



DOMESTIC PHOTOVOLTAIC FIELD TRIALS

Good Practice Guide: Part II
System Performance Issues

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**PV DOMESTIC FIELD TRIAL
GOOD PRACTICE GUIDE
PART 2 – SYSTEM PERFORMANCE ISSUES**

ETSU S/P2/00409/00/00

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INTRODUCTION

Achieving good practice in the design, installation and operation of photovoltaic (PV) systems is key to instilling customer confidence, optimising system performance and establishing the PV industry as a whole. This is especially important when introducing a new technology into the market, allowing suppliers, designers, installers and service companies to offer a good quality service, based on collective experience.

Part 2 of the Guide is aimed mainly at system suppliers and consultants who are responsible for the design of the PV system and the choice of components. However, local authorities, housing associations, developers, utilities and end-users will also find it informative in regard to the decisions to be made and, in particular, how to maintain good performance during system operation. It aims to provide an outline of what to look out for and how to complete a PV building project for maximum system performance.

This Guide is based on the experiences of the Photovoltaic Domestic Field Trial (PV DFT), funded by the New and Renewable Energy Programme of the DTI. The PV DFT comprised the installation of more than 470 PV systems (totalling over 750 kWp) in a wide range of domestic building across the UK. The Guide aims to signpost the wide range of issues that need to be addressed. It references other key publications and standard texts applicable to PV projects, and should therefore be treated as a supplement and used in conjunction with these other publications (see Section 8). The issues raised in Part 2 of the Guide are relevant to both individual installations and those incorporating clusters of domestic installations, i.e. installed by developers or housing associations.

The Guide is in two parts. This document, Part 2, focuses on maximising system performance of the PV system through issues related to system planning, design and operation. Part 1: Project Management and Installation Issues, reviewed good practice with respect to building integration, covering issues from project development through design to operation and maintenance. Note that this Guide is based on the PV systems used within the DFT. The market is changing rapidly and new and more advanced systems are becoming available, however most of the principles discussed here will still apply.

Background to the DFT Guide

This part of the Good Practice Guide covers the key issues in the performance of grid-connected PV systems in domestic settings. Considerable experience has been gained through a detailed monitoring programme and additionally through feedback from developers, installers and end users involved in the programme. The box on the right gives some statistics showing the range of projects, which include a wide variety of properties:

PV Domestic Field Trial Statistics

- Over 470 dwellings benefited
- Over 740 kWp of PV installed
- 28 projects
- 16 new-build, 10 retrofit, and two projects with both types
- Two-thirds social housing or mixed developments
- Exemplar energy efficiency technology
- New-build located mostly on brownfield sites
- Total budget £4.7m excluding management costs
- Initiated in 2001, completed 2006

houses, flats, bungalows; and different types of PV systems: PV tiles, laminates and modules.

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1 PROJECT PLANNING

General planning considerations for domestic PV systems, including contractual and scheduling aspects, were discussed in Part 1 of this guide. Here consideration is made of the aspects that might directly impact on the initial and on-going performance of the PV system.

The choices regarding the location and allowable size of the PV array are made during the planning process, taking into account all the required factors relating to fixing of the array on the building and the location of the remaining of systems components (particularly the inverter). Access to both the array and the electrical system during operation should also be considered so as to allow maintenance activities to be undertaken. In terms of the array, this would be expected to be occasional only, but may be necessary for either repair or cleaning of the modules. Where the initial installation is part of a new-build process, it is important to ensure that it will still be possible to access the array after the construction of neighbouring buildings. The inverter should be in a position where it can be checked in regard to performance when required. Since this component is usually located in the loft space, access should be provided in terms of fixed ladders, appropriate lighting, etc.

Within the selection of the system components, discussed in Section 2 on PV System Design, the issue of equipment warranties should be considered. However, this also impacts on the project planning process in terms of ensuring that a clear assignment of responsibility is made for situations where there may be a claim against the warranty for any specific component. Minimisation of the time taken to resolve any query and to arrange for repair or replacement under a warranty system can have a significant influence on PV system operation and acceptability. This relates not only to the most obvious aspect of the PV system output, but also to the user confidence level and the likelihood of their recommending, or otherwise, the use of a PV system to others.

Summary

- Ensure that the layout will allow access to both the PV array and the electrical system during operation, particularly in new build situations when construction of neighbouring buildings is planned.
- Plan to place inverters where they can be checked periodically, including allowing for appropriate support, i.e. lighting in loft spaces.
- Ensure that appropriate and effective system and component warranties are in place.

2 PV SYSTEM DESIGN

Good design of a PV system involves the correct choice and matching of components (PV modules, inverter and other equipment), the avoidance of electrical losses where possible and the minimisation of losses where unavoidable. This document does not discuss the overall principles for design of a PV system, but makes some observations from the Domestic Field Trial regarding the details of the specific design of domestic systems for the UK. These will be useful for the system designer, but also for other interested parties wishing to understand the important design features of a PV system.

2.1 PV Modules

The choice of PV module depends on the available roof area, the desired power output, the fixing method chosen and the cost and availability of modules on the market. Results from the DFT show that, as expected, the efficiency of roof tiles is generally lower than for standard modules. This is mainly due to the fact that the packing density of the cells is lower. Essentially, individual roof tiles are smaller in area than most of the modules and that leads to a higher proportion of unused space due to the edge width necessary for encapsulation. Roof tile arrays also tend to operate at higher temperatures due to their method of integration although this is not a substantial effect if care has been taken to ensure ventilation behind the tiles. However, despite the lower efficiency, roof tiles are often chosen because of their appearance, blending with the remainder of the roof area. Thus, selection of the module/tile must take account of factors other than efficiency.



Montagu Road - example of PV roof tile



Corncroft – example of PV module system

The aim of good system design is to ensure that the resulting system efficiency is as close as possible to the efficiency of the module selected, within the constraints of the site and application. The choice of inverter and the minimisation of shading losses are discussed in later sections.

