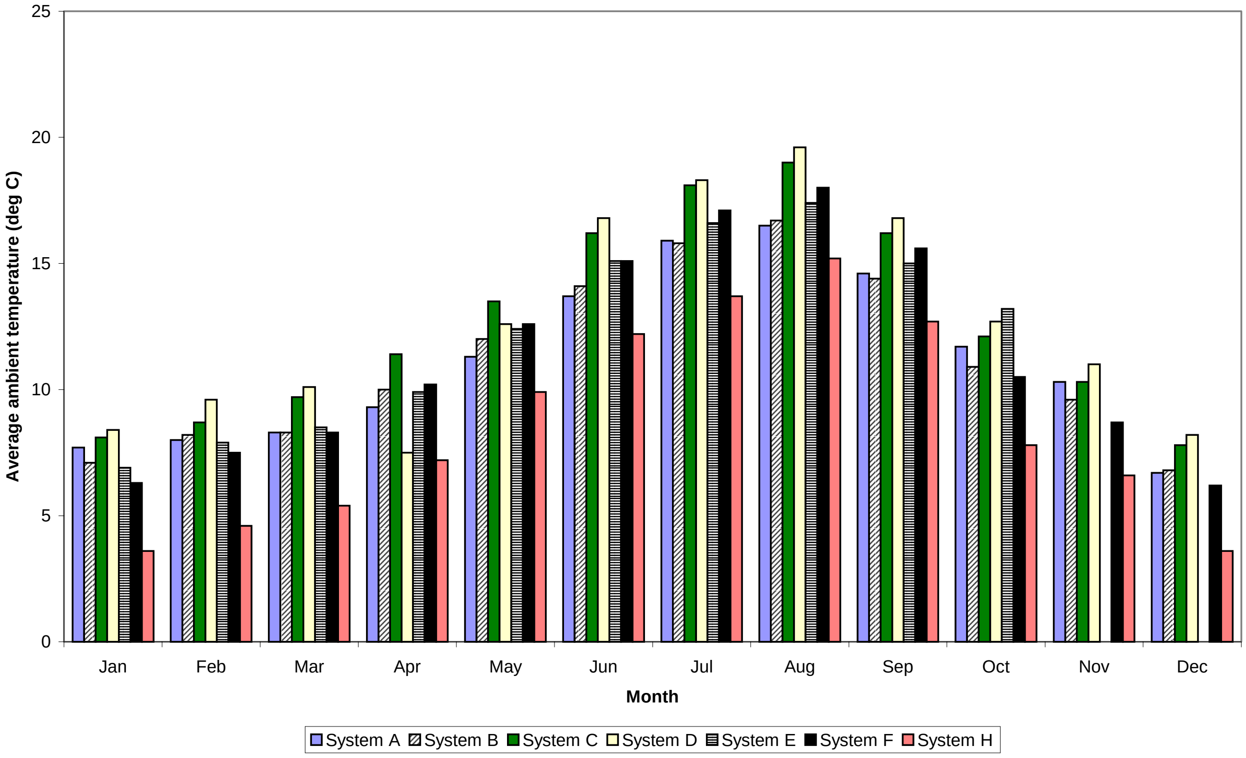

Figure 12b. Variation of average ambient temperature with month for 2002.

If we now consider average array temperatures, as shown in Figure 13(a) and (b), then it can be seen that again System H shows a significantly lower value than the other systems. Whilst there is a high level of consistency between the other four systems during the summer months, the integrated array of System A shows a higher winter temperature than the roof mounted, stand-off arrays of Systems D, E and F. It should be noted that these average temperatures are calculated for the full day (i.e. 24 hours) and so module temperatures during operation of the array will be significantly higher.

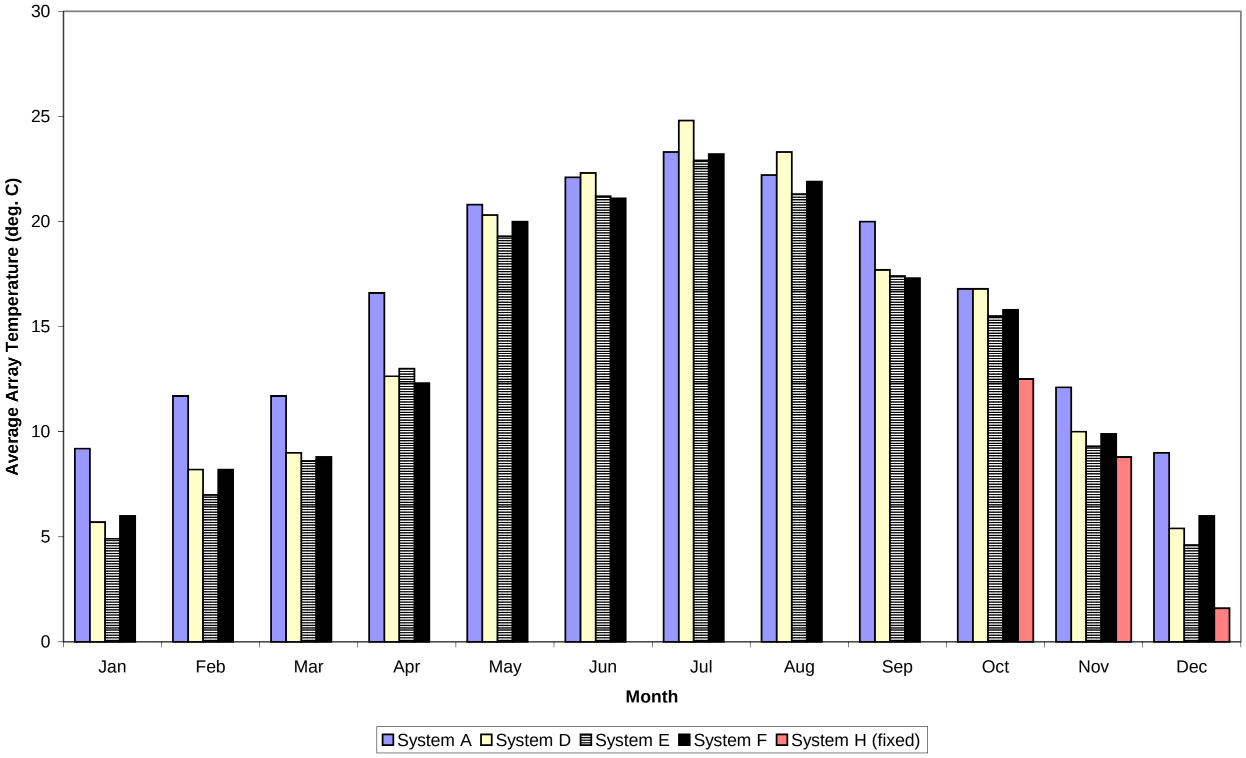

Figure 13a. Variation of average array temperature with month for 2001.

Calculation of the array temperatures over only the operating period for the full data set was outside the scope of this project, but a limited amount of analysis has been performed. Figure 14 shows a plot of the difference between the daily operating temperature (averaged over the operating period of the system only) minus the daily ambient temperature (averaged over 24 hours, as is provided in most climate databases) as a function of daily irradiation. This plot is for System F in July 2001, although similar plots can be obtained for the other systems and other months. By fitting a straight line through the data points, an effective temperature coefficient can be produced. Table 11 shows the coefficients calculated for four of the systems for the months of July and November 2001.

Table 11. Array temperature coefficients for the difference between daily average array and ambient temperatures calculated for July and November 2001 (values in degrees Celsius per kWh).

System	**A**	**D**	**E**	**F**
July 2001	2.90	2.06	2.27	2.19
November 2001	5.14	4.02	2.92	3.45

In all cases, a higher value is obtained in the winter months, due to the fact that the transfer of heat from the module is more rapid when the ambient temperature is lower. This means that there is less thermal lag in the system.

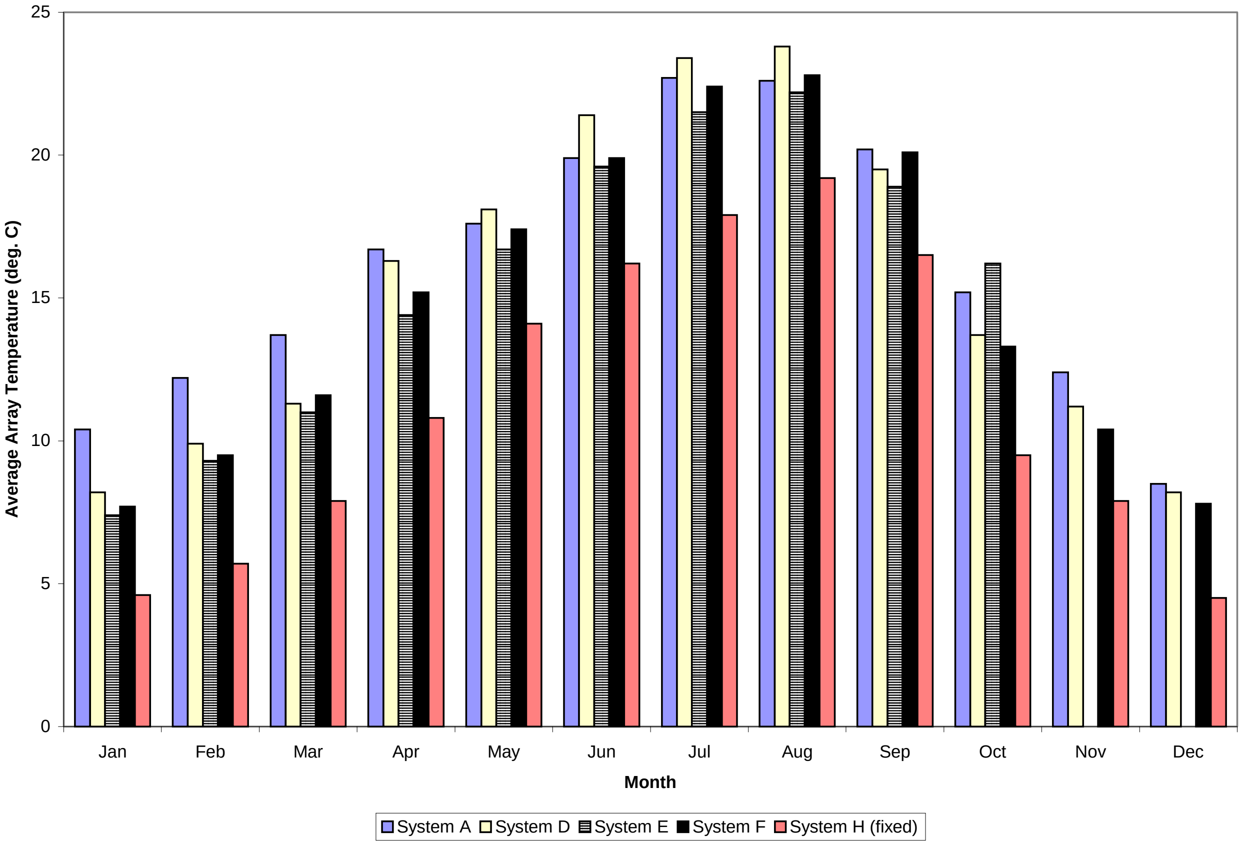

Figure 13b. Variation of average array temperature with month for 2002.

