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**M27 TRIAL OF HIGHWAY NOISE BARRIERS AS SOLAR ENERGY GENERATORS**

Final

by **D R Carder and K J Barker**

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## Executive summary

Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Sources of renewable energy have considerable potential for increasing security of supply and reducing CO<sub>2</sub> emissions although, in most cases, they require significant initial investment. An application that has been steadily gaining interest is that of incorporating photovoltaics into highway noise barriers to recover solar energy. The initial attraction of mounting photovoltaic modules on noise barriers is that a proportion of land and support structure costs can be avoided thus improving the economic production of renewable energy. This report describes a full scale trial to recover solar energy using photovoltaic noise barriers installed on the M27. This demonstration trial is particularly relevant as a significant infrastructure of noise barriers already exists on UK highways and unshaded areas of south facing barrier provide a convenient mounting for solar panels which has little environmental impact.

Two 54m long parallel rows of solar barrier were installed in a cutting to the east of Junction 9 of the M27. One row was placed at the toe and a second row at the crest of the cutting slope. The row at the crest of the cutting was installed on a new support frame about 1m immediately in front of the existing 2m high wooden acoustic barrier, and is the same height so that there is no visual impact from outside of the Highways Agency boundary. The solar barrier at the toe of the slope is 2.5m high and installed about 3m back from the kerb of an unused road to avoid communications cabling installed during 2003. The electrical performance of the system was monitored over its first two years in service. AC and DC currents and voltages, together with AC power and daily (and total) energy were logged from each of the four inverters used in the system.

The AC energy exported to the local grid was 6.4MWh in each of the first two years in service with both the upper and lower photovoltaic barriers contributing equally to this output. The energy output and actual installation costs were used as a basis for whole life costing when constructing a 2km length of similar barrier. The whole-life cost analyses have shown that, for the assumptions made, the initial installation costs of the photovoltaic installation will be far greater than the cost of the power generated by the solar modules over 30 years. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and/or significant reductions in the costs of the components. Analyses were carried out where (i) no allowance was made for the added value of the barrier in its noise reducing capacity, and (ii) costs were defrayed against those of a conventional noise barrier. In both cases payback over a 30 year accounting period is only obtained in (i) and (ii) if there is an early life increase in the price of electricity (possibly by government subsidy) by a factor of 10 and 6 respectively. Nevertheless in remote areas, although it is unlikely that there is a need for a highway noise barrier, a source of electricity may be invaluable in avoiding the probable high cost of laying cable from a remote grid supply.

A study was also carried out into the potential impact of the array on road safety as there was a concern that the array may prove distracting to drivers and as a result may lead to a general reduction in safe driving at the site. The study utilised video techniques and indicated that under similar road and weather conditions, there was no observed driver behaviour that might indicate driver distraction.

An important issue with regard to the construction of any noise barrier alongside a highway is the potential for increasing the reflected noise received by properties situated along the opposite carriageway. The findings from a noise survey at this site found that the photovoltaic barrier does increase traffic noise levels on the opposite side of the motorway by 0.3dB(A), although this would not be expected to cause any change in the disturbance from road traffic noise.

In terms of maintenance, the control of any nearby vegetation remains an important issue in the design of photovoltaic barriers of this type. No cleaning of the photovoltaic surfaces was found necessary at this site as occasional heavy rainfall proved effective in this respect.



## Abstract

Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Renewable sources of energy have considerable potential for increasing security of supply and reducing CO<sub>2</sub> emissions although, in most cases, they require significant initial investment. This report describes a full scale trial to recover solar energy using photovoltaic noise barriers installed on the M27. In addition to the electrical performance of the system, whole life costs studies were undertaken to assess the benefits of a wider implementation of the technology. Any impact on driver behaviour due to the presence of a visible technology adjacent to the highway was also investigated, as were the implications on reflected noise levels of using a photovoltaic barrier as opposed to a conventional noise barrier.

## 1 Introduction

### 1.1 General

Incorporating photovoltaics into highway noise barriers to recover solar energy is an application that has been steadily gaining interest following large-scale demonstration projects which have been undertaken in the Netherlands, Switzerland, Austria, France, Germany and other countries. Further information on these is given in the International Energy Agency database ([www.iea-pvps-task2.org/index.htm](http://www.iea-pvps-task2.org/index.htm)). The initial attraction of mounting photovoltaic (PV) modules on noise barriers is similar to that of mounting PV on buildings. A proportion of land and support structure costs can be avoided. Operating experience gained from these demonstration projects demonstrates the technical feasibility and electrical generation potential of such installations.

Renewable energy technologies, such as photovoltaics, are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. For this reason, there has been an increasing emphasis on the generation of energy from renewable sources in response to the sustainable development and “green” energy agenda. Recognising the importance of developing renewable energy resources, the Highways Agency commissioned a study (Carder, 2005) to explore the feasibility of PV noise barriers and assess the possibility of renewable energy generation being exploited from within the highway network. Renewable sources of energy have considerable potential for increasing security of supply although, in most cases, they require significant initial investment.

The Highways Agency responded positively to this feasibility study and implemented a full-scale trial of electricity generation using photovoltaic barriers on the M27 near Junction 9. The demonstration trial is particularly relevant as a significant infrastructure of noise barriers already exists on UK highways and unshaded areas of south facing barrier provide a convenient mounting for solar panels which has little environmental impact.

### 1.2 Objectives

The main objectives of the trial of PV noise barriers on the M27 are:

- to provide experience in the installation and use of photovoltaic systems adjacent to the highway and assess their durability,
- to monitor performance and provide advice on design, installation, cleaning and maintenance procedures,
- to gain experience in electrical grid-connection,
- to refine preliminary whole life costing studies so that the best value for money can be obtained from a larger investment programme,

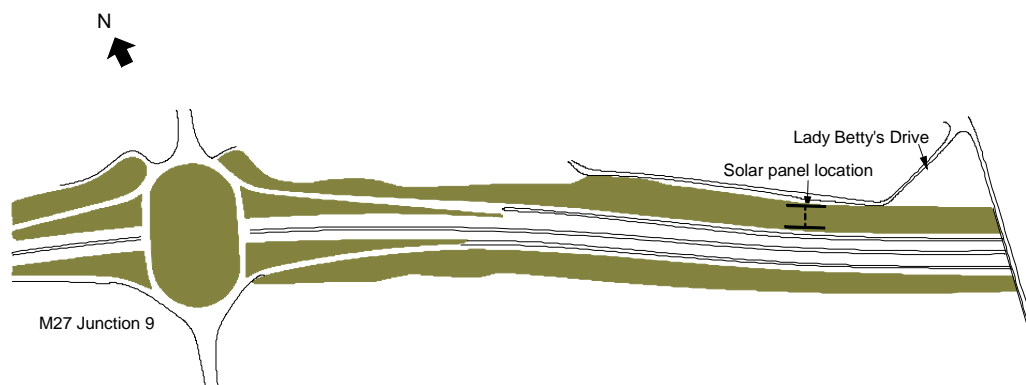
- to assess public response and any impact on driver behaviour to the presence of the panels,
- to carry out a preliminary evaluation of any issues related to the performance of PV barriers with respect to their noise reducing capability.

The findings and conclusions related to each of the above objectives are discussed in this report.

## 2 Site location and environmental assessment

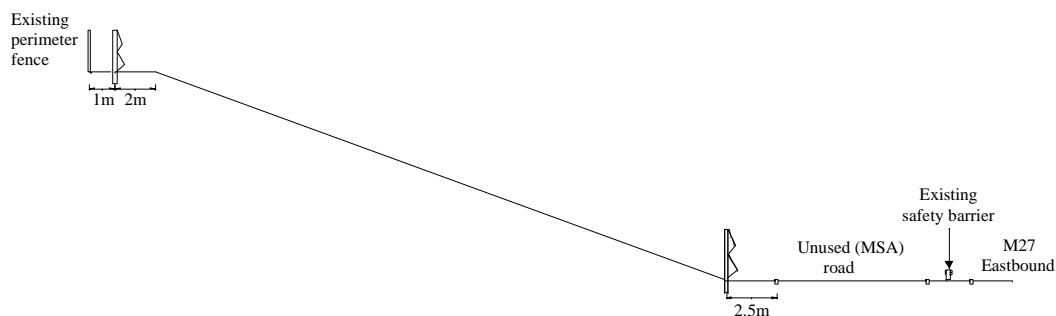
### 2.1 Site location

The site for this trial is on the south-facing verge of the M27 just to the east of junction 9 as shown in plan in Figure 1. At this location the motorway lies in a steep cutting and as such is shielded from the neighbouring residential area to the north and industrial area to the south. The trial site is shielded from the adjacent residential areas by a 2m high perimeter fence which provides both acoustic and visual screening.