It is also important to make sure that the modules used comply with all relevant standards (both related to the electrical performance and to building requirements) and show a performance level close to the nominal value. It is highly recommended that modules (or tiles) comply with IEC standards for PV

module qualification (IEC 61215 for crystalline silicon cell based modules and IEC 61646 for amorphous silicon based modules).

The design of the system and the expected output both assume that the module power output will be equal to the nominal value given in the module specifications. If the actual modules installed have a lower output, the system output will be below expectation. Within the DFT, one roof tile showed consistent behaviour indicating that its actual output was substantially below the nominal rating. Whilst this problem does not appear to be widespread, based on the evidence of the DFT, it is important for customer confidence that this situation does not occur often. Since it would be very difficult for individual installation companies to undertake module measurements before installation, the most straightforward action on this problem would be for companies to request performance data for each module (based on the serial number) from the module company. These data should be checked on delivery and sub-standard modules returned for replacement.

Summary

- Consider the choice of PV modules according to the requirements of the site/developer.
- Ensure that the modules chosen comply with the relevant PV standards, especially the IEC standards for PV module qualification.
- Consider the request of performance data on modules supplied to ensure that they fall within the nominal range.

2.2 Support structures

The choice of support structure will depend on the module type and size and the roof construction. Further information on possible support structures and their installation methods can be found in Part 1 of this Guide.

In terms of performance, two factors are important. Firstly, where possible, the structure should allow ventilation beneath the modules in order to reduce operating temperature. This has a direct impact on system efficiency and hence overall output. Secondly, the profile of the support structure should be low enough to avoid shading of the cells for low incidence angles and, particularly at the bottom edge, to prevent excessive dirt build-up that may also shade some of the cells.

On one site in the DFT, birds appear to be using the space behind the array as a nesting area, presumably because of the warmth afforded by the modules. As yet, no operational problems are evident from this activity, but there is the risk of damage to electrical wiring on the rear of the array and so nesting should be discouraged. On sites where this is deemed a risk, it is suggested that a means of blocking the access to the rear of the modules is considered, whilst still maintaining ventilation (for example, use of a mesh to cover the gaps between the structure and the roof).

Summary

- Where possible, the structure should allow ventilation beneath the modules.
- Ensure that the profile of the support structure is low enough to avoid shading of the cells and to prevent excessive dirt build-up.
- Consider the possibility of external activities, such as bird nesting, causing damage to wiring etc.

2.3 Array tilt angle and orientation

The high latitude of the UK means that the optimum tilt angle for a PV array (in order to provide the maximum number of kWh across the year) is around 45° . However, most domestic roofs have a shallower pitch than this and the majority of the systems in the DFT were installed at between 25° and 35° tilt. The additional energy that would be gained by increasing the pitch of the array out of the plane of the roof would not usually be justified by the extra cost of the installation and the less acceptable appearance. Therefore, it is recommended that the array be installed at the existing roof pitch provided that this is not less than 25° and not more than 60° . For flat roof systems, modules should be installed at as close to the optimum angle as practicable. As a guide, for an array facing south, if the tilt angle is 15° either side of optimum, a 3% loss in annual energy production can be expected. At 30° away from optimum, the loss would be approximately 12% (see <http://www.beyondoilsolar.com/pvorientation.htm>). This corresponds to an approximate cosine correction.

The array orientation should be between southeast and southwest to get the best outputs. It is not necessary for the array to face due south, with only a small percentage loss from moving a few degrees east or west of south. High annual yield values have been observed for DFT systems up to 30° off south and it is much more important to ensure that all system losses are low than to optimise the orientation. More substantial output reductions are observed if the orientation is more than 45° off south (i.e. east of southeast or west of southwest).

Where arrays are installed on more than one area of roof with different orientations, it is important to separate the parts of the array electrically to ensure the highest output levels. This is because the sunlight levels will be different for the different planes and thus the operating point of the array will differ.

Summary

- The array can be installed at the existing roof pitch, provided that the tilt angle is not less than 25° and not more than 60° to the horizontal.
- For optimum output the orientation should be between southeast and southwest.
- Separate the electrical connections for arrays at different orientation and tilt angles.

2.4 Inverter

There are standard design procedures to inform the selection of an inverter for correct matching with a particular PV array, in terms of overall power capacity and input voltage ranges, and these should be followed in designing domestic PV systems for the UK. However, there are particular requirements for good operation the UK, which is characterised climatically by a relatively high proportion of time when the sunlight level is low and electrically by a relatively high voltage on the electrical grid.

In the DFT, two problems have been observed relating to the high grid voltage. One of these relates to the inverter turning off intermittently as a result of the grid voltage being higher than the allowed maximum level. The UK grid voltage has been harmonised with that of continental Europe and is nominally 230V but is allowed to vary by -6% / $+10\%$. These limits allow the UK to continue to provide 240V to the consumer, even though the nominal voltage is now 230V. Thus, the inverter should be selected to allow operation at up to 253V (230V $+10\%$).

Secondly, some inverters modify the voltage range over which the maximum power point tracking (MPPT) function operates according to the value of the grid voltage. One such inverter is the SMA Sunny Boy series, which is the inverter type most widely used in the DFT. Thus, when the grid voltage is high (although still within allowed limits), the minimum voltage of the MPPT window is also increased. Whilst the PV array is operating under good sunlight conditions, this does not normally affect performance, since the operating voltage remains within the required range. However, under poor sunlight conditions and for low string voltages, it is possible for the operating voltage to fall below the MPPT window. In this case, the voltage is fixed at the low end of the MPPT range and significant losses can be incurred since the array can no longer operate at its maximum power point. An example of this is given in Section 6, Case Study 6.1.