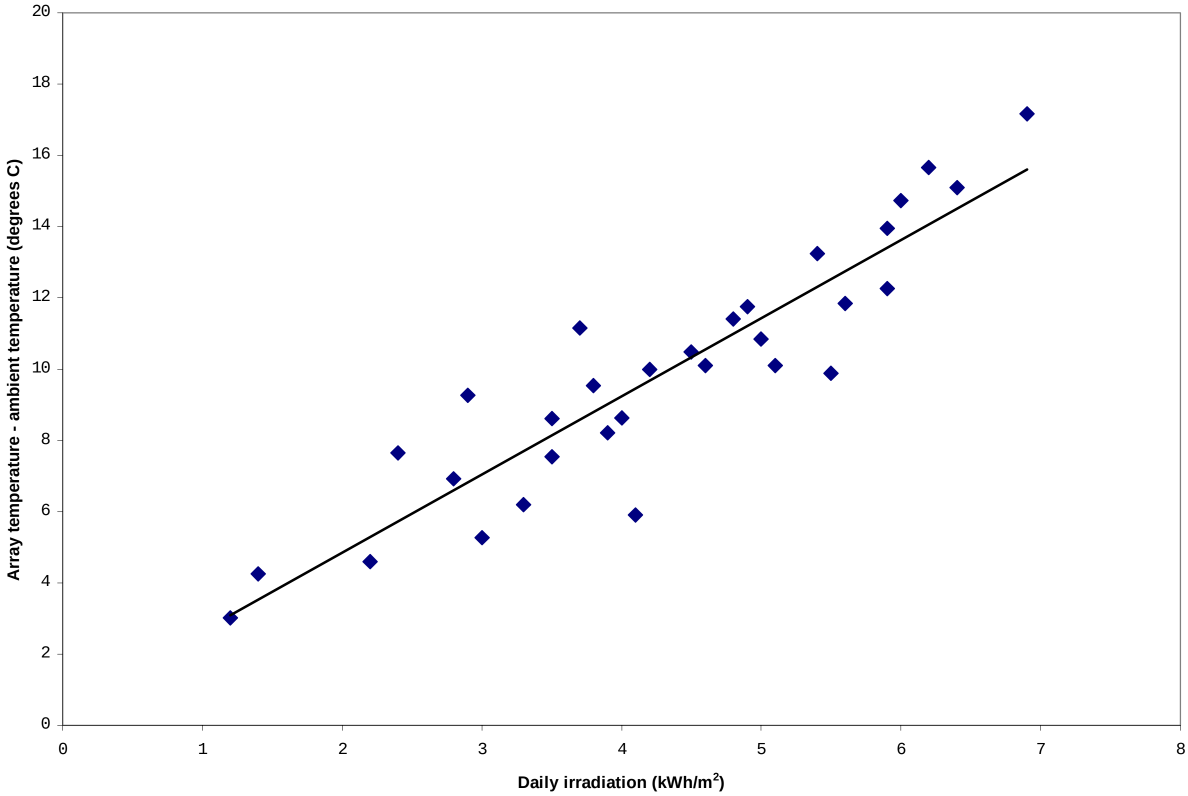

Figure 14. Difference between average daily array temperature and average daily ambient temperature as a function of daily irradiation value for System F in July 2001.

It is also instructive to consider the highest recorded operating temperatures for some of the systems. System F recorded a temperature of 65.8^{o}C in July 2002 and this is the highest level of any of the measured systems. This was for a high irradiance level of 962W/m^2 and a particularly high ambient temperature, recorded at 36^{o}C. No other site exhibited this high an ambient temperature and this probably explains why the array temperature was also the highest. The ambient temperature level was checked for consistency both at that site and between sites and there is no indication that this reading was in error.

System A recorded an array temperature of 60.7^{o}C, also in July 2002, for an irradiance level of almost 930W/m^2 and an ambient temperature of 25^{o}C. Unfortunately, the temperature sensors on Systems D and H were only calibrated to a level of 55^{o}C and the array temperature exceeded this value several times during the months of July and August.

System G is the only one where an array temperature could be measured for an integrated system, but only a small amount of data is available for that site. The array reached 52.4^{o}C in early May for an ambient temperature of around 14^{o}C and an irradiance of about 660W/m^2. These values are obviously much lower than those for which the maximum temperatures were recorded for other systems. It is difficult to reproduce operating conditions for different systems, but comparing the temperature for System G with that for Systems A, D and F under similar conditions, it is estimated that System G is operating 5-10 degrees hotter than the stand-off systems of D and F and a few degrees hotter than the integrated array of System A. Similar thermal behaviour to that for System G would be expected for Systems B and C.

The effect of temperature on the system performance can be seen in Figure 15, which shows the instantaneous output power as a function of irradiance for System F in early June 2002. This system shows one of the lowest temperature dependencies of the systems studied, but the difference between the performance in the morning (the upper groups of points) and the afternoon (the lower group of points) is obvious. This is due to the heating of the array during the central portion of the day and the array temperature therefore being a few degrees higher during the afternoon.

5.3 Comparison with System Simulation

In this section, the performance parameters derived from the measured data for several systems will be compared with the results of system simulation. In this case, average insolation values for the array planes were obtained from Meteonorm (Version 3) and system simulations were performed using PVSyst 3.1. Both these software packages are used extensively by the PV community in the design of systems and for output predictions. In particular, the comparison has considered horizontal and in-plane insolation, annual yield, system efficiency and performance ratio.

System simulations have been carried out for Systems A, B, C, D and F. Only the south facing array has been considered for System C. System E experienced several problems with inverter trips and, whilst it is possible to predict the output values for these periods, it requires several assumptions to be made. Therefore, it was not felt to be suitable to include this system in the simulations. There is insufficient data for System G and System H is too complex to be simulated in a conventional package.

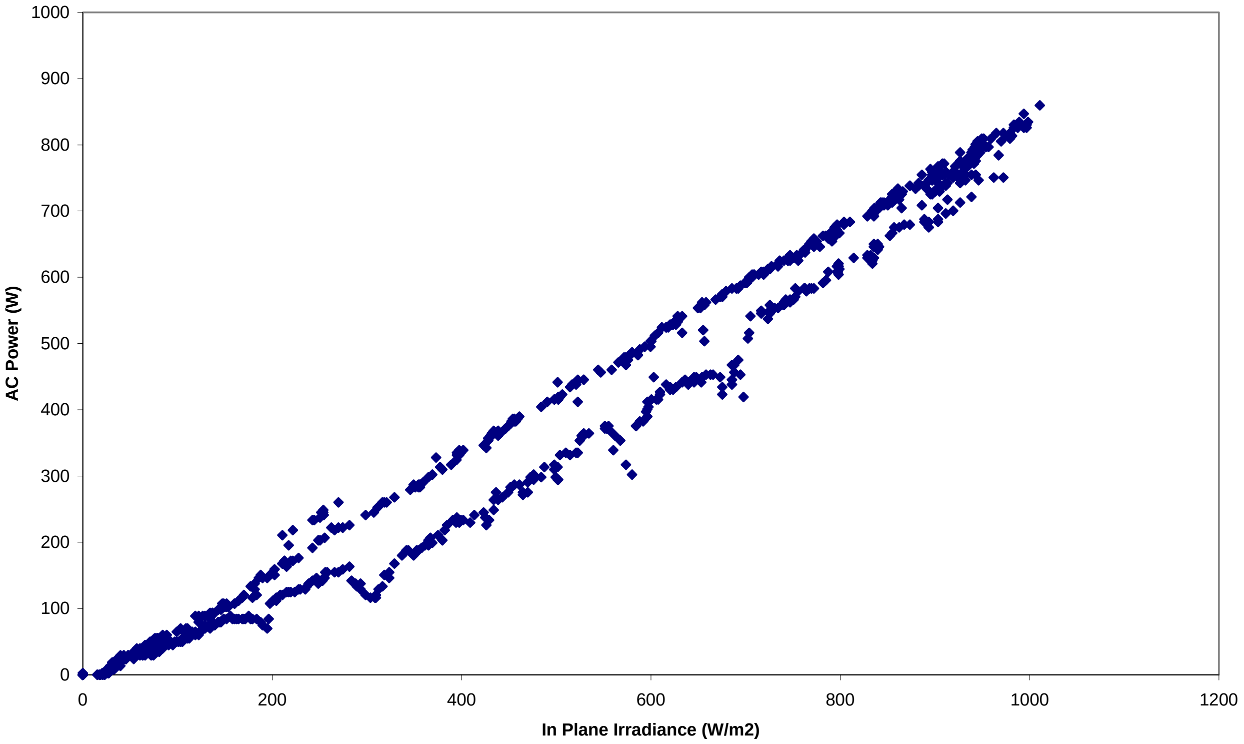

Figure 15. Graph of AC power output versus irradiance for System F on 1st June 2002.

5.3.1 Insolation Levels

In the first instance, the insolation levels in the plane of the array were obtained from Meteonorm and from the embedded database in PVSyst for the five systems. This included a range of orientations (-45° for System B, +64° for System D and zero for the other three systems) and tilt angles between 11° (System C) and 40° (System A). Databases such as Meteonorm and the insolation records used by system simulation programs use either average insolation values or representative annual data (such as Test Reference Years). This project has collected actual insolation values for two years or less. Therefore, the measured data would not be expected to yield similar values to the prediction programmes. However, comparison of the values can allow the measured performance to be judged against the predicted performance, taking into account different insolation conditions.

Figure 16 shows the comparison of the predicted in-plane insolation values for System F as an example. The bar chart contains four data series. These are the two database series from Meteonorm and PVSyst, both for the selected location of Birmingham. This was identified as the nearest location available in the database. The third and fourth data series are measured data for 2001 and 2002 respectively. It can be seen that the databases generally predict the variation of the insolation well, apart from a few months where the measured data are unusually high or low. However, some care must be taken in the selection of the appropriate location within the database. Figure 17 shows a similar plot for System A and here two alternative Meteonorm sites are compared with the PVSyst and measured data. The first site is Efford, which is the closest in terms of latitude and longitude to the System A site, although still a significant distance to the east. The second site is London, which is the nearest major city in regard to latitude and which is also included in the PVSyst standard database. It can be seen that there is a substantial difference between the Efford and London data sets, particularly in the early months of the year. Indeed, the databases for these two sites differ substantially more than has been observed for the measured data obtained in this study.