**Figure 1. Location of the Solar Panel Trial on the M27 (Junction 9)**

Figure 1 and the section view in Figure 2 shows the nature of the trial installation which provides for two 54m long parallel rows of solar barrier centred on marker post 33/1A+70m. One row is placed at the toe and a second row at the crest of the cutting slope. The row at the crest of the cutting is installed on a new support frame about 1m immediately in front of the existing 2m high wooden acoustic barrier, and is the same height so that there is no visual impact from outside of the Highways Agency boundary. The solar barrier at the toe of the slope is 2.5m high and installed about 3m back from the kerb of an unused road to avoid communications cabling installed during 2003. The unused road comprises a two lane construction for a proposed motorway service access (MSA) which it is now not intended to implement. This access runs parallel to the M27 and is separated from the motorway by a vehicle restraint system.



**Figure 2. Cross sectional view through the centre of the trial site**



## 2.2 Environmental assessment

An initial environmental assessment was undertaken prior to construction and the findings were reported by Mott MacDonald (2003). The assessment covered landscape and ecological issues in detail, and provided comment on the likely impact on noise, water quality and drainage, cultural heritage, pedestrian and community effects, and possible construction and maintenance impacts. In addition to the locations of the two rows of barrier, the impacts of trenching for underground cabling up the slope between the barriers were investigated.

The main construction impacts were identified as being likely to arise from vegetation clearance if it coincided with the bird nesting season. The construction timetable was therefore arranged for this activity to be completed by February 2004. The loss of small amounts of existing established vegetation of the cutting slopes was not considered to result in any significant visual impacts, and replacement was not therefore required.

No plant species protected under the Wildlife and Countryside Act 1981 were recorded on the environmental database for this area. Although several notable and scarce plant species (e.g. wild service tree, marsh cinquefoil and lesser fleabane) were identified to the east of the site, these species did not occur on the site of the works. The whole site provided a habitat for the "common" species of reptiles (adder, grass snake, common lizard and slow worm). These species of reptile are protected against intentional or reckless killing, injury or sale under their inclusion on schedule 5 of the Wildlife and Countryside Act 1981, as amended by the Countryside and Rights of Way Act 2000. Appropriate care was therefore taken during the construction works.

In terms of any potential visual or acoustic disturbance for nearby residents, there were considered to be no implications. There are very few visual receptors other than the motorists, as there are no residential properties with a view of the highway. The planning department of Winchester City Council was also consulted for any other issues prior to barrier construction, but none were identified.

## 3 Design and installation of the solar system

### 3.1 Design

The photovoltaic system was designed and incorporated in a free standing structure of dimensions which were typical of those used for conventional highway noise barriers. Two 54m long barriers were installed; one (2m high) was at the top and the other (2.5m high) at the bottom of the cutting slope. A cross-section through each barrier is shown in Figure 3.

The photovoltaic capacity was achieved by using triple junction amorphous technology in the form of both framed modules and flexible laminates. Triple junction amorphous technology was selected to provide sensitivity to a wide range of frequencies and provide better output under the cloudy conditions often encountered in the UK. Amorphous technologies are also more suited to mass production and their cost may reduce in the future more quickly than other types, which is an important consideration for a trial with the objective of informing future decisions on generating renewable energy. Forty framed Uni-Solar US-64 modules (1.366m long by 0.741m) were incorporated in each of two rows to form the upper barrier (Figure 3a). Ten Uni-Solar PVL-128 laminates (5.486m long by 0.394m) were arranged in four rows to form the lower barrier as shown in Figure 3b. The rating of each barrier was therefore 5.12kW peak, ie. 10.24kW peak for the whole system.

Optimisation of the theoretical electricity output was carried out within the constraints of minimising the footprint of the structure as land availability is often a premium when installing noise barriers

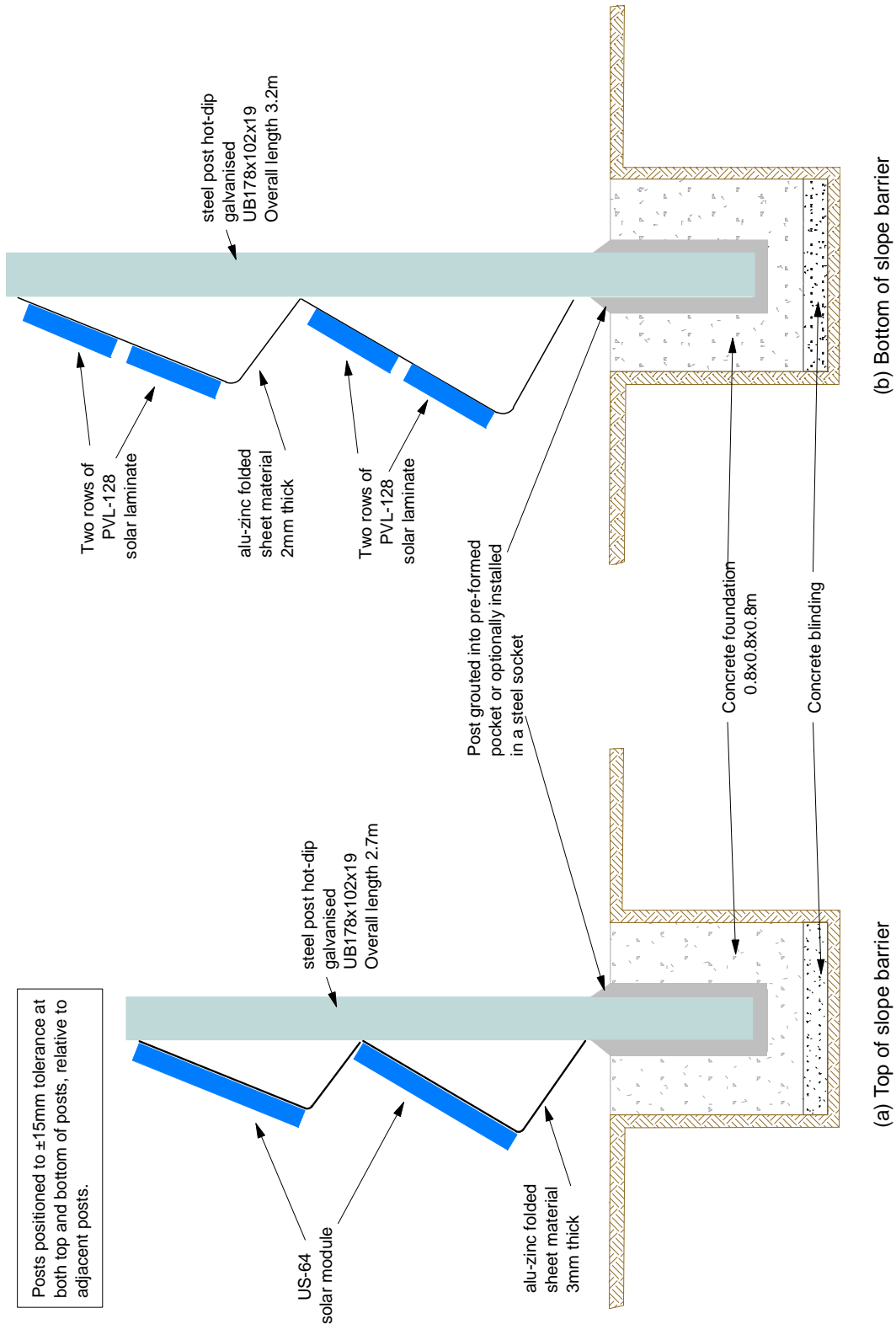


Figure 3. Cross section through the barriers located on the slope

adjacent to the highway, giving consideration to the winter energy yield, and ensuring that the tilt was such that the panels were self-cleaning. For this reason the pitches of the upper rows and lower rows of both barriers were arranged at 68° and 60° to the horizontal respectively as shown in Figure 3.