This situation is only likely to occur where the number of modules in the series string is sufficiently low that the string voltage falls below the MPPT window under low light level conditions. It has been observed that standard software packages for system design do not usually model scenarios of low light levels and high grid voltages at the same time. It is therefore recommended that system designers choose a string configuration that provides a nominal string voltage in the centre of the normal tracking window, rather than opting for a design that might risk low string voltages in combination with high grid voltages.

Because of the relatively high proportion of low light levels in the UK, it is important to ensure good low light level performance of the system. In accordance with other studies, we recommend that the inverter capacity be around 75% of the array capacity, although the DFT has not provided the opportunity to confirm this recommendation. The voltage threshold (and thus the light intensity threshold) at which the inverter starts up and shuts down is also important in determining overall performance. The value should be set as

low as possible consistent with not operating the inverter when the parasitic losses are higher than the output from the array. In this way, the maximum output can be obtained from the system.

Summary

- Check that the inverter has been selected to correctly match the PV array, in terms of overall power capacity and input voltage (recommended inverter power capacity is around 75% of the array capacity).
- Ensure that the inverter selected also has a sufficiently high maximum grid voltage to allow operation under normal UK conditions and that it is tolerant in operation in the high grid voltage region.
- Choose a string configuration that provides a nominal string voltage in the centre of the normal tracking window of the inverter.

2.5 Cabling and switching

All cabling and switching on the PV array side of the inverter should be rated for DC electricity at the appropriate voltage and current levels and designed to keep the voltage drop from modules to inverter to less than 3%. All external cabling, conduits and junction boxes should be suitable rated for external use, including UV exposure. Any degradation of the electrical connections will result in partial or complete loss of output at best, and at worst, over-heating and associated fire risk. So it is important that the appropriate standards are enforced in both the system design and installation.

2.6 Shading

After losses due to inverter outages, the next biggest loss mechanism in the DFT was shading of the PV array, indicating that this factor is not yet incorporated well enough into the design process. There are numerous potential shading sources for domestic PV systems, including trees and shrubbery, neighbouring buildings and self-shading from the building itself. The choice of array location and the electrical connection of the array should be such as to minimise the effect of shading.

Perhaps the most common cause of severe shading is a mature tree (or trees) in close proximity to the array. The potential for shading depends on the height of the tree, the distance from the array and the direction of the tree with respect to the array. Trees that are between east and south east or between west and south west of the array are generally more problematic than those that are due south, since the sun is lower in the sky in these directions. However, large trees can cause problems at any time. Where possible, the trees should be restricted in height so that they do not lead to array shading. It is also important to maintain the trees in this condition throughout the operation of the system as discussed later in Section 5.



Example of shading by nearby trees. Clearly, this is an extreme example where the trees will cause a substantial reduction in output.

One of the most commonly overlooked sources of shading is that from the building itself. Domestic properties in the UK offer a range of potential shading sources from chimneys and aerials to dormer windows. Terraced houses quite often have several houses set back or forward from the rest to give visual interest to the row. However, this causes shading of the roofs of properties that are set back at certain times of the day. If a PV array is placed on that roof, then the array is also shaded. In general, modules should not be positioned close to the adjoining edge of property that is set further forward than the one on which the array is positioned.

Example of self shading due to difference in roof heights. The building on the left of the picture causes shading of the roof on the lower property.



If some shading is unavoidable, the electrical connections of the system can be designed to minimise the effect. The general principle is that the array should be divided into strings such that any shading occurs in the same string(s) and some strings remain unshaded throughout. If possible, shaded and unshaded strings should be connected to different inverters, to allow maximum power point tracking of the separate parts of the array.

Summary

- Consider the potential shading sources, trees, neighbouring buildings and self-shading, etc.
- If possible choose an array location and the electrical connection of the array to minimise the effect of shading.
- Aim to restrict tree height, during the whole operational lifetime of the system.

2.7 User display

Whilst not a necessary part of the PV system for energy production, it is highly recommended that an appropriate display unit is provided for the user to be able to see the output of the system. Since the PV system does not require any direct intervention by the user in normal operation, it is easy for it to be disregarded, which may have serious consequences for the maintenance of high performance levels, as discussed in Section 5. An important point, however, is that the user has some appreciation of the amount of electricity being supplied and its contribution to their needs. This can be addressed by having a display unit provided that it meets certain requirements.

Ideally, the display unit should provide both cumulative totals of electricity provided and a measure of the instantaneous power output (which can be useful for operational checks – see Section 5). The displayed values should be easily understood and accessed. If the display also includes some information on the consumption of the dwelling, then the user can see how much the PV system contributes and it also encourages energy efficiency.

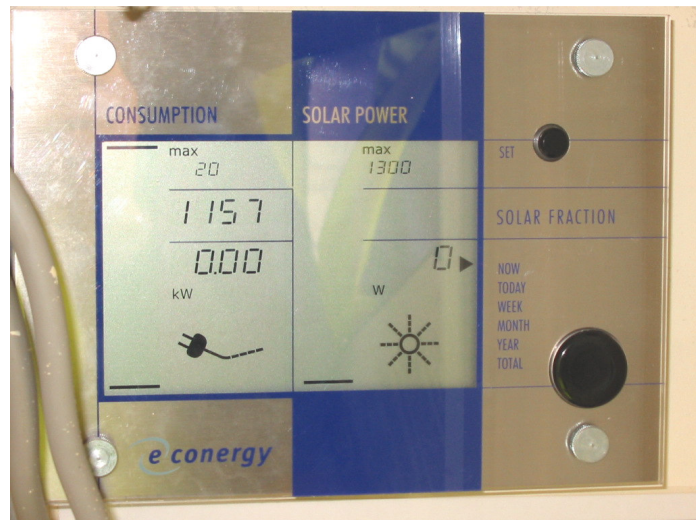
The display unit should be in an accessible position or it may not be viewed regularly. Experience from the DFT shows that display units placed inside cupboards are rarely consulted. In some cases, display meters have been installed in an open area (e.g. the hallway) but either too high or too low to be easily viewed. In other cases, the display is difficult to read. For example, some DFT projects use a small cumulative kWh counter where the meter is vertical, making the observer turn their head to read it, and the figures are very small. Both of these difficulties mean that the display is unlikely to be consulted on a regular basis.