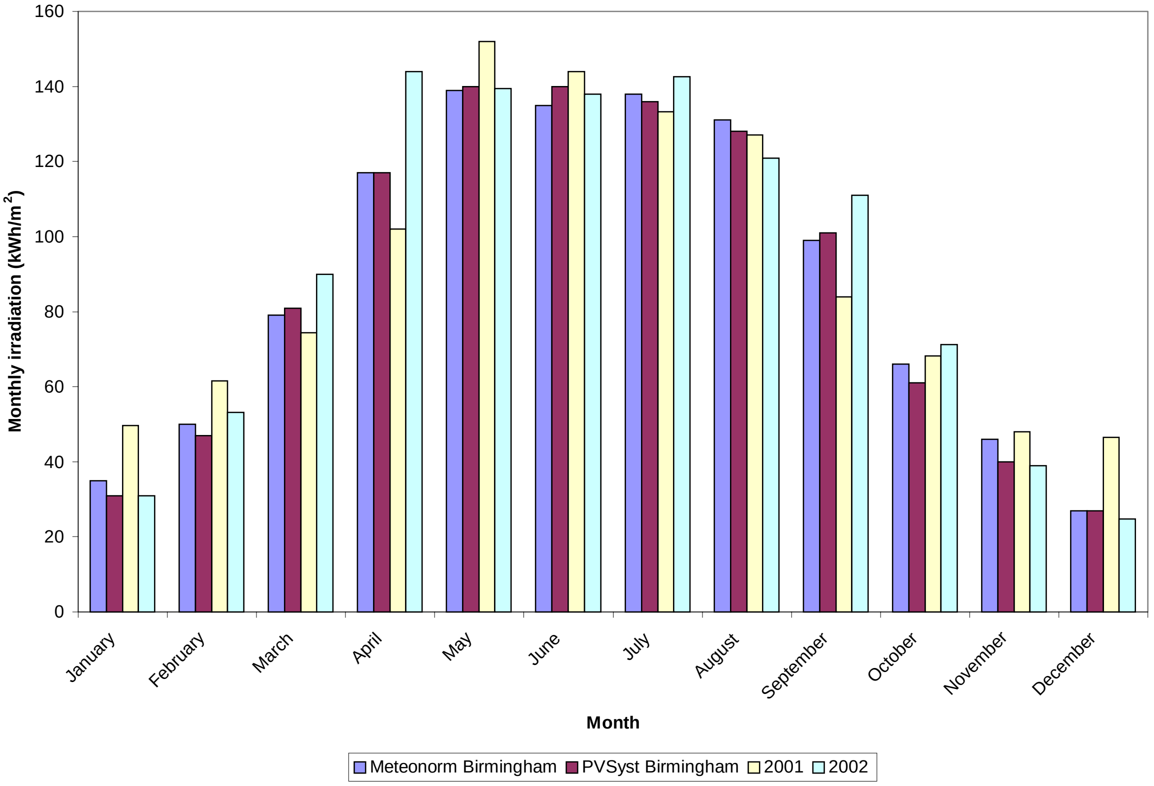

Figure 16. Comparison of insolation levels of Meteonorm and PVSyst databases and measured data for System F.

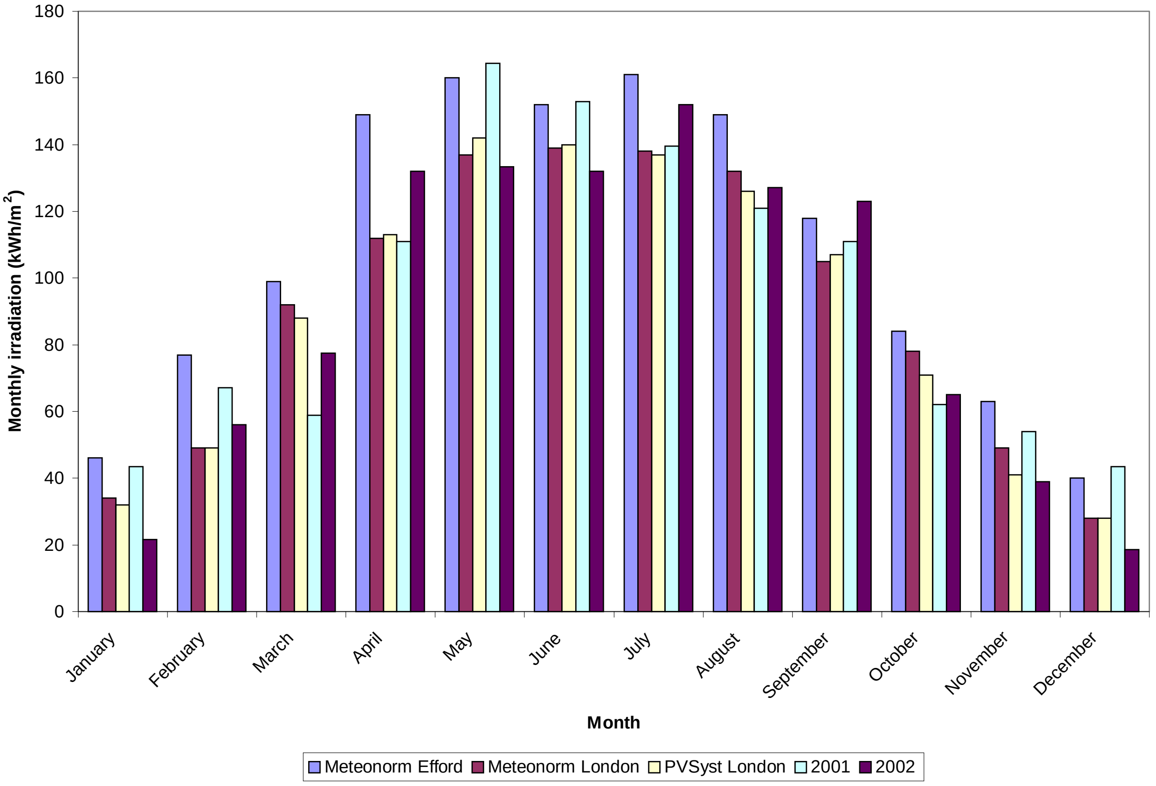

Figure 17. Comparison of insolation levels of Meteonorm and PVSyst databases and measured data for System A.

The comparisons of annual insolation levels are shown for all five systems in Table 12. This gives a measure of the variation provided by the generally available databases. It can be seen that PVSyst generally predicts lower values of insolation and that measured data are quite close for some sites. For others (e.g. System D) there is considerable variation.

Table 12. Comparison of annual irradiation values for databases and measured data.

System	Data Source and Location	Annual Horizontal Insolation (kWh/m^2)	Annual In-Plane Insolation (kWh/m^2)
A	Meteonorm – Efford	1100	1298
	Meteonorm – London	958	1093
	PVSyst – London	997	1072
	Measured – 2001	n/a	1129
	Measured - 2002	n/a	1077
B	Meteonorm – Efford	1100	1203
	PVSyst – Birmingham	962	991
	Measured - 2002	936	1057
C	Meteonorm – London	958	1029
	PVSyst – London	999	1020
	Measured - 2002	939	n/a
D	Meteonorm – London	958	988
	PVSyst – London	999	979
	Measured – 2001	878	906
	Measured - 2002	811	850
F	Meteonorm – Birmingham	922	1062
	PVSyst – Birmingham	962	1049
	Measured – 2001	970	1091
	Measured - 2002	908	1105

5.3.2 System Performance

The system performance was then simulated using the detailed project option in PVSyst and Table 13 provides a summary of the results obtained. A corrected annual yield has also been calculated from the measured value by using the ratio of the measured insolation level to that used by PVSyst in the prediction. This is only an approximate correction, since it does not take account of the monthly variation in this ratio.

For the simulation, the correct module type and electrical configuration, inverter type and size, array orientation and tilt angle were used as inputs. The only exception was System A in which it was not possible to represent the two different types of modules and only 50Wp modules are assumed. All other parameters were left as the default values. Whilst an experienced user would be able to modify some of the model parameters to obtain a better representation of their system, most design studies will be carried out with the default settings. The locations selected for the definition of insolation levels were as given in Table 12.

It is clear that, with the exception of System F, the measured values of system performance are significantly lower than those predicted by PVSyst. This implies that there are system losses that are not taken into account in the simulation and this implication is discussed further in the next section. However it is worth defining what PVSyst does take into account at this stage. In general, the assumed losses include around 3% for cabling and bypass diodes, 2% for module mismatch (assuming operation at maximum power point rather than fixed voltage) and 3% on module quality (i.e. modules being below the nominal rating although within the allowed tolerance range). The thermal model assumes a free-standing system and amending this model requires some knowledge of the thermal characteristics of the array being considered. There do not appear to be any explicit losses due to the accuracy of maximum power point tracking although a sophisticated inverter model is implemented.

Table 13. Main results from performance simulation using PVSyst.

System	**A**	**B**	**C**	**D**	**F**
Measured annual yield (kWh/kWp)	668	733	639	538	844
PVSyst annual yield	755	812	835	800	846
Measured yield corrected to PVSyst insolation level	665	649	680	620	801
Measured system efficiency (%)	3.6	6.5	8.5	9.3	10.3
PVSyst system efficiency	4.1	8.2	9.7	10.0	10.5
Measured performance ratio	0.61	0.65	0.69	0.73	0.76
PVSyst performance ratio	0.68	0.79	0.79	0.79	0.78

Notes to Table 13:

- For System B, the measured annual yield has been calculated for May 2001 – April 2002 since the system was not operational in the summer of 2002.
- For System D, the measured annual yield has been calculated using a corrected output for April 2002 to allow for the low monitoring fraction in this month.

5.4 System Losses

Having established that the measured performance parameters are generally significantly lower than those predicted from the system simulation, it is then important to establish whether there appear to be credible loss mechanisms in the systems that are not taken into account in the simulation. This will provide some information on how such packages can be used in system design and assessment.

The main losses to be considered are:

- Temperature – this has been discussed in Section 5.3. It can be argued that all the systems considered in this study, with the exception of the free standing tracking array of System H, will be operating at a higher temperature than assumed in the simulation program. The losses will be greater for the integrated monocrystalline silicon systems (B, C and G) although the integrated amorphous silicon system would be expected to exhibit a lower effect.
- Inverter losses – these are generally taken into account in the model with the exception of the maximum power point tracking accuracy. This may be an important effect for System A due to the difficulties of tracking the maximum power point of the amorphous silicon array. For System C, the simulation indicated that the inverter is undersized for the system (the ratio of inverter capacity to array capacity is 0.64) and the effect of this is discussed in more detail below. Performance ratios are also reduced by inverter trips which have been observed for several of the systems.