Groups of PV strings are connected back to DC junction boxes and double pole isolators. The isolator outputs within each row of each barrier are then connected to the DC input of a Sunny Boy inverter, i.e. two inverters were used for each barrier. All DC cabling and connectors were housed within the profile of the aluminium zinc alloy folded sheet.

The PV installation was designed to satisfy the requirements of BS7671 (Requirements for electrical installations. IEE Wiring Regulations) and followed guidelines detailed in DTI/Pub URN 02/788 (Photovoltaics in buildings – Guide to the installation of PV systems). System earthing connections conformed to BS7430 and lightning protection was in accordance with the requirements of BS6651.

### 3.2 Technical approval

The structural design of the solar noise barriers was subject to the normal HA Technical Approval procedure to ensure that the barrier conformed to the requirements of HA66/95 (Environmental Barriers: Technical Requirements, DMRB10.5). The stability of the barrier depended on the support provided by the cantilevered posts which located into steel sockets in a concrete pad foundation. A pad foundation of 800×800×800mm was preferred because the presence of roots in the ground would have made the preparation of augered holes more difficult. The pad foundations were designed to accommodate the dead loads of the structure and the wind loads which were derived from BS6399. The steel posts were hot-dip galvanised universal beams (178×102×19mm) and were installed at a spacing of 2.7m between post centres. The solar panels/laminates were mounted on aluminium zinc alloy folded sheet of 3mm thickness. BS5950 (Structural use of steelwork in building) and BS8118 (Structural use of aluminium) were used in the design of these components.

### 3.3 Installation

The site installation of the solar panel system was carried out in the following sequence:

- levelling of ground and clearance of vegetation;
- installation of galvanised steel posts (Figure 4);
- installation of folded sheet mountings (Figure 5);
- installation of solar modules for barrier at top of the slope (Figure 6);
- installation of solar laminates for barrier at bottom of slope (Figure 7);
- installation of all electrical connections and inverters.

Photographs of the completed installation are shown in Figures 8-10. Figure 10 is taken from the opposite side of the M27 motorway.



**Figure 4. Installation of the galvanised steel posts**



**Figure 5. Installation of the folded sheet mountings**



**Figure 6. Installation of the solar modules at the top of the slope**



**Figure 7. Installation of the solar laminates at the bottom of the slope**





**Figure 8. Completed installation of the solar laminates at the bottom of the slope**



**Figure 9. Completed installation of the solar modules at the top of the slope**



**Figure 10. Completed installation as viewed from the opposite side of the M27 motorway**

### **3.4 Grid connection**

Output of three phase AC electricity at a nominal voltage of 230 to 240v was via a new overhead cable to the location of transformer pole 11944 on Lady Betty's Drive owned by the Scottish & Southern Energy PLC. This connection was made in compliance with all relevant standards including G59.

## **4 Performance monitoring**

### **4.1 Monitoring procedure**

AC and DC currents and voltages, together with AC power and daily (and total) energy were logged at 15 minute intervals from each of the four inverters using a Sunny Boy Control Plus (SBC+) for the data acquisition, manipulation, and storage. The SBC+ also monitored the AC power and daily (and total) energy exported to the grid.

Using extra analogue and digital channels included in the SBC+, other instrumentation was also monitored. Three solarimeters were installed at different inclinations to monitor incident solar radiation at the site. One of these solarimeters was installed horizontally to measure global radiation, whilst the other two were installed at the two pitches used for the solar modules/laminates. One was therefore installed at 68° to the horizontal and the other at 60° to the horizontal.

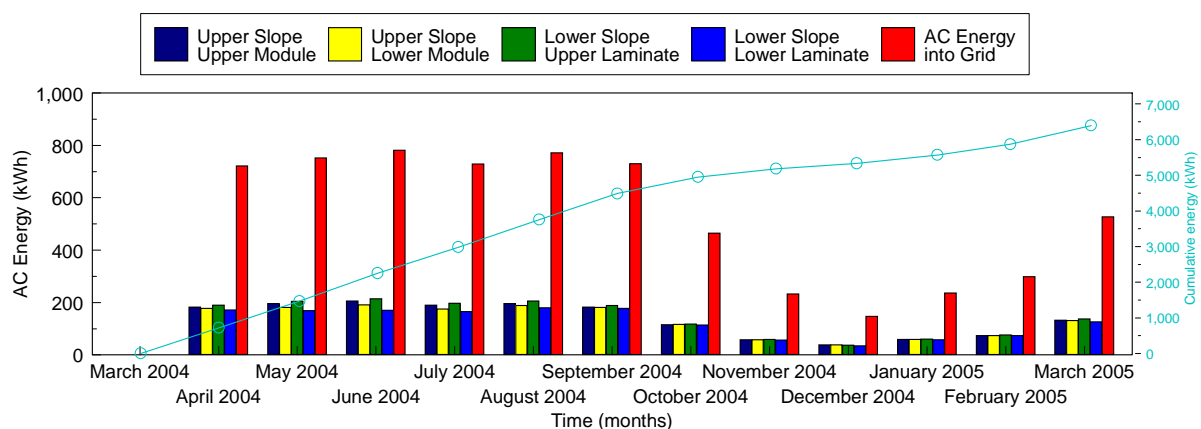
The cell efficiency of a PV module decreases as the temperature increases and to investigate this effect patch temperature sensors were installed on the back of the solar modules/laminates. One sensor was installed on the top row and one on the bottom row of each barrier, i.e. four temperature sensors in all. Outputs from these sensors were also logged using the SBC+.

## 4.2 Performance during first year in service

### 4.2.1 AC Energy output

A summary of the AC energy fed into the grid during each month and the cumulative energy produced since April 2004 is shown in Figure 11. Generally production during the first six months up to and including September 2004 proceeded at a fairly constant rate of about 760kWh/month with total output of 4.544MWh. A dip in production was first recorded in October 2004 due to the persistently cloudy and rainy weather and, with the onset of winter, production fell further reaching a minimum during December 2004. The generation rate then starting increasing again with 528kWh being produced in March 2005.

It should be noted that during the first 8-10 weeks of operation, the manufacturer advises that electrical output may exceed specific ratings and be up to 15% higher than achieved later.



**Figure 11. AC Energy production during the first year in service**

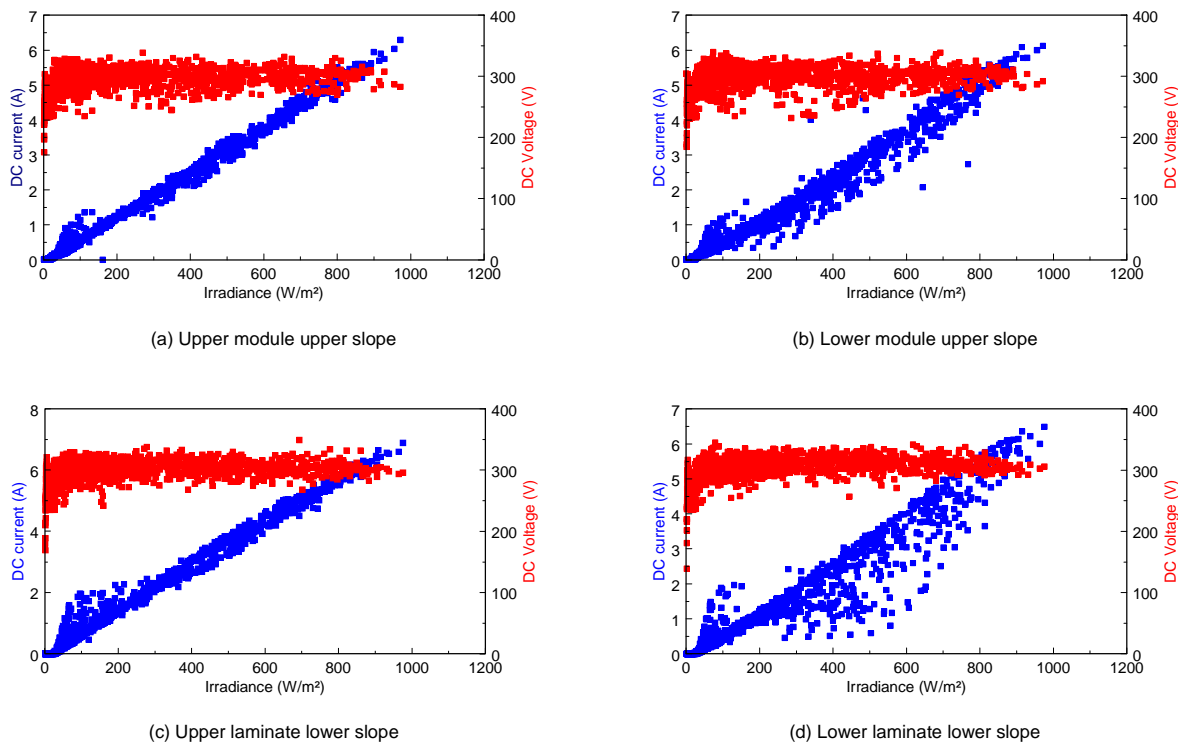
The total energy output to the grid from 1<sup>st</sup> April 2004 until 31<sup>st</sup> March 2005 was 6.398MWh. Both the upper and lower photovoltaic barriers contributed equally to this total. The significance of this output can be assessed in relation to the following typical electricity usage by domestic property:

- one to two bedroom house – 2.5 to 4MWh/annum,
- three bedroom house – 5MWh/annum.

### 4.2.2 Dependence of module efficiency on irradiance

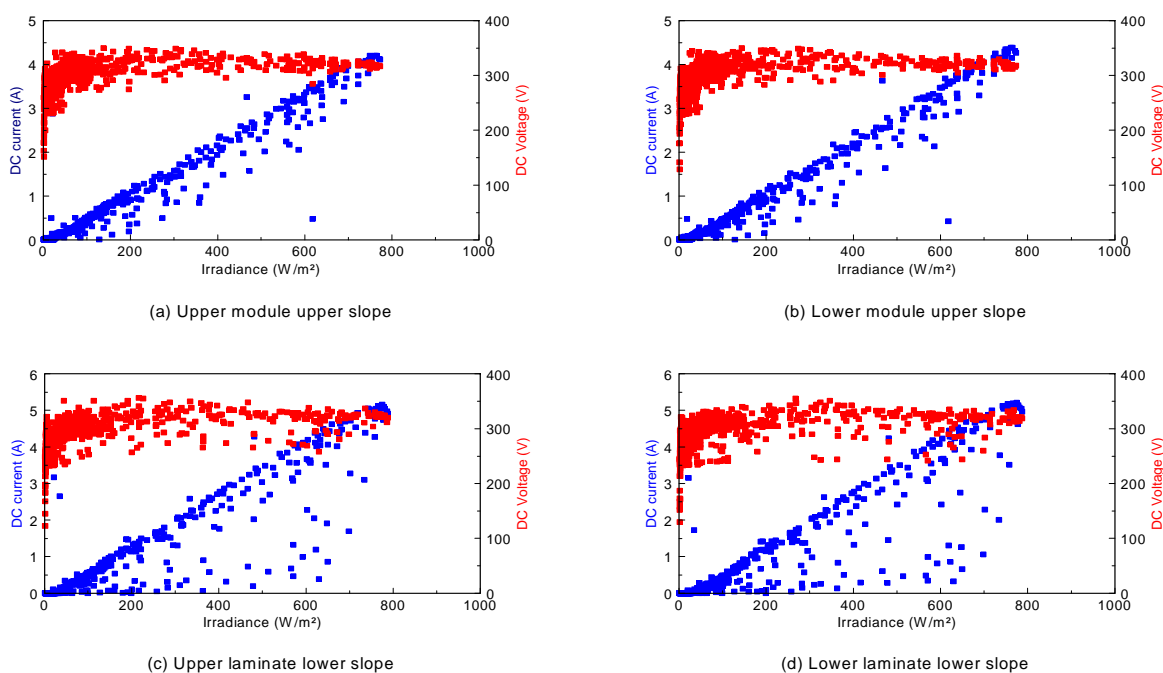
The variation of the DC current and voltage outputted by each row of modules/laminates with measured irradiance is shown in Figure 12 for June 2004 when energy production was high. In each case the irradiance was determined from the solarimeter inclined at the same angle as the particular row of solar modules/laminates being investigated. In all cases the voltage rose rapidly to about 300volts when any irradiation fell on the solar modules. The current output showed a reasonably linear relationship to the measured irradiance with a maximum of about 6amps being produced for each row of each barrier. Slightly more scatter was observed in the current against irradiance plot for both the lower rows of modules and laminates on their respective barriers. This was accounted for by some very slight partial shading of the lower row by the upper row on occasions when the sun was high, whereas this was not recorded at the solarimeter locations. This possibility was appreciated at the design stage, but tolerated in order to minimise the “footprint” of the noise barrier structures.





**Figure 12. Variation of DC voltage and current with irradiance during June 2004**

Figure 13 shows a similar set of graphs determined for December 2004 when energy production was at a seasonal low. The results show similar behaviour to that in Figure 12, although the maximum output current was only about 5 amps in response to the reduction in peak irradiance to about 800W/m<sup>2</sup>.