Example of analogue meter showing instantaneous power output. In this case, the meter was mounted high on the wall, close to the ceiling, and was consequently hard to read due to the angle of viewing.

Whilst analogue meters are easy to understand for instantaneous power measurements, they do not show cumulative values. If an analogue meter is used, the scale of the meter should be chosen to be compatible with the system. For example, for one DFT system, meters of 2 kW full scale have been used for PV systems of just under 1 kW in capacity. This means that, even under bright sunlight conditions and for good system operation, the needle never rises above halfway on the scale and this is not good for user confidence in the system. However, for a range of parameters to be provided, including both power and cumulative energy readings, a digital display is recommended.

Example of digital display meter, also showing the energy being used in the house. This is the most complex of the meters used in the DFT, but does help to promote energy awareness and efficiency measures. However, in the case shown, the display was placed inside the meter cupboard, which is not recommended since it is not readily viewed.



Summary

- It is highly recommended that an appropriate display unit is provided for the user to be able to see the output of the system.
- Ideally, the display unit should provide both cumulative totals of electricity provided and a measure of the instantaneous power output.
- The display unit should be placed in an accessible position.

2.8 PV system design software

It is usual for system designers to make use of specialist PV system design software to compare component options and array designs. This software may be proprietary to the company or one of the generally available tools (e.g. PVSyst, PVSol and many others). Most project teams within the DFT produced estimated annual system outputs based on one of these software programs. Comparison of measured outputs with those estimates indicated that there was general agreement.

It should be remembered that all system design programmes have assumptions embedded in their calculations and the accuracy of the output depends on the accuracy of those assumptions in the case being considered. The software is generally designed to be generic in approach but uses default values for a number of influential operating parameters unless the user

specifically changes those values. Usually, those default values apply to climates with higher sunlight levels and higher temperatures than the UK.

The only specific recommendation from the DFT results is in relation to minimum string voltages, as discussed in Section 2.5. In this case, it is suggested that an additional safety margin be allowed in case the grid voltage is high and the bottom end of the maximum power point tracking range is increased as a result. This can lead to failure to track the maximum power point even though the standard design software does not indicate a problem. The string voltage should be chosen so as to be well within the operating window of the inverter and not too close to the minimum value.

Performance prediction requires the assumption of sunlight levels at the site and most of the software packages have either embedded solar data or import data from packages such as Meteonorm¹. The packages include a limited number of sites in the UK and some care should be taken in the choice of site used to provide the estimated output. The nearest available site by distance may not be the closest in terms of meteorological conditions, especially where either the installation site or the site where the solar data are measured is close to the sea. The DFT did not show any systematic variation of system performance with location. System designers should attempt to select a data site that is both climatically suited to the installation site and at similar latitude, but with the former condition being more important. Where there is some uncertainty about the best data site, it may be useful to investigate output predictions for several options.

¹ Meteonorm is a software package developed by Meteotest in Bern, Switzerland, and providing meteorological data for many sites around the world; for further information see www.meteotest.ch

3 INSTALLATION AND COMMISSIONING

The installation and commissioning phases of the project provide the means to implement the good design practices discussed in the previous section. However, the use of both high quality components and installation procedures is not just a matter of adherence to regulations (see Part 1 of this Guide for further information on the regulatory aspect of PV system installation). The quality of the system installation has a strong influence on the ongoing performance of the system and in meeting expected system lifetimes and output levels.

Having selected appropriate components for the PV system, it is important that they are installed in accordance with the manufacturer's recommendations, especially in terms of required fixings, ventilation, operating temperature range and safety aspects. Failure to adhere to the correct operating conditions can lead to poor performance levels, reduction of lifetime of components and even failure of the system in some cases.

Attention should be paid to minimising cable lengths and, particularly, to ensuring that all connections are correctly made and protected. Whilst it may not affect the initial performance of the system, a poor connection can become more influential with time and lead to performance reduction in the long term. Performance losses due to poor connections can be significant but are generally time-consuming to identify and rectify, especially if they are within the array. It is much better to ensure the quality of the connections at the time of installation than to have to address this issue later during system operation.

Excess cable should be avoided wherever possible. Where a small excess is necessary (such as when allowing for a system component to be moved for inspection without disconnection), the excess should not be coiled as this will reduce the cable's ability to dissipate heat, and could also lead to inductive voltage spikes being transmitted to the inverter on disconnection of the array or a string.

Whilst perhaps not impacting directly on the initial performance of the system, the quality of the physical installation of the system, particularly the PV array, can influence the long-term performance of the system and its costs. Poor fixing of array components can result in damage to the array during adverse weather conditions, resulting in loss of output and the need to repair or replace part of the array. It can also lead to damage to other parts of the roof, in some cases affecting the weatherproofing.

The commissioning procedure allows a check of system performance at the time of installation. The recommended commissioning procedure is given in "Photovoltaics in Buildings: Testing, Commissioning and Monitoring Guide"² and will not be repeated in full here. Certain aspects of the commissioning will be discussed in terms of their relation to system performance issues.

² Photovoltaics in Buildings: Testing, Commissioning and Monitoring Guide, ETSU Report No. S/P2/00290/REP, 1998

Summary

- PV system components must be installed in accordance with the manufacturer's recommendations.
- Attention should be paid to minimising cable lengths and to ensuring that all connections are correctly made and protected.
- Excess cable lengths should be avoided. Do not coil cables.
- It is important that the quality of the physical installation of the system, particularly the PV array is good.