- Shading – in all the simulations, it has been assumed that there are no shading losses. The daily performance profiles of the systems have been inspected in this regard and shading is indicated for several of the systems. This is discussed in more detail below.
- Cabling losses – these are taken into account in the model and, except for the tracking array of System H which is remote from the house, there is no reason to expect higher losses in the real systems.
- Mismatch – this is taken into account in the model and there is no reason to expect higher losses with the exception of System A. There is likely to be a significant loss associated with the use of two different modules on this system, although it would be difficult to quantify even if the detailed electrical configuration was known.
- Module quality – this is included in the model. The real losses may be more or less than assumed but cannot be established without direct measurement of the module performance.
- Soiling – since all the systems have been installed for longer than 12 months, it is likely that a small loss will occur due to soiling. It is unlikely to be more than 2-3% unless the local conditions are particularly difficult in this regard, but will contribute to the apparently lower performance from the measured systems.
- Operation mode – most of the systems operate in maximum power point tracking mode but the two arrays at System H operate at fixed voltage. This cannot be simulated easily in the model, but the measured data indicate that this results in a severe penalty on overall system output.

Two aspects of the above list of factors have been investigated in more detail. These are the inverter performance and shading issues.

5.4.1 Inverter Performance

Inverter trips resulting in several days of lost output have been observed for 3 of the systems (B, C, and E) and this directly reduces the apparent performance of the system. System D showed regular drop outs of the inverter in the summer months as discussed in Section 4.5.

In addition, the average inverter efficiency will be affected by the ratio of the inverter capacity to the array capacity, due to the lower inverter efficiency at the low end of the inverter power range. The optimum ratio for northern Europe is in the region of 0.7 – 0.8. System G has a ratio of 1 and would be expected to have a lower inverter efficiency than the other conventional grid connected systems. However, if the ratio is too low, there is the possibility of saturation of output at high irradiance levels. This can be clearly observed for System B in Figure 18. This system has an inverter/array capacity ratio of 0.64.

Saturation has also been observed for System E, which has an inverter/array capacity ratio of 0.67. Figure 19 illustrates the behaviour of this system. However, it should be noted that the output plateau occurs at power levels below the rated capacity of the inverter (around 650W compared to the nominal capacity of 700W). This is likely to lead to significant losses in overall output.

Finally, the inverter threshold (i.e. the irradiance level at which the inverter turn on and off) is quite high for both systems A and E. This can be observed for the latter in Figure 19, where the output falls to zero at irradiance levels below about 80W/m^2, and in Figure 20, where a similar threshold can be observed for System A.

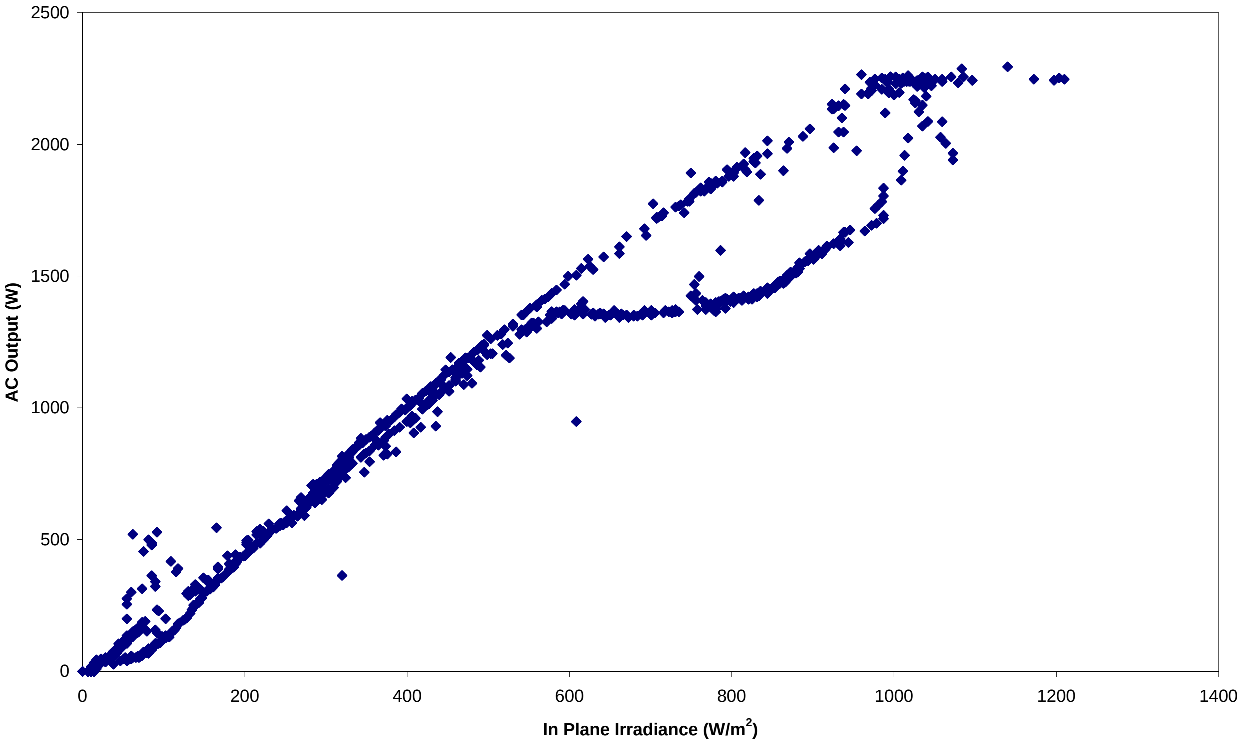

Figure 18. Variation of AC output of System B for 15th July 2001. This plot shows both the saturation of the inverter output at about 2.3kW and the reduced performance due to shading in the early afternoon. The associated loss in output has been calculated at just over 7%.

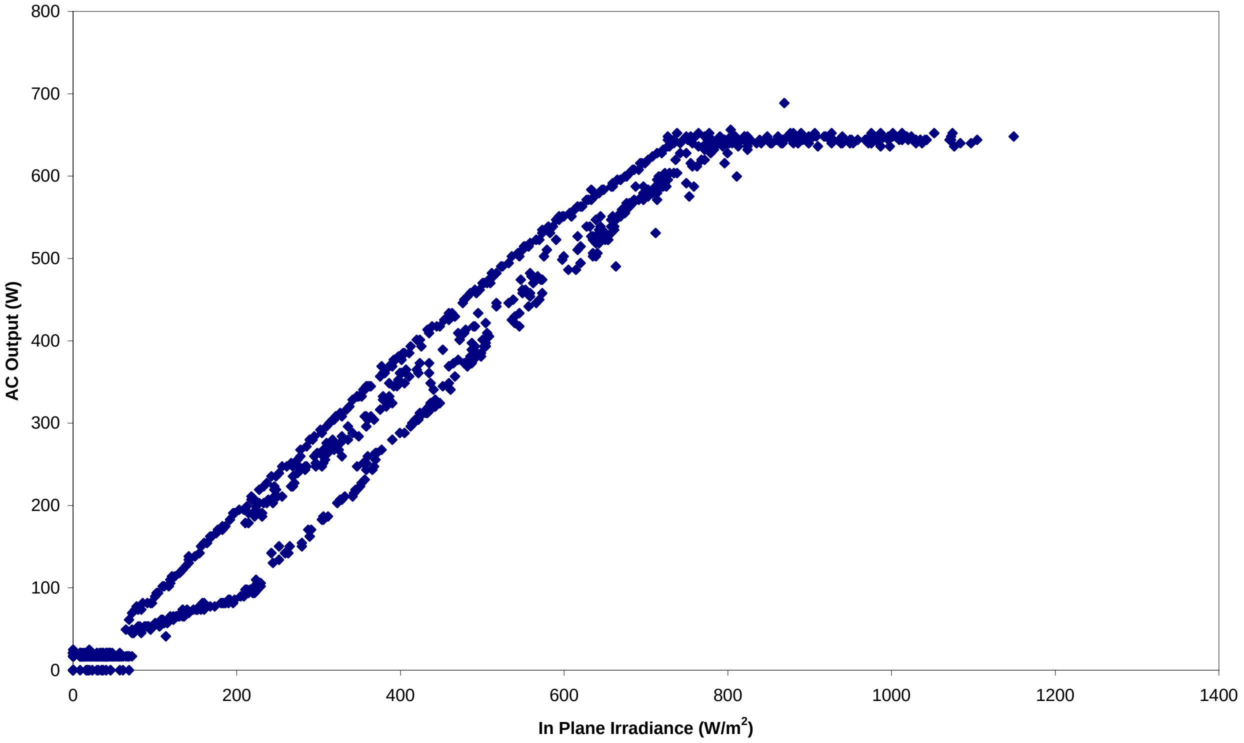

Figure 19. Variation of AC output of System E for 31st May 2002. The saturation of the inverter output at high irradiance values and the high inverter threshold can both be observed.

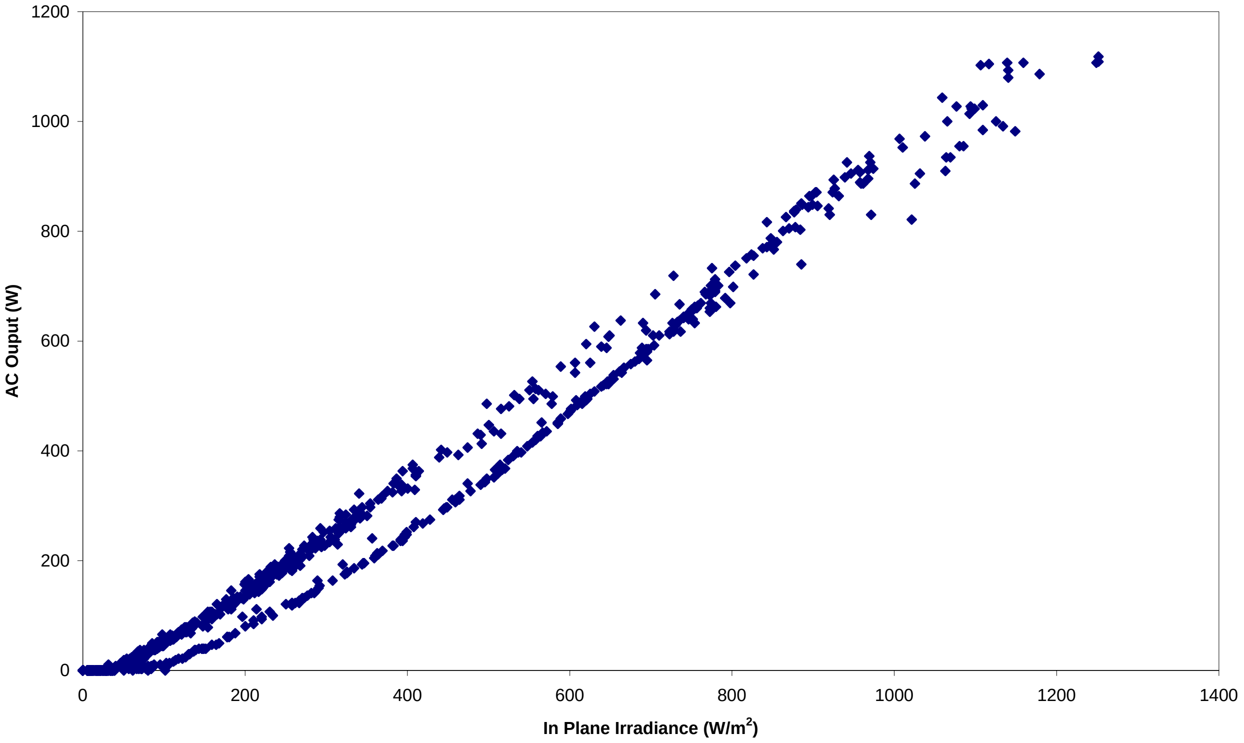

Figure 20. Variation of AC output of System A for 26th April 2002. This shows a relatively high inverter threshold but no other anomalous behaviour.