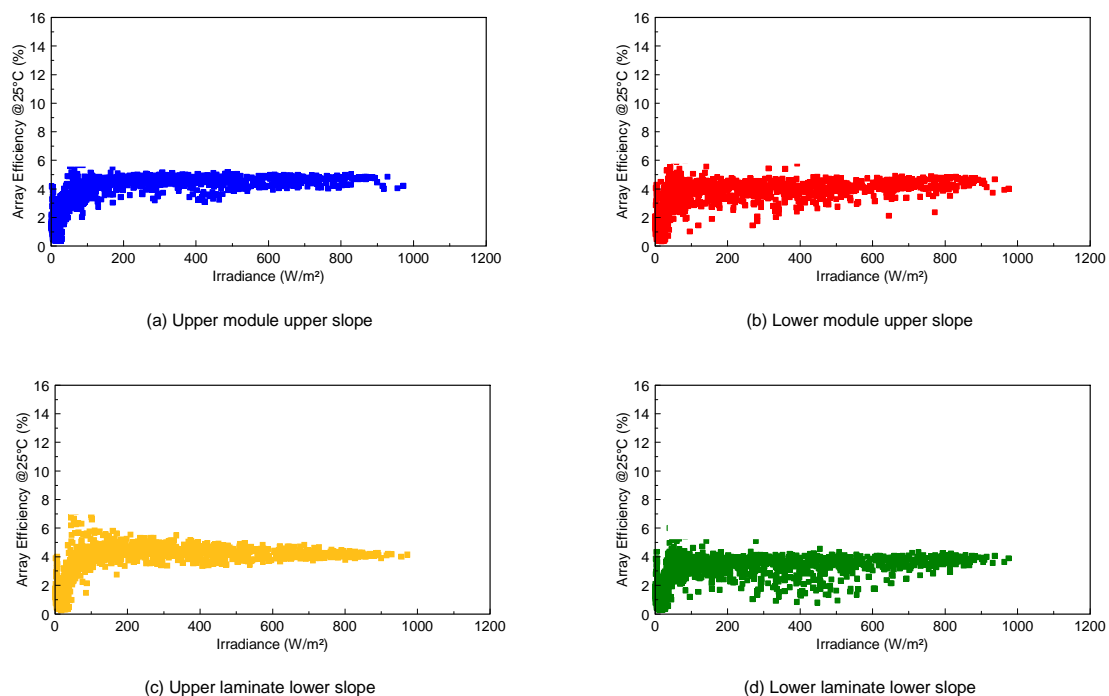


**Figure 13. Variation of DC voltage and current with irradiance during December 2004**

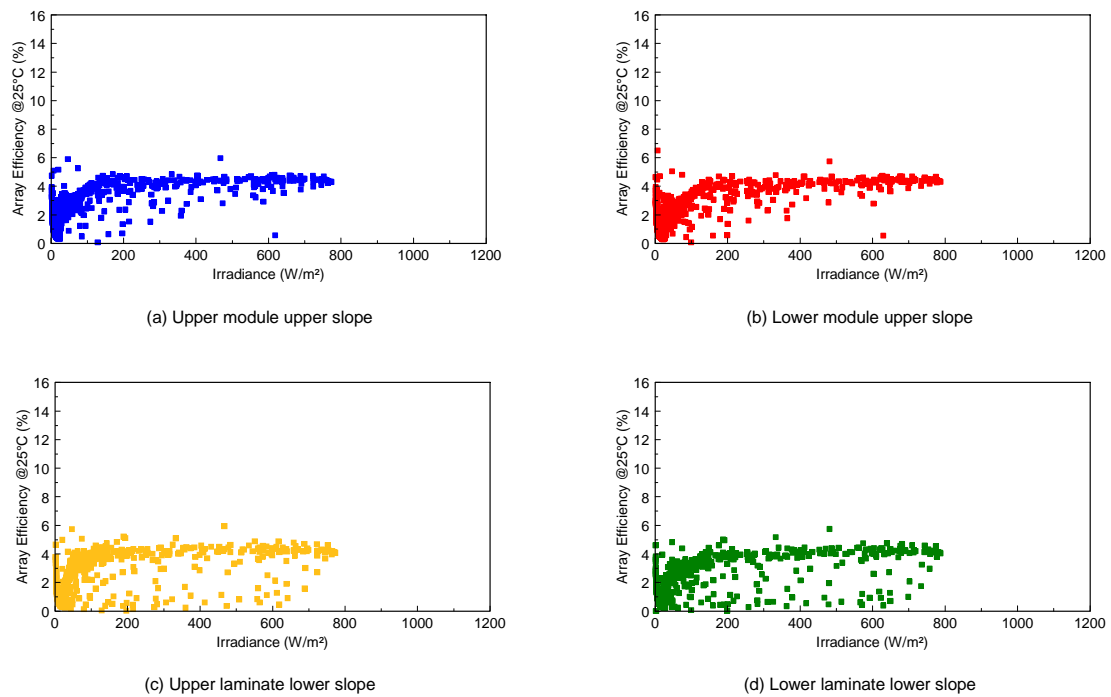
In Figure 14 the array efficiency has been determined by dividing the data for the DC power output by the incident solar irradiance measured during June 2004. As efficiency has a dependence on the module temperature, values are corrected using measured temperatures to the standard module temperature of 25°C as is standard practice within the industry. On this basis, an efficiency of 4-5% was found for the modules in the various rows of the barriers at the top and bottom of the slope.

This value was lower than the 6.8% calculated at an irradiation level of 1000W/m<sup>2</sup> from the rated power output of 64 watts and the effective module area. However, various factors account for this. For example, lower irradiance levels are actually seen by the modules in service than the standard level of 1000W/m<sup>2</sup> used in their calibration, and there is a cyclical decrease and increase in efficiency related to the frequency of rainy periods when wash off of the module surface occurs. It should also be noted that module connection losses may account for a 10% reduction in the array efficiency calculated from the performance of a row of modules.

Similar trends are identified in Figure 15 for the data obtained during December 2004. Once again the peak irradiance was less in this winter month and reached only about 800W/m<sup>2</sup>, although the array efficiency remained at about 4%. Slightly more scatter in the calculated efficiency is noted in Figure 15c and 15d for the laminate arrays forming the lower barrier; this may be because the irradiance measurements taken at the upper PV barrier have been assumed to apply to the lower barrier. This assumption may not be so valid in winter months when shading is produced at very slightly different times due to cloud movement.



**Figure 14. Array efficiency (corrected to 25°C) against irradiance during June 2004**

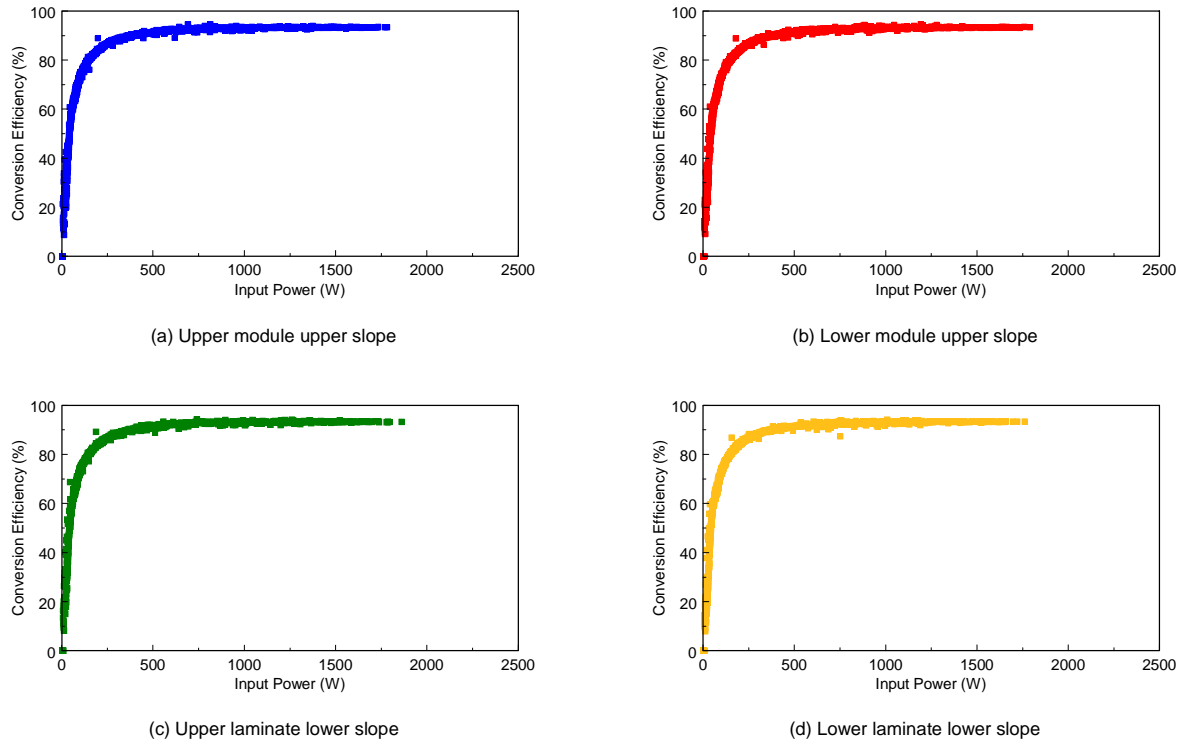


**Figure 15. Array efficiency (corrected to 25°C) against irradiance during December 2004**

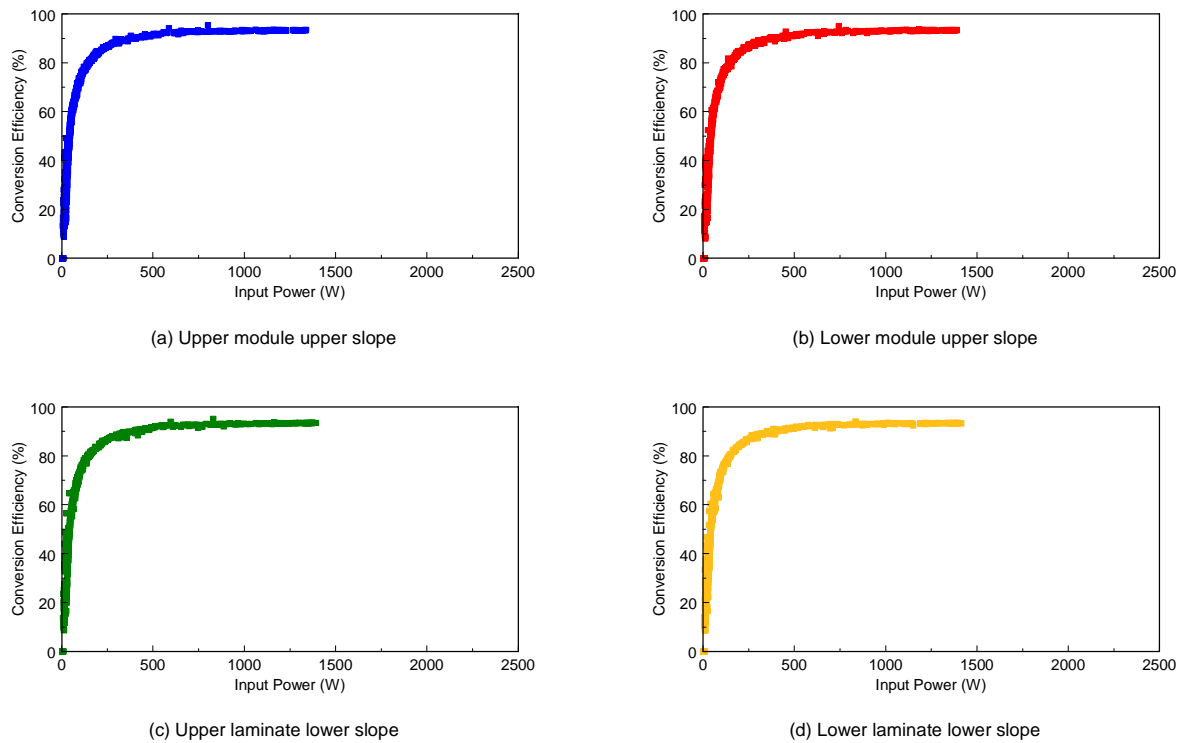
#### **4.2.3 Conversion efficiency of the inverters**