3.1 Component Testing:

For domestic systems, it is not common to test the individual system components before installation to verify performance levels and it would probably be prohibitively expensive to do so. However, the adherence or otherwise of components to their nominal specifications can influence the performance of the system and any judgements made about that performance to a significant extent. In particular, the real output of the PV modules will govern the output of the overall system, and how well this matches the predictions based on module specifications.

Underperforming modules are not as common as they used to be and only one incidence of this was observed in the DFT, and this did lead to the system performing substantially below expectation. Thus, it is not recommended that all modules be tested independently to ensure compliance. However, it is recommended that (a) the supply companies be asked to provide the manufacturer's production test results for each module and (b) the level of system output is checked at the commissioning stage. The module test results referred to in (a) would also provide a benchmark for any subsequent claim on the module warranty and so should be retained by the system owner.

In order to assess the level of the system output (point (b) above), it is necessary to measure the in-plane irradiance level and compare the measured system output with a predicted level for that irradiance. Preferably this measurement should be carried out at several irradiance levels to eliminate other loss factors. For the DFT, where monitoring of the system performance was required, irradiance level sensors were installed. However, in most domestic installations, monitoring is not included and the commissioning organisation will need to provide temporary irradiance monitoring for the commissioning tests. Note that the commissioning guidelines include the requirement to translate measured string outputs to normalised conditions, i.e. a check of the performance level of the system. However, this does not seem to be adopted in practice or, at least, is not generally reported in the commissioning documentation. It is recommended that this procedure is carried out and that performance levels at installation are recorded as a reference for the assessment of future operation.

Summary

- Performance levels should be recorded at installation to be used as a reference for the assessment of future operation.

3.2 Grid Connection

As discussed in Section 2.4 and also considered in Section 6, the connection of the system to the grid and particularly the grid voltage at site can have a significant influence on system performance. It is not always easy to test this at the time of installation – it may be the wrong time of year or the wrong load conditions to see any problems that might occur. However, it is suggested that, where there is a reasonable expectation of problems, the commissioning tests include consideration of the grid voltage level, logged over a period of time, rather than just measurement of instantaneous values. This will increase the chance of observing any grid voltage problems. The way in which commissioning tests could identify and address this problem requires further development. The DFT has observed that this can be a significant factor in system performance (see, for example, Case Study 6.2) but the development of a solution was beyond the scope of the project.

Summary

- Commissioning tests will provide the best information if they include consideration of the level of the grid voltage.

4 GRID CONNECTION AND EXPORT

The regulations for grid connection of PV systems are discussed in Part 1 of this Guide. The main performance related issue in regard to grid connection is the influence of the grid voltage as discussed in Sections 2 and 5.

The export of electricity from the PV system occurs when the output exceeds the local load and is part of the connection agreement. It is important that the connection hardware, particularly the meter(s), is compatible with the export of electricity. In the DFT, problems were encountered where pre-payment meters were damaged due to power flows in the reverse direction. Some pre-payment meters have an anti-tampering feature which causes disconnection of the supply if reverse flow of power is detected, causing a complete shutdown of the system. Thus, it is essential that suitable meters are installed where a PV system is to be provided.

Within the DFT, several different options for payment in regard to exported electricity have been implemented. More information on export tariffs and arrangements can be found in Part 1 of this Guide.

The receipt of payment for exported electricity, provided that it is explicit (i.e. not hidden within the electricity bill and thus not visible to the user) encourages the user to pay attention to the system output. This promotes both awareness of the advantages of having the system and early attention to any problems, since a reduction in output has a financial implication. During the DFT, a higher level of engagement has been observed for users where they have explicit knowledge of the export arrangements, in comparison to those who have no export agreement or who do not have a straightforward way of knowing how much is being exported.

Summary

- Ensure that the connection hardware, particularly the meter(s), is compatible with the export of electricity.
- The receipt of payment for exported electricity should be explicit for the user.

5 OPERATION AND MAINTENANCE

Assuming that good design rules have been followed and the appropriate quality control procedures have been applied to the installation and commissioning process, then the PV system should have a good performance level at the start of its operation. However, it is important that this performance level is maintained throughout the system lifetime in order to obtain the most benefit from the PV system. This section deals with operational issues that can reduce that performance level and recommends operating and maintenance procedures to minimise those losses.

5.1 Inverter operation

The most severe reductions of output are observed when there are operational problems with the inverter. In the worst case, the inverter closes down, either due to a fault within the inverter itself or because it has tripped due to a grid fault and failed to restart automatically. The remedial action required and the time it takes to complete that action will depend on the nature of the fault. However, the first step is to recognise that the fault exists. Since the PV system requires no regular tasks to be performed by the user in normal operation, it is easy for a fault to go unnoticed for a considerable period of time (up to several months) and this has serious consequences in relation to system output.

In most domestic systems, the inverter is located in the roof space and may be viewed infrequently if at all. Therefore it is important that there is a method of checking system operation in an accessible location and in a simple manner. It is highly recommended that a display be provided in a position where it can easily be seen. In addition, it is necessary that the parameters being displayed allow the user to see quickly and easily whether the system is operating.

To check whether the inverter is on, it is simply necessary to see that there is power from the system when the sun is shining. This means that the output display should be capable of displaying instantaneous power output and that the user should be asked to check that this is above zero (or above a certain minimum level as defined for the system) under sunny conditions.

Alternatively, the display might have some indication light that shows when the inverter is on. If the sun is shining and the light is not illuminated, that indicates that there is a problem. However, it would still be useful to confirm this via the display of power output.

Therefore, in order to minimise the down time, the user should know how to check that the system is operational and be encouraged to do this on a sufficiently regular basis to pick up inverter malfunctions of more than a few days. Contact details should be provided for the company/organisation that is responsible for attending to the system fault in the first instance.

The inverter operation can also lead to significant losses if it regularly drops out, so failing to provide power for certain periods in the day. The most common cause of this behaviour is that the grid voltage is outside the specified operating limits of the inverter and almost always because that voltage is too

high. This can lead to high losses in some months and the losses often vary with season.