5.4.2 Shading

Significant shading was not indicated for any of the systems, either in the initial discussions of their inclusion in the study or in subsequent site visits. In some cases, it was acknowledged that there was possible shading from nearby buildings or trees. The performance curves of several systems indicate that shading is present at certain times of day. The systems considered here are B, C, D, F, G and H (fixed array). There is no clear evidence of shading for the remaining two systems.

System B exhibits a seasonal shading effect which is quite severe. This can be seen in Figure 18 above where a significant reduction in power output is observed in late morning and the first half of the afternoon. Whilst a small proportion of this could be due to temperature rise on the array, the effect is much too large to be assigned to temperature. In addition, the shape of the curve indicates shading of the array over a few hours, but then the shadow moving off the array later in the day. At this time, the power output returns rapidly to the expected value.

It has been observed that the pattern of the performance curve changes with season, becoming more severe in the summer months, although the timing of the shadow remains reasonably constant. Figure 21 shows a curve from earlier in the year to illustrate this effect. In the winter months, the shading effect is hardly observable. The timing of the shadow in the day and the seasonal variation strongly suggest that the shading is caused by trees situated S-SW of the array and for which the foliage is much thicker in the summer.

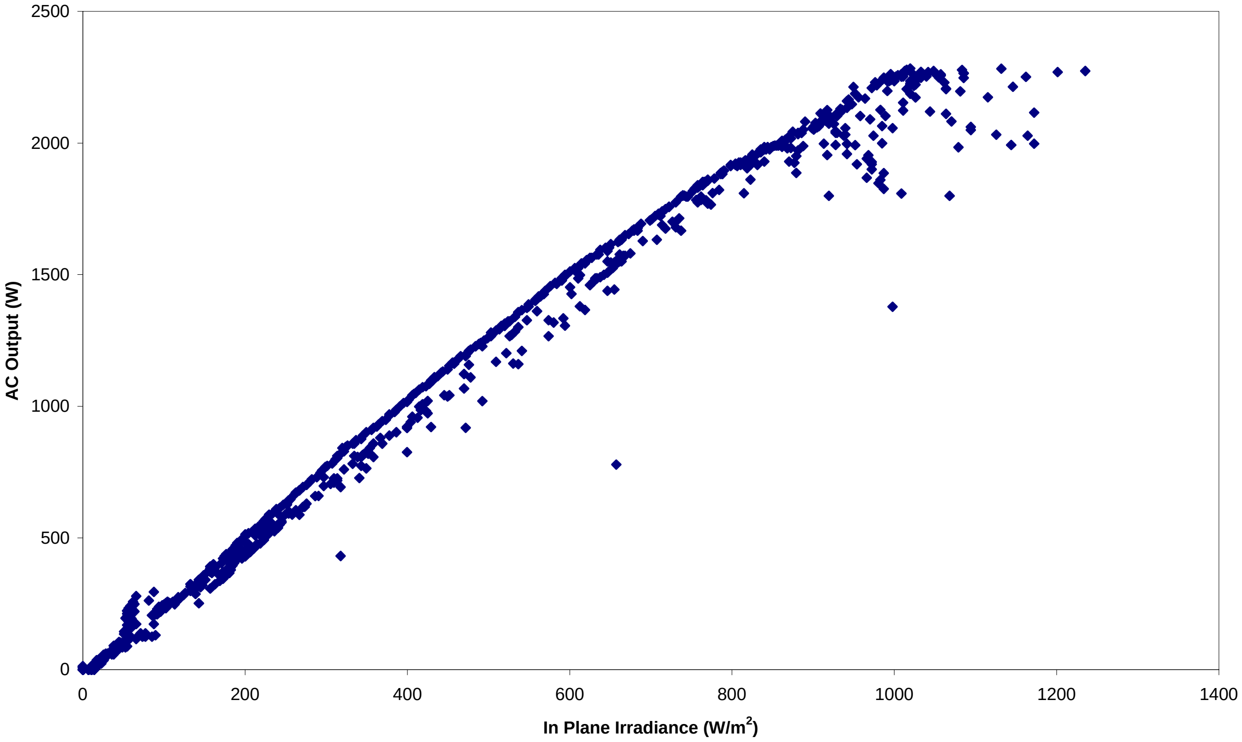

Figure 21. Variation of AC output of System B for 30th April 2001. The reduction of the afternoon shading can be seen by comparing this plot with Figure 18.

System C shows a small amount of shading in the early morning, as illustrated in Figure 22, and Systems D and F in the afternoon (Figures 23 and 24 respectively). In none of these cases does the effect appear to be severe enough to lead to significant losses. For System G, the performance curves indicate shading of the array in the afternoon (Figure 25) and the effect is quite pronounced. This is probably from a nearby church observed during the site visit. The performance curve also indicates a significant thermal effect on system efficiency.

The fixed array on System H shows a lower efficiency than the tracking array and the performance curves indicate a significant amount of shading at low sun angles in the morning (Figures 26 and 27). The irradiance range over which the shading occurs varies with season and the effect disappears in June (Figure 28), when the sun elevation is at its highest. This indicates that the shading is caused by a fixed object, possible part of the roof of the house, to the south east of the array.

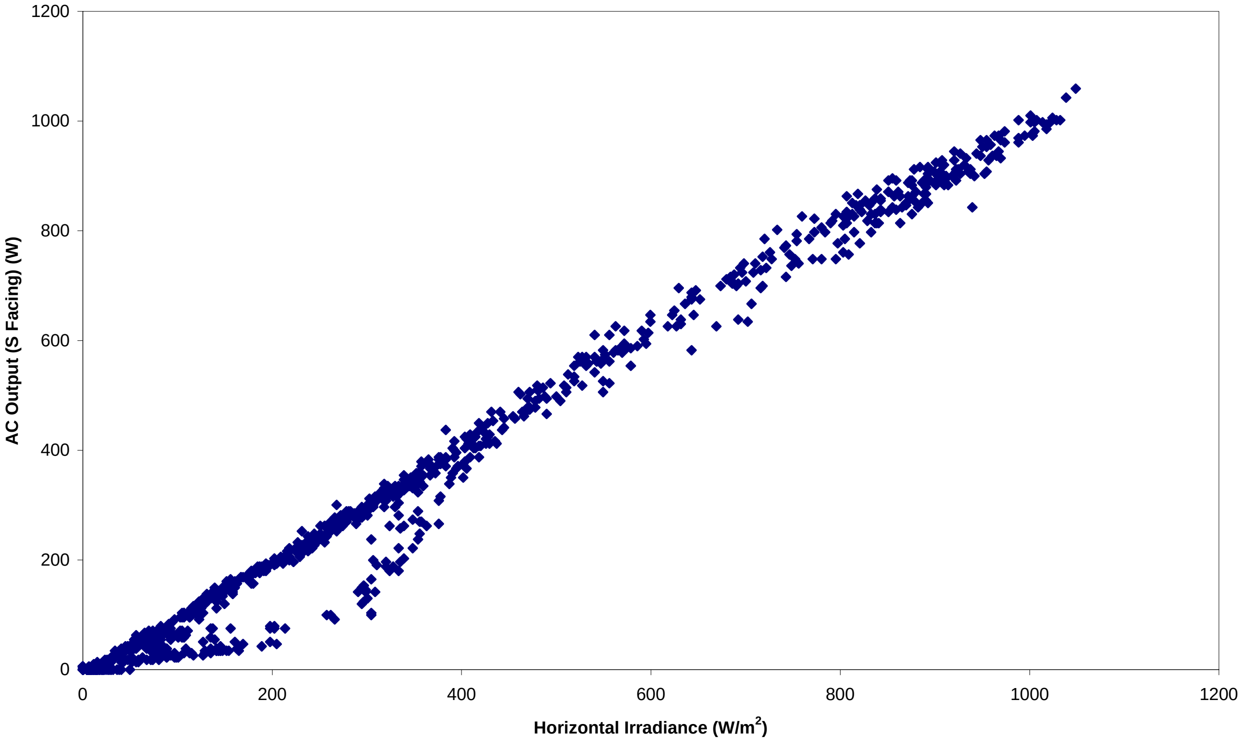

Figure 22. Variation of AC output of System C for 31st May 2002. A reduction of output can be seen at low irradiance levels. This has been identified from the data set as relating to the morning.

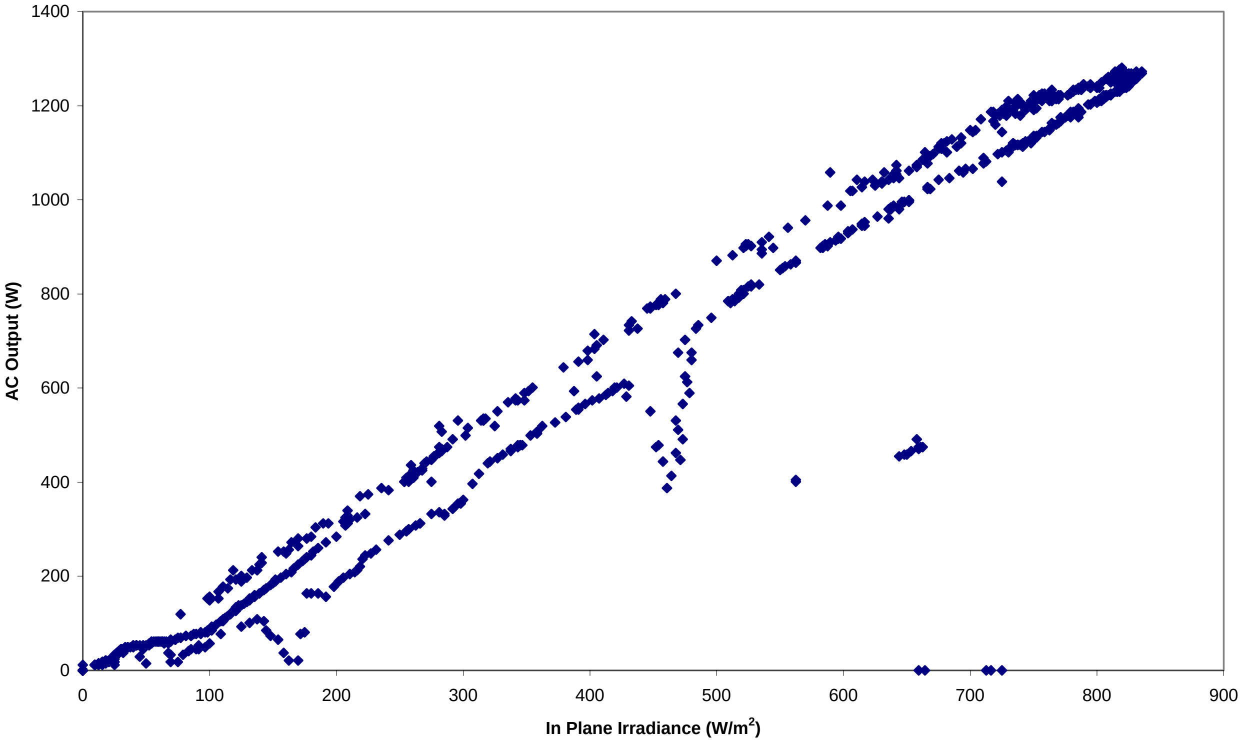

Figure 23. Variation of AC output of System D for 14th August 2002. Two short periods of output reduction are observed in the afternoon. This does not appear to be related to the inverter problem and is tentatively assigned to shading.