In terms of whole life costing, the conversion efficiency from DC power to AC power by the inverters is an important parameter. For this particular installation, the same “Sunny Boy” inverters were used with one for each module/laminate row of both barriers. Figure 16 shows the measured conversion efficiencies during June 2004 which are very similar in all cases and indicate efficiencies of about 93% when operating at input DC powers exceeding about 500 watts per inverter.

Examination of Figure 17 which shows the inverter efficiencies during a winter month (December 2004) again demonstrates that these are about 93% when operating at input DC powers exceeding about 500 watts per inverter.



**Figure 16. Conversion efficiency for each of the inverters during June 2004**

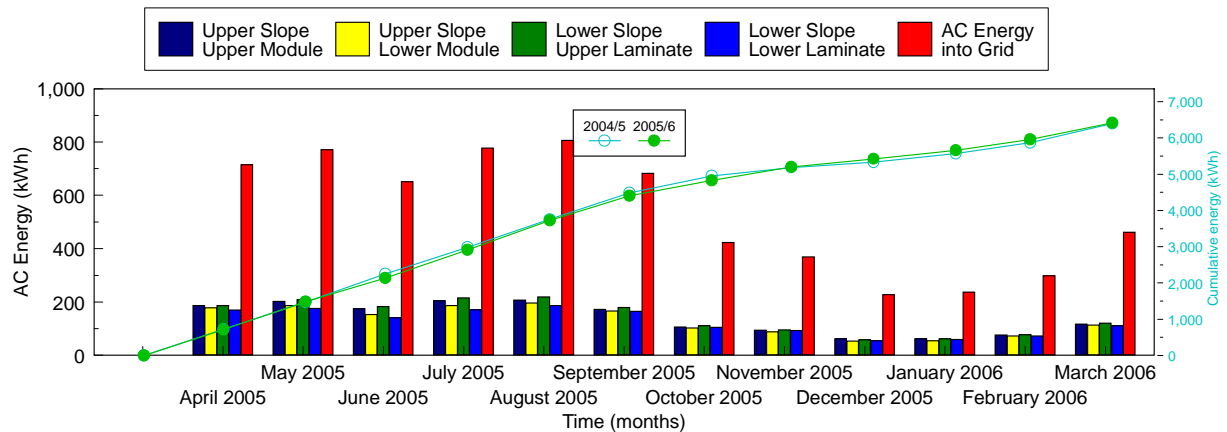


**Figure 17. Conversion efficiency for each of the inverters during December 2004**

### 4.3 Performance during second year in service

#### 4.3.1 AC Energy output

The AC energy from each of the four inverters and the cumulative energy to the grid are shown in Figure 18 for the second year in service from April 2005 to March 2006 inclusive. The cumulative energy produced in this period is also compared in Figure 18 with that produced during the first year in service (extracted from Figure 11).



**Figure 18. AC Energy production during the second year in service**

The cumulative output over the second year in service (6.421MWh) was near identical to that produced in the first year (6.398MWh). The main difference between the two years was that slightly higher outputs were produced in June and September 2004 than in the same months in 2005, however this was compensated for by marginally higher outputs during other months especially December 2005 and January and February 2006.

On the basis of the data over the first two years in service, it is concluded that the electricity production level was reasonably consistent at about 6.4MWh.

#### 4.3.2 Dependence of module efficiency on irradiance

The variations of DC current and voltage with measured irradiances during the second year in service are given for completeness in Figures A1 and A2 of Appendix A for June 2005 and January 2006 respectively. No discernible differences were found from similar plots for 2004 (Section 4.2.2). Once again the current output showed a reasonably linear relationship to irradiance, with the DC voltage rising rapidly to about 300volts almost immediately any irradiation was incident on the solar modules/laminates.

Likewise, graphs of array efficiency plotted during June 2005 and January 2006 showed no significant change from the findings in 2004. These data are shown in Figures A3 and A4 of Appendix A. Array efficiencies of just over 4% were confirmed both for the solar modules and laminates of the upper and lower barriers respectively.

#### 4.3.3 Conversion efficiency of the inverters

The inverter efficiencies of about 93%, when operating at input DC powers exceeding about 500 watts per inverter, measured during 2004 were confirmed by the data obtained during 2005/06. No

deterioration in the efficiency of any of the four inverters was detected. These results are presented in Figures A5 and A6 of Appendix A.

## 5 Maintenance issues

### 5.1 Vegetation

Vegetation, both 1.5m behind and in front of the new noise barrier, was cleared to ground level at the time of installation during February 2004. Although the edges of the lower rows of modules/laminates were deliberately designed to be about 300mm above ground level to avoid shading by vegetation, the rate of its growth had been underestimated. Some grass, weed and bramble growth was evident by July 2004, which would have eventually led to some minor shading. The offending vegetation was therefore cut-back at this time, and although vegetation growth subsequently re-occurred by September the major part of this then died back at the end of the growing season. However the persisting problem of bramble growth, from behind and over the top of the barriers, remained and this growth was cut-back in late June 2005.

Following this operation in June, a visit was made in October 2005 to assess the extent of growth of the vegetation. Photographs taken during this visit are shown in Figure 19. Grass growth in front of the upper barrier had reached the bottom of the solar modules and some minor obscuring was occurring at a few locations (Figure 19a), although generally this was considered likely to have little impact on electrical output. Although there was little grass but more weed in front of the lower barrier (Figure 19b), it was also considered unlikely that output would be affected.

It was concluded that, at the M27 site, clearance of vegetation was advisable at least once a year in mid-summer well into the growing season. This clearance needs to involve strimming to ground level over a distance of 1.5m in front of each barrier and also a distance of 1.5m behind each barrier. The latter was particularly important to prevent brambles from growing over each barrier from behind.

Control of vegetation remains an important issue in the design of photovoltaic barriers of this type and the whole life costs of either (a) establishing a maintenance regime of annual/biannual cutting back, or (b) installing the barrier in a paved or asphalt area, needs to be considered.

### 5.2 Cleaning

Regular observations were carried out of any build-up of grime and the surface condition of the module/laminate surfaces. Generally the barrier surfaces at the top of the slope remained fairly clean compared with those at the toe of the slope and nearer to the M27 carriageway. By July 2004 there was some traffic grime build-up at the lower slope location, however, just when cleaning was being considered, heavy and persistent rainfall occurred which acted to efficiently clean the exposed surfaces.

Since then regular inspections have been undertaken at 3 monthly intervals and these have confirmed that no cleaning regime for this type of module/laminate is required. This is considered to be the result of a protective surface coating of tetrafluoroethylene used in their manufacture and the angle at which the module/laminate is installed. During these visits the surfaces of the solarimeters used to monitor global and in-plane irradiation were however cleaned.