The UK has a relatively high grid voltage in certain areas and, when load levels are low and PV system generation is high, this can lead to periods where the voltage is higher than the acceptable level. Whilst this can sometimes be identified at the time of installation, the seasonal and intermittent nature of the problem means it is often not observed even though the normal test procedures have been observed.

This behaviour is much more difficult for the user to observe than for the case of the inverter failure discussed above. Because the system condition varies with time, it is a matter of chance as to whether the user observes the instantaneous power level at the time when it has fallen to zero rather than the time when the inverter is operating normally. There is ongoing R&D work at European level to determine straightforward ways of identifying problems such as this, using field data from existing systems. In the meantime, it remains problematic to identify in all cases where there is no performance monitoring.

It is possible to identify the presence of major faults, although not diagnose their cause, from comparison of cumulative monthly output readings with expected levels. Because of the natural variation of monthly sunlight levels from year to year, any problems with inverter dropout that only leads to a small reduction of output will not be picked up. However, if the system output is less than half of the lower limit expected for that month, then an operational problem is likely. It would require investigation to establish whether the cause is inverter dropout or one of the other problems described here.

The likelihood of inverter dropout is higher where the grid voltage is known to be high at the site, as evidenced by any problems with the inverter at installation or in the early stages of operation. However, even if inverter dropout does not occur in the first months of operation, it can be triggered by local conditions on site at a later time (e.g. due to the installation of further embedded generation systems on the local network) and so users should be aware and encouraged to check output occasionally to determine whether additional losses are being experienced.

In Section 2.4, losses due to incorrect setting of the inverter threshold were discussed. If this is correctly handled at the time of installation, there should be no requirement for adjustment during operation. However, if it should be necessary to replace the inverter, then the correct threshold settings should be used for the new component.

Summary

- It is important that there is a method of checking system operation in an accessible location and in a simple manner.
- The parameters being displayed should allow the user to see, quickly and easily, whether the system is operating or not.
- Ensure the user knows how to check that the system and encourage them to do this on a sufficiently regular basis.
- Contact details must be provided for the company/organisation that is responsible for attending to the system fault.

5.2 Shading

Shading of the PV array should have been minimised at the design stage in order to obtain the highest system performance possible. However, since many shading sources relate to vegetation, particularly trees, the shading conditions tend to change with time and become more severe as the vegetation grows. If action is not taken to control the growth of trees, then it can lead to substantial loss of output from the system. In general, shading losses increased in the second year of monitoring of systems in the DFT suffering from this problem. It is, of course, not necessary to remove trees, just to ensure that they stay low enough to prevent significant shading of the array.

A second source of shading that can arise in the course of operation is any equipment that is placed on the owner's roof or on a neighbouring roof where it will cause shading of the modules at some time of day. Examples of such equipment observed in the DFT include TV aerials, satellite dishes and even the cabling from these having been placed over the modules. Finally, modifications to the house or to neighbouring houses can lead to additional shading problems.

The first requirement is that the system owner understands that shading of the array can cause losses and that these can be substantial depending on the array configuration. At the time of installation, the installing company should point out potential sources of shading and give some indication of the maintenance activities that should be undertaken to keep the shading to the minimum level. Shading is one of the largest loss mechanisms observed in the DFT and therefore it is of particular importance to make sure that it does not worsen during the operational lifetime of the system.

Summary

- Ensure that the system owner/user understands that shading of the array can cause losses.
- Point out potential sources of shading to the owner/user and give some indication of the maintenance activities required.

5.3 Dirt Accumulation

Since the array is in an outdoor location, it will accumulate dirt over the course of operation and this reduces the light input to the solar modules and hence the

output of those modules. Previous studies of domestic PV systems³ have indicated that it is not necessary to provide regular cleaning of the panels since much of the accumulated dirt will be washed away by rainfall provided that the panels are installed at a reasonable tilt angle (>15 degrees). The remaining residue does not usually cause more than a few percent reduction in output. However, it has been recommended that panels are cleaned well every few years (around 5 years has been suggested) to remove this residue. The length of the DFT and the variability of output due to other loss mechanisms have not allowed us to investigate this aspect in detail. As such, there is no evidence from the DFT that would disagree with these general conclusions.

However, there are some situations in which soiling could be expected to be higher than average and some remedial measures may need to be taken in the case where there is an identified source of soiling in the vicinity of the array. The two most common cases are high levels of bird activity (e.g. a seaside location with a high number of seabirds) or building work in the vicinity of the array.

Finally, as has been discussed previously, high edge profiles on modules can lead to dirt accumulation at the bottom edge. This should be addressed by the original choice of module and mounting system.

Summary

- It is suggested that cleaning of the PV array be carried out every 5 years and more frequently if there is an identified source of soiling in the vicinity.

5.4 Electrical connections

As with all electrical systems, the circuit should be checked at regular intervals (every 5 years is recommended) to ensure that there are no problems with loose connections, corrosion etc. If the correct components have been used in the first instance, there should be few problems with the external connections to the array, but these may need checking if there appears to be a reduced output and no other causes can be found. Both high resistance and open contacts will substantially reduce the electrical output of the array, and may constitute a fire risk.

The DFT did not observe any problems that could be assigned to the electrical connection of the systems, but these would tend to occur later in the operation in any case.

Summary

- The electrical circuit should be checked for output and excessive voltage drops at regular intervals (every 5 years is recommended) to ensure that there are no problems with loose connections, corrosion etc.

³ See, for example, publications on the results of the 1000 Roofs project in Germany.

5.5 Damage

It is unusual for damage to occur to the PV modules except as a result of vandalism. The location of modules on the array makes it difficult for anyone to gain access and cause accidental or malicious damage in most cases. We have observed a few examples in the DFT where the location of the array allowed access to vandals due to the availability of a vantage point from which to launch small missiles at the modules. Careful consideration of the location of the array can minimise this problem. It is also possible for damage to occur if work is being carried out near to the array.