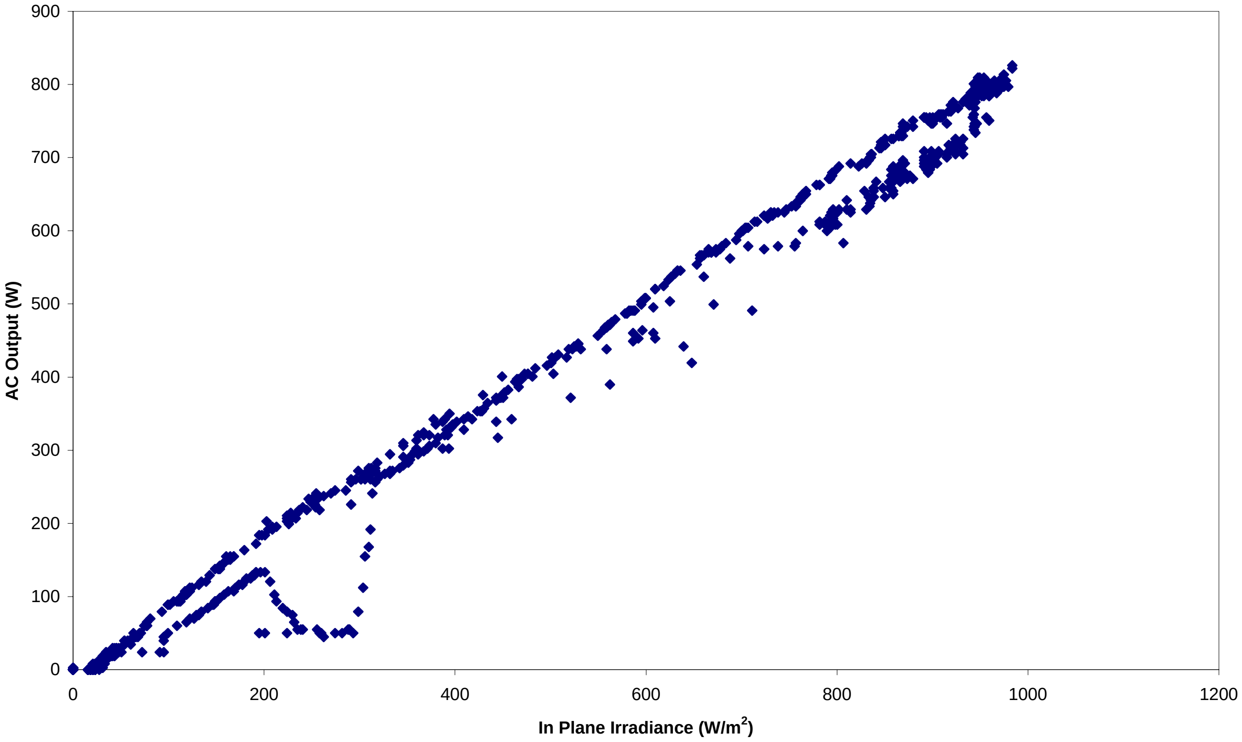

Figure 24. Variation of AC output of System F for 24th April 2002. A short period of reduced output is observed in the afternoon. This does not occur all year round.

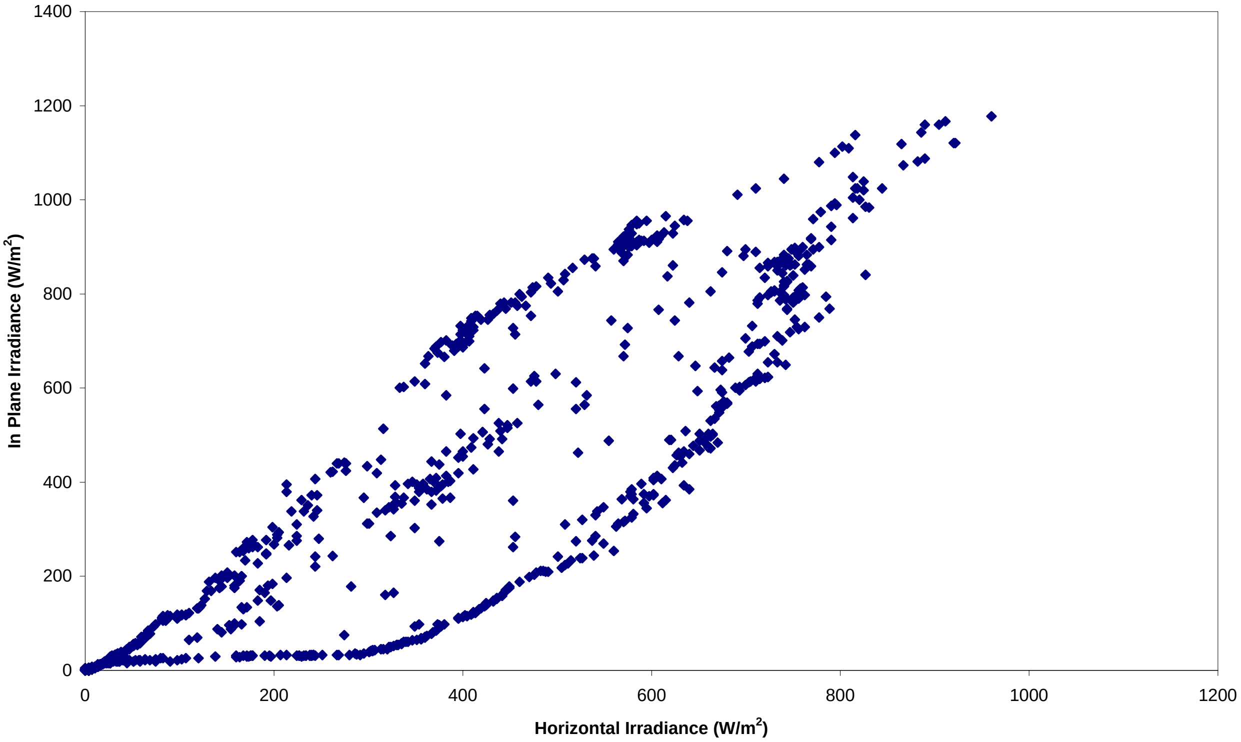

Figure 25. Variation of AC output of System G for 24 April 2002. A wide range of values can be observed. The plot indicates the likelihood of significant shading in the afternoon and a higher temperature effect than the stand-off systems.

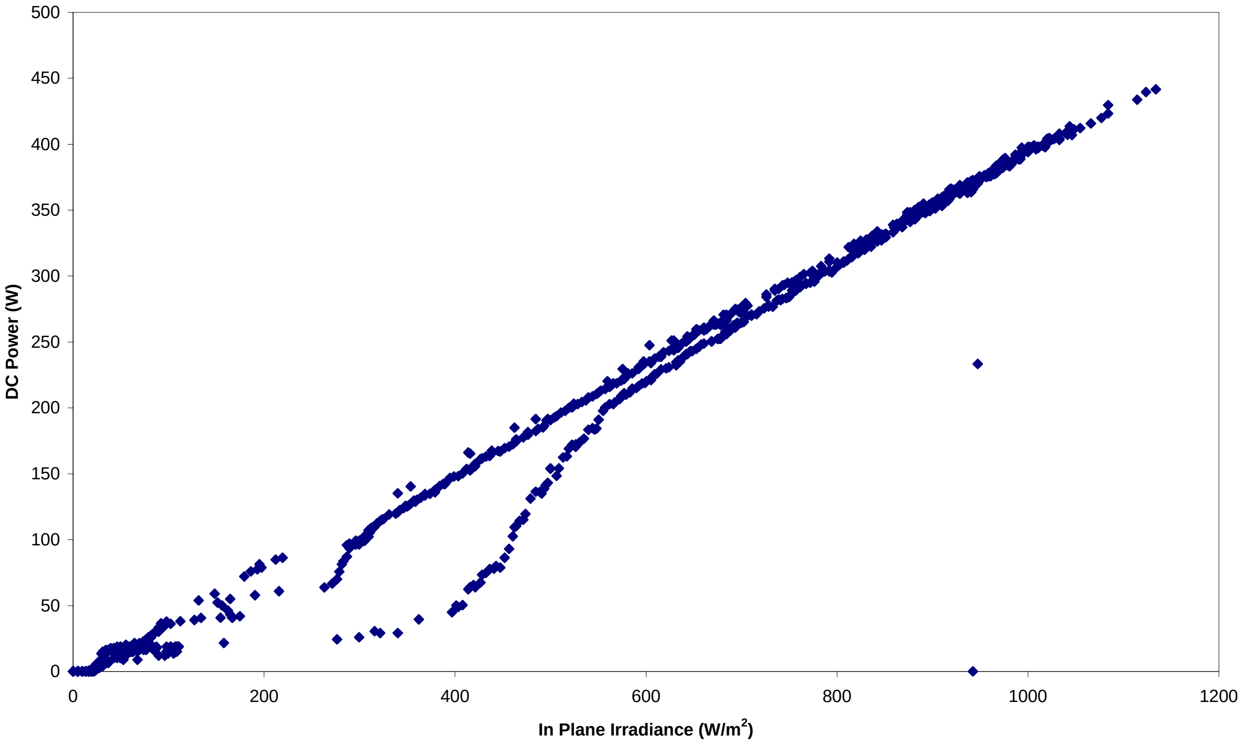

Figure 26. Variation of DC output of System H (fixed array) for 5th May 2001. This shows shading of the system at low irradiance values in the morning.