*(a) Upper barrier*



*(b) Lower barrier*

**Figure 19. State of the vegetation during October 2005**

## 6 Discussion of cost data, driver behaviour and noise issues

### 6.1 Cost data

Table 1 shows the actual costs of the installation of the upper barrier and lower barrier. The values in the table are not the direct costs, but include the normal profit margins that would be charged by a Contractor.

Also shown in Table 1 are the estimated costs predicted if a 2km length of each type of barrier were to be constructed. For a barrier such as this, some items do not increase on a pro rata basis as economies can be made in cost when designing and constructing longer barriers. For example, on this basis, a minimum reduction in component costs of 10% has been assumed because of bulk purchase.

Account has also been taken of the extra costs involved in the development of the prototype system used in the demonstration trial, now that this trial has been completed only refinements in the system should be necessary. Wider implementation of the same type of photovoltaic barrier on a 2km long scheme is therefore expected to be more cost effective and this is particularly reflected in the design costs in Table 1.

It should be noted that the costs of the instrumentation and Sunny Boy Control Plus have not been included in this evaluation as these were for research purposes only.

Given that the electrical power ratings of the two barrier systems are the same, the findings in Table 1 demonstrate that the use of modules is more cost effective than the use of laminates<sup>1</sup>. The whole life cost analysis presented in Appendix B is, therefore, based on the figures given in Table 1 for the construction of a 2km long photovoltaic barrier using the module system.

Table 2 reproduces the findings on variation in whole-life cost with the price of electricity from Appendix B.

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<sup>1</sup> It should however be noted that the laminates are considered more theft resistant because they are installed in 5.5m long lengths and hence much harder to remove from their mounting framework. It is also possible that the mass production cost of laminates will reduce more quickly than that of modules in the longer term, which was initially one of the reasons for their inclusion in the trial.



**Table 1. Actual costs for 54m long and estimated costs for 2km long barriers**

| Element  | Upper barrier using modules |                            | Lower barrier using laminates |                            |
|--|-----------------------------|----------------------------|-------------------------------|----------------------------|
|  | Actual cost per 54m (£)     | Estimated cost per 2km (£) | Actual cost per 54m (£)       | Estimated cost per 2km (£) |
| <b>Project Management</b>  |                             |                            |                               |                            |
| Assumed as 5% of contract value                                    | 3,216                       | 64,087                     | 4,073                         | 83,783                     |
| <b>Design</b>  |                             |                            |                               |                            |
| Photovoltaic system  | 2,000                       | 1,600                      | 2,000                         | 1,600                      |
| Support frame  | 6,546                       | 6,077                      | 6,546                         | 6,077                      |
| HA technical approval  | 462                         | 1,538                      | 462                           | 1,538                      |
| <b>Components</b>  |                             |                            |                               |                            |
| Photovoltaic modules/laminates                                     | 16,507                      | 463,218                    | 21,071*                       | 610,781*                   |
| Inverters  | 2,463                       | 85,791                     | 2,573                         | 85,698                     |
| Cabling, isolators, and trunking                                   | 2,964                       | 58,572                     | 3,096                         | 58,509                     |
| Cabinets   | 1,477                       | 16,994                     | 1,543                         | 18,783                     |
| Meters   | n/a                         | 4,291                      | n/a                           | 4,287                      |
| Support frames (excluding posts)                                   | 7,870                       | 236,171                    | 13,208                        | 378,999                    |
| Posts and sockets  | 1,522<br>(2.65m long posts) | 50,733                     | 1,743<br>(3.2m long posts)    | 58,100                     |
| <b>Pre-site assembly</b>   |                             |                            |                               |                            |
| Adhering laminate to Zn-Al backing                                 | n/a                         | n/a                        | 4,675                         | 71,455                     |
| <b>Mechanical and electrical installation on site</b>              |                             |                            |                               |                            |
| Ground levelling and preparation, trenching for electricity cables | 2,027                       | 60,059                     | 2,027                         | 60,059                     |
| Installation of posts  | 5,724                       | 169,600                    | 5,724                         | 169,600                    |
| Installation of cabinets   | 425                         | 7,870                      | 425                           | 7,870                      |
| Provision of site storage  | 441                         | 14,678                     | 441                           | 14,678                     |
| Delivery of equipment to site                                      | 807                         | 26,857                     | 807                           | 26,857                     |
| Installation of support frame and PV panels                        | 1,993                       | 23,077                     | 4,045                         | 46,154                     |
| Installation of all electrical items (cabling, inverters)          | 4,200                       | 45,000                     | 4,200                         | 45,000                     |
| Grid-connection  | 3,503                       | 5,000**                    | 3,503                         | 5,000**                    |
| Supervision of electrical aspects                                  | 2,936                       | 1,600                      | 2,936                         | 1,600                      |
| Testing and commissioning  | 453                         | 3,005                      | 453                           | 3,005                      |
| <b>Total</b>   | <b>67,536</b>               | <b>1,345,818</b>           | <b>85,551</b>                 | <b>1,759,433</b>           |

\* Cost of laminates was higher than that for modules however, because of their length, theft of laminates is less of an issue and installations are more secure.

\*\* Estimated on the basis that power is fed into the HA private electricity grid and that a connection point is nearby.

**Table 2. Variation in whole-life cost with price of electricity**

| <b>ELECTRICITY PRICE (£/MWh)</b>             | <b>WHOLE-LIFE COST (£)</b> | <b>NET PRESENT VALUE OF POWER GENERATED (£)</b> | <b>NET PRESENT VALUE OF OPERATION AND MAINTENANCE (£)</b> | <b>NET PRESENT VALUE OF DECOMMISSION AND SALVAGE (£)</b> |
|--|----------------------------|---|---|--|
| 60   | 1,194,200                  | -126,600  | 96,500  | -121,500   |
| 120  | 1,067,700                  | -253,100  | 96,500  | -121,500   |
| 240  | 814,500                    | -506,300  | 96,500  | -121,500   |
| 480  | 308,300                    | -1,012,500                                      | 96,500  | -121,500   |
| Increasing from 60 to 120£/MWh over 30 years | 1,153,800                  | -167,000  | 96,500  | -121,500   |
| Increasing from 60 to 240£/MWh over 30 years | 1,091,700                  | -229,100  | 96,500  | -121,500   |
| Increasing from 60 to 480£/MWh over 30 years | 993,900                    | -326,900  | 96,500  | -121,500   |

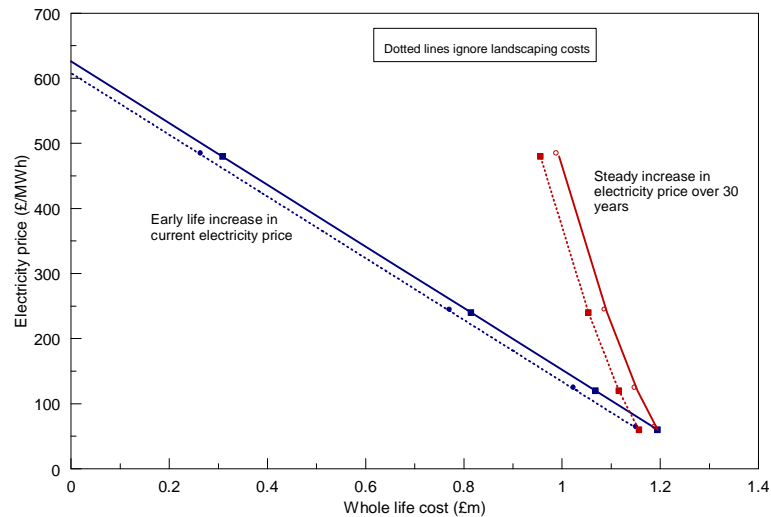
The whole-life costs given in Table 2 can be considered in three ways:-

- by making no allowance for the cost of the photovoltaic barrier as a noise barrier,
- making an allowance by defraying the whole-life costs against the costs of a conventional noise barrier,
- making an allowance for installation of the barrier in remote areas where electricity is required for other purposes and the cost of cable laying would be significant.