Physical damage to a module usually consists of broken or cracked glass on the front, which may or may not also include damage to one or more cells. In the case where only the glass is cracked, the initial effect on the system performance may be minimal with only the aesthetic effect being important. However, a breach of the encapsulation may lead to more severe problems later as moisture ingress can cause degradation of the cells, so consideration should be given to replacing the module if possible.

The owner can check for module damage by conducting a visual check of the modules and looking for anything unusual or altered from the last inspection. This can often be done easily from ground level using a pair of binoculars so access to the roof is often not required. Where easy inspection is possible, a quick check on a six monthly or annual basis is recommended. Where it would require access to the roof and this is difficult, an inspection should be carried out if the possibility of damage is suspected.

As with all roof-mounted equipment, adverse weather conditions, particularly high winds, can cause damage to the structure or the surrounding roof. Whilst no examples of damage due to weather conditions were observed in the DFT, it is good practice to check for damage to the PV array at the same time as the rest of the roof if particularly bad weather conditions have been experienced.

If the installation of the PV system has followed good practice in terms of the electrical wiring, particularly fixing the cabling rather than allowing it to hang loosely, there is a low chance of damage. However, care should be taken in working in close proximity to the electrical wiring to avoid accidental damage.

Summary

- Periodically check for damage to the PV array and the mounting system.
- Vandalism can be a problem: choose the site to avoid this.

5.6 User Engagement

One of the most important factors in ensuring continuing good performance of the PV system is the engagement of the user. They are the only people who can check for inverter operation, sensible output levels, shading problems and obvious damage to the system during its general operation. Whilst they may then need to call in specialists to resolve the problem, it is the user who initiates this action. It is therefore very important that the user understands

what can lead to performance loss and how to make the necessary checks. It is the responsibility of the system installer (or the organisation that oversees the installation, e.g. a housing association or council) to ensure that the relevant information is passed to the user.

A complication in the domestic sector is that properties change ownership or tenancy on a regular basis. In the experience of the DFT, information on the basic operation of the system is often not available to the new owner or tenant. It needs to be ensured that the information is in an accessible format and easy to pass on, in the same way as information is transferred on all other aspects of the dwelling (e.g. the heating system, alarms etc.).

The user display is the main interface between the user and the system and the main source of information on system performance. As we have seen, in order to be able to identify problems, the display should ideally include instantaneous and cumulative outputs for the PV system, together with an indication of the overall building loads. It should also be positioned such that, whilst not being intrusive, it is easily visible and accessible.

The results from the DFT show that a PV system of around 1.5 kWp in size can deliver a substantial proportion of the energy required by the household (on average, around 50%), albeit with about half of that electricity exported to the grid and then imported when required. Of course, the proportion provided for any specific system is highly dependent on the electricity usage of the household. In research on PV systems around the world, it has consistently been found that the ownership of the system can encourage energy efficiency and enhance other environmentally conscious behaviour. However, this only occurs when the user interest is engaged and when there is a direct measure of the contribution of the PV system.

In many cases within the Field Trial, the users are not sufficiently well informed to obtain the full advantage of their system. The main problems are:

- Lack of understanding of the operation of the system
- Lack of documentation for reference and for transfer to new owners/tenants
- Lack of a suitable display system that is informative whilst being easy to understand and accessible.

It is highly recommended that user engagement is included as an essential part of project design.

Summary

- One of the most important factors in ensuring continuing good performance of the PV system is the engagement of the user.
- Information should be in an accessible format and easy to pass on to a new owner/user.
- The user display is the main interface between the user and the system and as such must be easy to view and understand.

6 CASE STUDIES

The two case studies presented here illustrate some of the operational losses that can be experienced due to high grid voltage, firstly in relation to maximum power point tracking and secondly with respect to inverter outages.

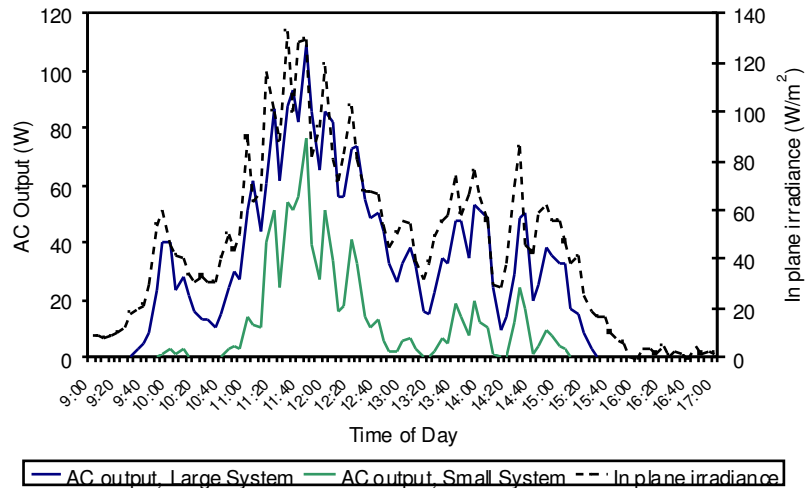
6.1 MAXIMUM POWER POINT TRACKING

The inverter used in a PV system is designed to have high conversion efficiency over a range of operating conditions and different designs will use different strategies to accomplish this. The SMA range of Sunny Boy inverters generally incorporate a variable voltage window over which maximum power point tracking is accomplished and this is related to the voltage of the electrical supply grid. As the grid voltage increases, the tracking window is moved to a higher voltage range.

This does not normally affect operation of the PV system adversely, since high local grid voltages often coincide with high output from the system. However, in some locations in the UK, the grid voltage is high for all conditions of operation.