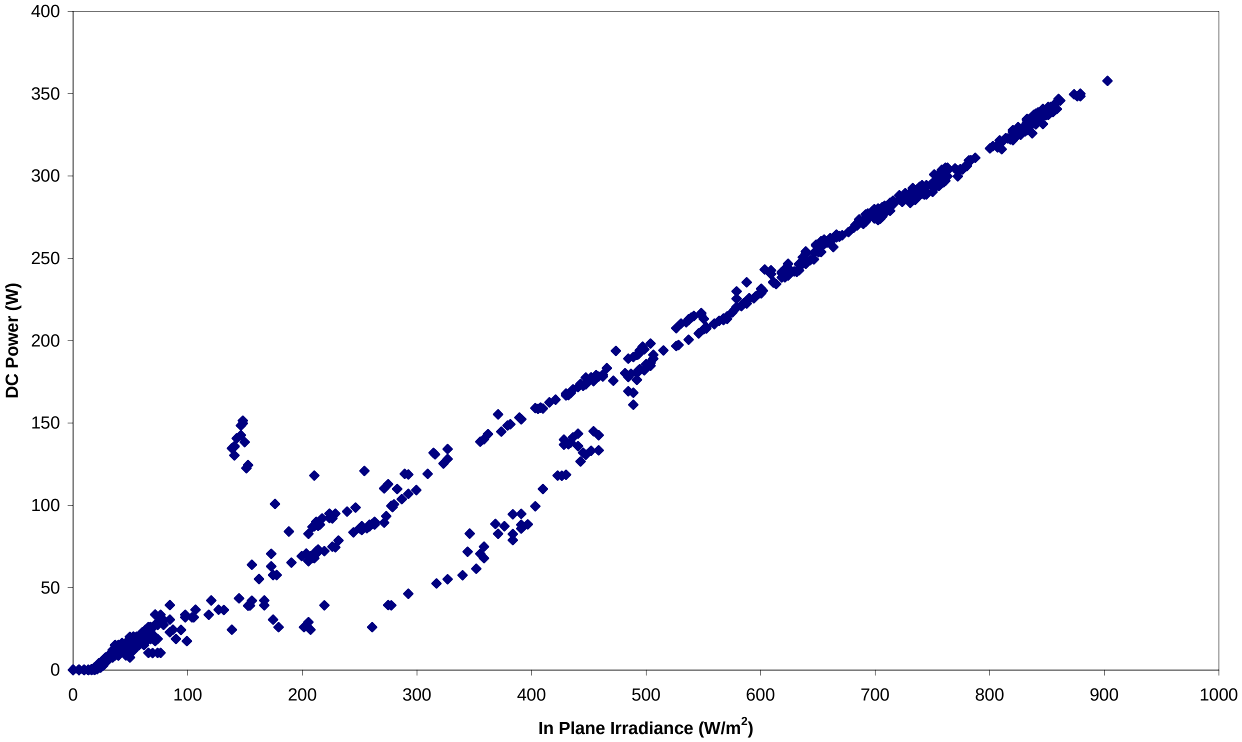

Figure 27. Variation of DC output of System H (fixed array) for 2nd September 2002. This shows similar behaviour to that in Figure 26.

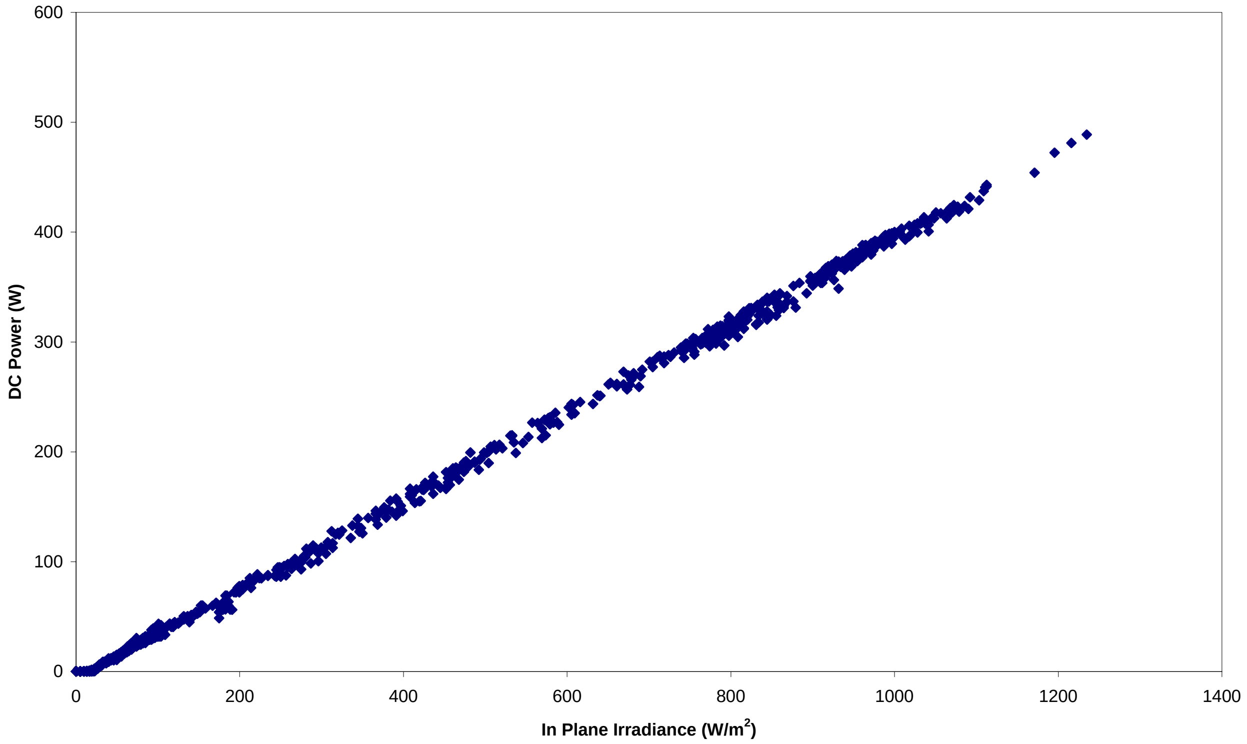

Figure 28. Variation of AC output of System H (fixed array) for 17th June 2002. The shading problem does not occur in this month.

Table 14 shows the measured and predicted performance ratios (where available) and indicates the magnitude of the additional losses implied by these two values. The nature of those losses, both identified by analysis of the data and expected from consideration of the system design are then presented for each system. Whilst it would be possible to quantify some of the identified inverter and shading losses, this would take a considerable amount of time since it is not easy to automate such a task. This was outside the scope of this project.

5.5 Contribution to Building Loads

In addition to measuring the electrical performance of the PV systems, data have been gathered on import and export of electricity to the properties in order to consider the contribution of the PV system to meeting the household loads. Of course, the contribution made will depend strongly on both the size of the PV system and the typical load levels. The latter depends in turn on the lifestyle of the occupants and the detail of the electrical equipment used. This project was not designed to assess the effects of lifestyle on the use of PV systems and so there is no load analysis presented. However, some comments can be made regarding the contribution of the PV system outputs for seven of the sites (excluding System G).

The contribution can be expressed in a number of ways and, in this report, the following quantities have been considered. These are all related quantities but provide different insights into the use of the PV system output.

Table 14. Summary of loss mechanisms for the monitored systems.

System	Measured PR	PVSyst PR	Additional measured losses (%)	Identified or expected losses
A	0.61	0.68	10	Higher temperature than free standing – integrated system (but low temperature coefficient of modules). Mismatch between modules. Reduced efficiency of maximum power point tracking. High inverter threshold.
B	0.65	0.79	18	Higher temperature than free standing – integrated system Significant shading in summer Undersized inverter Saturation of inverter at high irradiance levels Inverter trip
C	0.69	0.79	13	Higher temperature than free standing – integrated system Inverter trip Calculations based on horizontal so lower accuracy of measured PR
D	0.73	0.79	8	Higher temperature than free standing – stand-off system Inverter drop out in summer months Some shading in afternoon
E	0.58	n/a	n/a	Higher temperature than free standing – stand-off system Inverter trips (severe) Undersized inverter Saturation of inverter above 800 W/m^2
F	0.76	0.78	3	Higher temperature than free standing – stand-off system Small amount of shading
G	0.73	n/a	n/a	Higher temperature than free standing – integrated system Significant shading in afternoon. Very limited data set
H (fixed)	0.48	n/a	n/a	Operation at fixed voltage. Shading of system at low sun angles in morning. Higher temperature than free standing – stand-off system
H (tracking)	0.64	n/a	n/a	Operation at fixed voltage. Long cable lengths.

- Solar Fraction – defined as the part of the total load which is met by the output of the PV system. It is expressed as a percentage of the total load.
- Percentage of PV output used directly – this is the percentage of the total output of the PV system which is used directly to meet the load (i.e. not exported)
- Percentage of load met directly – this is related to the Solar Fraction but describes the percentage of the load which is met directly from the solar output (neglecting that part of the system output which is exported.

The Solar Fraction can be considered as the maximum contribution which the PV system could make to the building loads, whereas the other two quantities express the contribution if we discount the electricity that is exported. These quantities can be of interest in profiling the export behaviour and for economic optimisation, depending on the prevailing import and export tariffs.

Figure 29 shows the variation of the three quantities with time for System A as an example. Although the absolute values vary, all systems show similar seasonal trends. Table 15 indicates some characteristic parameters for the systems. The periods for calculation for each system are the same as those presented in the individual system tables in Sections 4.2 – 4.9 inclusive.

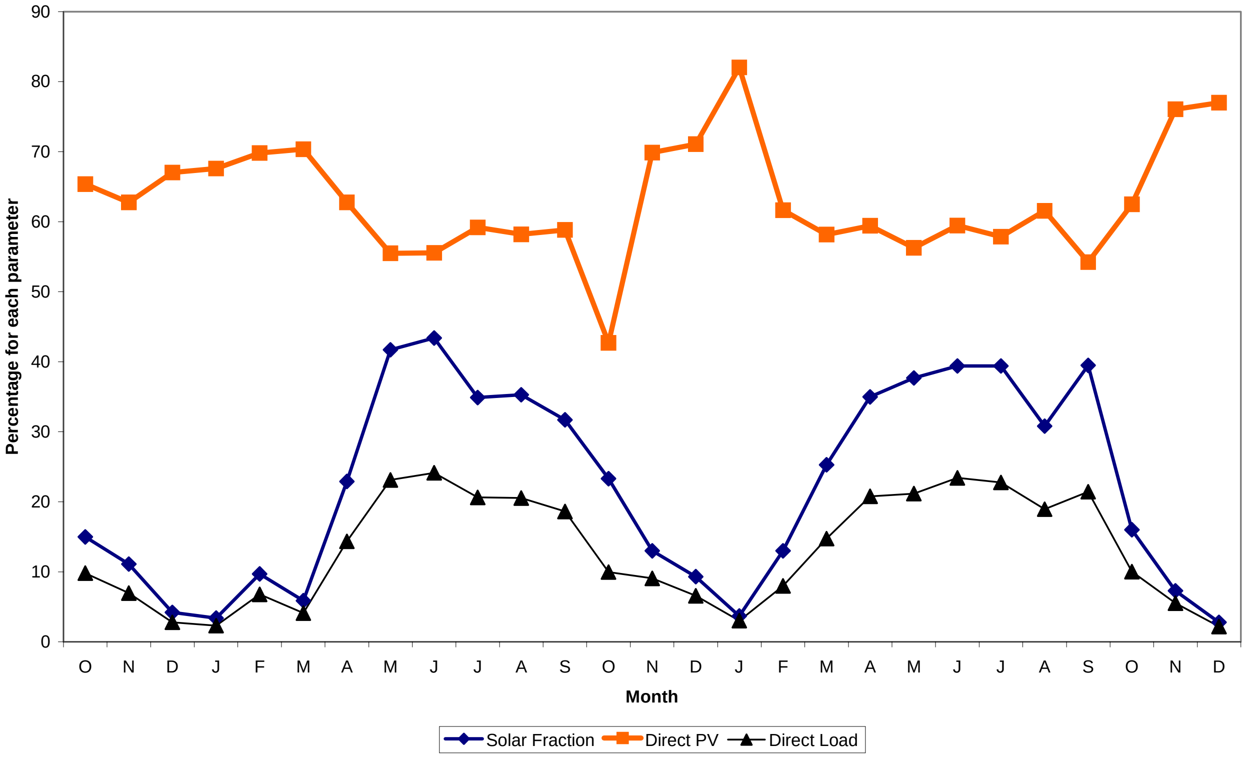

Figure 29. Monthly variation of usage parameters for System A.

The Solar Fraction shows a cyclic behaviour with a significantly higher value in the summer months, since not only is the PV system output increased but the load is also usually decreased. In the case of System A, the Solar Fraction peaks at just over 40% but this is quite a small system at 1.27kWp. The percentage of the load met directly follows the same trend but at a somewhat lower value. The percentage of the PV output used directly in the house is in anti-phase with the other two parameters. For lower outputs and higher loads, the percentage of the output which can be used at the time of generation increases, peaking for System A at a value of 82% in the second January of the monitoring period.

Table 15. Summary of system values describing the contribution of the PV system output to the household demand. Values for building load and export are in kWh. All other values are expressed as percentages.

System	**A**	**B**	**C**	**D**	**E**	**F**	**H**
Average monthly building load	356	515	263	398	418	504	542
Maximum monthly building load	953	886	325	690	542	946	950
Minimum monthly building load	209	371	128	108	344	244	358
Average Solar Fraction	22	40	56	29	16	18	13
Maximum Solar Fraction	43	95	113	65	32	38	24
Minimum Solar Fraction	3	6	5	4	0	2	4
Average percentage of PV output used directly	63	65	56	73	67	74	80
Max. percentage of PV output used directly	82	87	91	99	93	95	96
Min. percentage of PV output used directly	43	52	37	55	49	35	66
Average percentage of load met directly	13	24	27	19	10	13	9
Max. percentage of load met directly	24	50	80	37	20	26	16
Min. percentage of load met directly	2	5	5	4	0	2	4
Average monthly export	27	73	79	33	21	20	15
Max. monthly export	55	174	160	82	43	62	38
Min. monthly export	2	6	2	1	0	1	1

From the table, it can be seen that a range of building loads is represented, from quite high monthly averages (Systems B, F and H) to low values (System C). These variations are also reflected in the maximum and minimum load values. Four of the system owners (A, C, F and H) provided information on their energy sources. All the systems use either gas or oil for heating. A combination of electricity and gas is used for cooking by A and C, whilst F and H use electricity only. All sites use energy efficient light bulbs and some have other energy saving devices.

The Solar Fraction is, as expected, highest for the large PV systems (B, C and D) and low building loads (C, D). For System C, the Solar Fraction exceeded 100% for one month in the monitoring period and was over 95% for four other months.

All the systems use over 50% of the PV system output directly and System F as much as 80% on average. This is the smallest PV system in the survey with one of the highest average building loads. The average percentage of the load met directly from the PV system is generally in the 10-30% range.

Two of the systems (B and C) export over 70kWh per month on average, whilst the remainder have values around 20-30kWh. The maximum export values are 2-3 times the average value.

6. DISCUSSION

The monitoring of eight domestic systems in this project has allowed the assessment of performance and reliability issues and has also highlighted some aspects of the user influence. This section will discuss these aspects and then some overall recommendations will be provided in the final section.

6.1 PV Array

In all cases, the PV array performance has shown a high level of consistency within a given system, behaving as expected in terms of variations with insolation and temperature. There have been no reports of damaged or faulty modules, with the exception of the replacement of five modules for System A. This occurred shortly before the commencement of the monitoring.

The effect of operating temperature can be seen in terms of reduced array efficiency. Although it was not possible to measure the array temperature for two of the integrated arrays, limited measurements for System G and the general performance values obtained for Systems B and C indicate that temperature is a significant effect. Coefficients for expressing the operating temperature as a function of ambient temperature have been developed for several systems.

The monitoring has indicated shading losses of varying severity for most of the systems, even though these do not appear to have been identified at the design stage. It is clear that the design of systems for use in an urban environment needs to take account of surrounding buildings. These may not cause direct shading, but may reduce the diffuse levels sufficiently to affect system output. However, for the two systems showing the most severe shading effects (B and the fixed array of H), the shading appears to be trees and other parts of the roof respectively.

6.2 Inverters

A major proportion of the observed system losses have resulted from the inverter operation and the most serious problem is in regard to inverter trips since these represent the longest periods of system outage. In some cases, it is clear that the problem has arisen from an oversight following work on the household electrical system, when the inverter has not been switched on again after completion (e.g. the first outage on System E). However, in other cases, it appears that the inverter trip is triggered by a variation in the mains supply, but the inverter does not automatically restart. On System D, apparent problems with high grid voltage have also been observed.

In terms of design, two systems illustrate saturation of the inverter due to undersizing. This is especially severe in the case of System E, but the effect is exacerbated by the inverter saturating at an output level below its rated capacity.

6.3 User Influence

It is worth noting that inverter trips or outages which require manual restarting of the inverter are often not noticed by the user. This is partly because the inverter system is usually located in the loft space and is not readily visible. It is also partly due to the user often being unaware of how to check if the inverter is operating. A significant proportion of the output will be lost if the inverter remains off for periods of weeks or months, as sometimes seen in this project. It was usually the case that the system owner was informed of the problem by the project team after inspection of the monitoring data. Clearly, this source of information will be unavailable for most systems. If the maximum benefit is to be gained from the installation of PV systems, it is important to address and solve this problem. This implies not only the supply of display units in accessible places for the users (as is now being generally implemented in the Domestic Field Trial), but also the instruction of the user in how to recognise and deal with a problem. It probably will also require some type of notification of the problem (a warning light or similar) but this will need to be able to distinguish between normal and abnormal operation.

Significant output losses were also observed as a result of inverters dropping out for short periods during normal operation (System D and the first inverter on System A). In most cases, the user would be unable to observe this fault from any existing display units and without a thorough understanding of the system. Identification of the fault requires some reference value for the output, usually provided by an insolation measurement. This is not fitted as standard to a PV system and it may well be prohibitively costly to fit and use such a sensor.

For System A, the owner negotiated replacement of the inverter partially by demonstrating the poor performance of the original model. Data from this monitoring project were supplied as supporting information on the request of the owner. Whilst it is not claimed that this information directly led to the replacement of the inverter, it is interesting to consider how much weaker the owner’s case would have been without supporting measurements. In most cases, the data would not have been available for either the identification or the resolution of the problem.

Although the number of projects is rather too limited to make a firm conclusion, it also appears that inverters either tend to show repeated problems with trips or drop outs from the commencement of operation or are generally problem-free. Thus, attention to the system performance in the first year of operation should identify most recurrent problems.

Finally, it is worth recognising that there is a significant difference between a private owner, who has paid for and takes an interest in the performance of the PV system, and the tenant of a housing association, where the PV system is supplied to them. Identification and rectification of problems takes much longer in the case of the tenant. As PV systems become more widespread, a higher proportion of the users will be similar to the tenants in this project. It is important to simplify the identification of problems so that most systems can operate at their full potential.

7. CONCLUSIONS AND RECOMMENDATIONS

Based on the project results and the preceding discussions, the following conclusions and recommendations can be made.

- The use of proprietary design software such as PVSyst, whilst very useful in the design of systems, consistently underestimates the actual losses for all except one of the systems monitored in this project. In order to obtain more accurate predictions, it is necessary to modify some of the default values, particularly thermal behaviour and shading issues.
- The measured insolation values showed a high degree of consistency between sites. This is not always the case with available solar databases and care should be taken when interpreting performance data based on these.
- Almost all the systems showed some problems with shading. In particular, care should be taken regarding self-shading by parts of the same building and shading due to trees. It is possible that both these shading effects will not be obvious during site inspections.
- Undersizing of the inverter can cause significant losses due to saturation of output. This was not observed for systems with inverter/array capacity ratios over 0.75.
- The largest loss factor was related to inverter outages and these are not always observed until a significant period has elapsed. The period would be expected to be longer if the system in not monitored.
- Users have problems in identifying both short and long term problems with the inverter performance and attention should be paid to providing some simple and cost effective means of identification.

Many of the issues identified in this project will be able to be addressed in more detail by the Domestic PV Field Trial. This will provide similar data for a larger number of systems, a wider range of technology and a wider range of locations. It is recommended that the Field Trial considers the issues of inverter reliability raised in this study and assesses the prevalence and effect of array shading.

REFERENCES

1. Testing, Commissioning and Monitoring Guide for Photovoltaic Power Systems in Buildings, ETSU Report No. S/P2/00290/REP, December 1998

APPENDIX A

EXAMPLE OF MONTHLY SUMMARY SHEET

July 2002 – System A

Monitoring of Domestic PV Installations
ETSU Agreement No. S/P2/00319/00/00

System A, July 2002

System Information:
No system modifications

Monitoring Fraction: 100 %

Climatic Data

Average In-Plane Insolation	4.9 kWh/m^2/day
Average Ambient Temperature	15.9 degrees C
Average Array Temperature[1]	22.7 degrees C

PV System Output

Total DC Output	127.8 kWh
Total AC Output	121.5 kWh
Average Inverter Efficiency	95 %
Average System Efficiency	3.7 %
Performance Ratio	0.63
Total Import to House	238.5 kWh
Total Export from House	51.2 kWh
Building Load (calculated)	308.8 kWh
Solar Fraction	39.4 %
Total Monitored Output Since 06/07/2000	**1680.8 kWh**

Notes:

[1] Depending on the detail of the system installation, the location of the temperature sensor, and therefore its accuracy in representing the true operating temperature of the modules, varies between systems.

PV System Output for July 2002 - System A