One DFT project allowed us to identify this problem since it consisted of two sets of houses, located close together and using the same type of PV roof tiles and inverters. One set of houses had a 20% larger array size than the other set. This corresponds to eight more tiles and, since the array was connected as two series strings, there were four more tiles in each string. This raises the nominal string voltage by around 34V.

The performance of the two sets of systems was very similar in the summer months, when light levels are generally high. A significant drop in performance was observed for the smaller systems in the winter months, however, resulting in an output of only about two thirds of what was expected. The graph below shows a typical daily trace for a winter's day, comparing the output from two systems, one from each set, showing the reduced output from the smaller system.



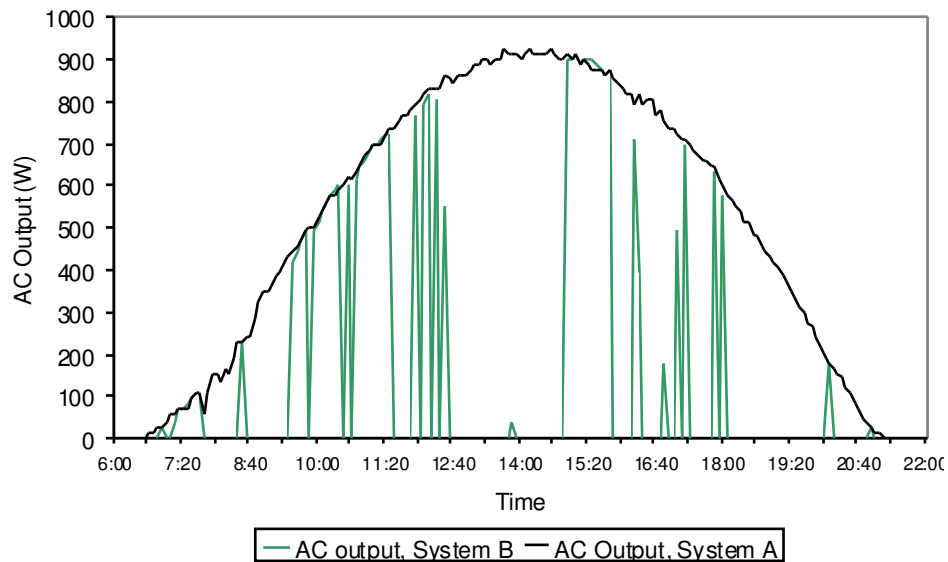
In order to address this problem, it is recommended that the design makes sure that string voltages are well within the tracking window of the inverter.

6.2 INVERTER OUTAGES

A high grid voltage can also lead to the suspension of inverter operation if it is above the maximum allowable value for the inverter. Since the grid voltage varies with load level, the inverter can turn on and off regularly under some conditions and operate continuously at other times.

This behaviour is characterised by repeated short-term stoppages in inverter operation, with normal behaviour at all other times. These stoppages can extend for a few minutes or a few hours depending on grid conditions. They are often not connected with any obvious change in operating conditions, since they depend solely on the grid voltage at the inverter connection. However, they do often occur in good weather conditions when the PV output is high and the load levels are low. As such, the stoppages are more common in the summer and can reduce overall system output by a substantial amount.

Again, the DFT has allowed us to observe this behaviour by comparison of systems on the same site. The graph below shows the output of two identical PV systems for a summer's day. System A operates continuously with an output matched to the sunlight profile for that day. System B, however, only shows very short periods of operation with the inverter being off for the majority of the day. When it is operating, it can be seen that the output level is very similar to that of System A.



The effect can be quite severe, although not always easy to observe. For the example presented here, System B had an output of only 40% of that for System A during the month from which the above daily profile is taken.

The susceptibility of the system to this behaviour depends on the local grid voltage and load conditions, the settings of the inverter and the position of the system on the supply feeder (systems close to the local transformer are the most vulnerable).

7 CONCLUSIONS

The design of the PV system, in terms of choice of components, electrical configuration and location of the array, should take account of local conditions in order to ensure maximum performance. Within the DFT, the most significant losses arose from issues with the inverter and shading of the array. In most cases, it is possible to minimise these losses by careful design.

For continued high levels of performance, it is necessary to make sure that shading losses do not increase in severity due to growth of trees or the introduction of new shading sources. Occasional checks should also be made on the operation of the inverter to make sure that any faults can be dealt with rapidly. In order to accomplish this, it is important to engage the user of the system by providing easy access to information.

The DFT has demonstrated that good performance can be obtained from PV systems installed on domestic systems in the UK. It has also identified the design aspects that must be considered to ensure good performance both at installation and during the operational life of the system.

8 FURTHER GUIDANCE

- Photovoltaics in Buildings: Testing, Commissioning and Monitoring Guide, ETSU Report No. S/P2/00290/REP, 1998
- British Standards website - www.bsi-global.co.uk
- Department of Trade and Industry (DTI): Photovoltaics in Buildings: Guide to the installation of PV systems, DTI/Pub URN 02/788,
- Domestic Field Trial (DFT) Website (for further detailed/technical information on the DFT); www.dti.gov.uk/renewables/renew_6.1h.htm
- The German Solar Energy Society, Ecofys, James & James 2005: Planning and Installing Photovoltaic Systems – A guide for installer, architects and engineers;
- IEE Wiring Regulations - requirements for electrical installations:, 16th Edition. BS 7671, 2001.
- Deo Prasad & Mark Snow; Earthscan 2005: Designing with Solar Power – A source book for building integrated photovoltaics (BIPV)
- Various papers and reports from IEA Photovoltaic Power Systems Programme, Task 2: Performance, Reliability and Analysis of Photovoltaic Systems, available from IEA PVPS website; www.oja-services.nl/iea-pvps/index.html

Disclaimer: This Good Practice Guide has been produced based on experience gained from the PV DFT as well as the wider PV market. However, it does not represent an extensive survey of present UK installations or an exhaustive review of all installation issues. The authors therefore can accept no responsibility for issues not raised herein.

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