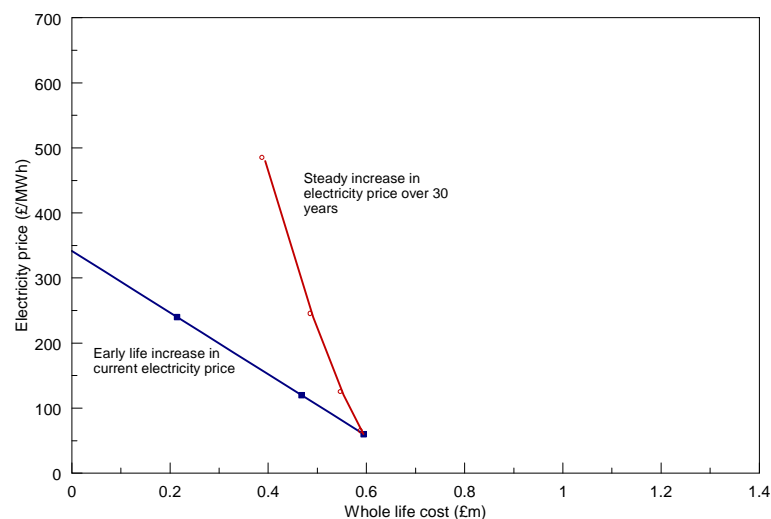
These are now considered in turn.

### **6.1.1 No allowance for noise reduction benefits**

The findings in Appendix B and Table 2 make no allowance for the value of the highway noise reduction. On this basis, whole-life cost is plotted in Figure 20a against the electricity price if it were immediately increased from the assumed level of £60/MWh (which includes allowance for Renewable Obligation Certificates which are a tradable commodity), and alternatively if a steady increase in price occurred over a 30 year duration. It is accepted that the former will only occur if a change in the subsidy for renewable energy production were implemented by the UK government in the early years in-service of a photovoltaic noise barrier.



(a) New PV barrier



(b) PV barrier costs defrayed by those of a conventional barrier

**Figure 20. Evaluation of whole life costs**

The results in Figure 20a indicate that, for the assumptions made, the initial installation costs of the photovoltaic installation will be far greater than the cost of the power generated by the solar modules. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and/or significant reductions in the costs of the components. For example, an early life increase in the price of electricity by a factor of about ten would be needed to be near payback over 30 years. Therefore, it is concluded that it is unlikely that an investment in a photovoltaic installation will give any financial benefits unless the initial cost of the installation and its operation and maintenance are considerably lower than those assumed and/or there are significant environmental cost benefits or subsidies that have not been taken into account in these analyses.

### 6.1.2 Defraying the costs against those of a conventional noise barrier

In many cases the costs of installing a conventional noise barrier would be incurred in any event, so it is only the additional costs of providing and installing the photovoltaic components which need consideration in the whole life costing. For this reason an analysis was carried out defraying the costs against those of a conventional noise barrier. Spon's Handbook (2004, 18<sup>th</sup> Edition) gives sample

costs of £111/m for a barrier with acoustical timber planks post support system. For a 2m high barrier of the reflective rather than absorptive type such as that at the M27, this would equate to a cost of £222 per metre length. The Handbook points out that cost may vary considerably depending on the performance requirements and specification for various locations.

This figure broadly agrees with the typical cost of £210 per metre length obtained from a number of suppliers for the supply and erection of a 3m high timber barrier as part of a separate TRL study for Transport for London.

These figures can be compared with the cost of £189,000 for a 630m long and 2m high noise barrier and associated earthworks issued by Highways Agency at the A3 Public Inquiry for Hindhead Tunnel. This relates to a cost of £300 per metre length.

At this particular scheme on the M27 if a conventional noise barrier had been selected, the breakdown in construction costs can therefore be estimated as about £222 per metre for supply and erection of the barrier, and about £30 per metre for ground levelling (from Table 1). If an allowance is made for the close supervision necessary on a live highway, the cost of £300 per metre length quoted for Hindhead tunnel is considered appropriate.

In Figure 20b the initial cost of £1,345,800 for the solar panel system is therefore reduced by the cost of a conventional barrier system (ie. £600,000 for 2km length), payback over a 30 year accounting period is then achieved if there is an early life increase in electricity price (possibly through government subsidy) to approaching six times its current value. Once again payback is not achieved over a 30 year period if a steady increase in electricity price is assumed.

### **6.1.3 Installation to supply electricity to remote area**

There may be remote areas on the highway network where the provision of electricity is required but there is no convenient supply available. Although in remote areas it is unlikely that there is a need for a highway noise barrier, a photovoltaic system in barrier form can nevertheless be used to supply electricity. In evaluating whole life costs of a photovoltaic barrier in this situation, the following factors will have a significant influence.

- the probably high cost of cable laying from a remote grid supply,
- the need to provide a maintained battery backed photovoltaic system to provide continuity of supply,
- the need to design the photovoltaic system to meet the required electricity demand in the winter months.

The above items are so site specific that it is not possible to include reliable guidance within this report. Each case will need investigation in its own right.

## **6.2 Driver behaviour**

As part of the research, a study was carried out into the potential impact of the array on road safety. In particular, there was a concern that the array may prove distracting to drivers and as a result may lead to a general reduction in safe driving at the site. The study utilised two video cameras, one mounted upstream of the solar panel site, located just above the safety barrier, and one mounted downstream on a 5m high mast. The upstream camera filmed vehicles from the rear as they approached the site. The downstream camera filmed vehicles from the front as they approached the site.

Fuller details of the experimental set up and the results are reported in Appendix C.

Under similar road and weather conditions, no significant difference in braking behaviour was observed before and after the installation of the solar array. Additionally there was no observed driver behaviour that might indicate driver distraction.

The solar array was separated from the motorway by an unused access road. It is possible that the array may have been more distracting if placed closer to the side of the road.

There is also the possibility that, although the solar panels are essentially non-reflective, the slightly shimmering appearance of the solar panels (which occasionally occurs) could prove distracting at certain times of day. This effect was not observed during the trials. Therefore, it was not possible to determine if this was likely to cause any distraction to drivers.

### 6.3 Noise issues

Highway noise barriers are constructed to shield properties behind them but an important issue is the potential for increasing the noise received to properties situated along the opposite carriageway. If this increase was found to be significant there would be concerns that there would be a degree of public dissatisfaction with such installations. The same constraints apply to a highway noise barrier which is also capable of generating electricity from renewable solar energy.

There have been several studies to estimate the increase in noise from road traffic due to reflection effects associated with noise barriers and these are described in more detail in Appendix D. One of these studies concluded that a vertical reflective barrier 3m tall increased the average noise levels  $L_{Aeq}$  by  $0.50 \pm 0.15$  dB at a 2m high receiver near the edge of the opposite carriageway when compared with a highly sound absorptive barrier (Watts and Godfrey, 1999). This sets up an upper limit to the differences that can be expected from the presence of the barrier in the present study. In a previous phase of the study numerical modelling of tilted barriers using the boundary element method (BEM) has indicated a very small increase of less than 0.1 dB(A) can be expected due to the presence of a 2m high tilted barriers inclined at  $20^\circ$  and  $30^\circ$  (Watts and Morgan, 2003).

For these reasons a noise survey was carried out at the M27 site, which was designed to estimate the increase in noise at a location on the far side of the road adjacent to where the solar panels were installed. The results are compared with the predictive estimates and a detailed discussion of the results is given in Appendix D.

The findings from the surveys carried out prior to and after the installation of the PV barrier were as follows:

- Although it was found that the PV barrier at this site does increase traffic noise levels on the opposite side of the motorway, the average increase over all periods sampled was 0.3 dB(A) and would not be expected to cause any change in the disturbance from road traffic noise.
- The results for high steady traffic flow conditions are comparable with predictions made with the boundary element noise prediction method i.e. less than 0.1 dB(A).
- Under relatively low flow conditions and under adverse wind conditions higher values may result. The exact size of the effect is difficult to quantify because traffic volume and weather conditions that may have introduced these changes under low flow conditions were not recorded as part of this limited study. However a previous study of the effects of a 3m tall plane reflective barrier under a range of wind conditions indicated an increase of  $0.5 \pm 0.15$  dB(A) when normalised to zero wind speed. In the current study the effects of tilting the barrier would be expected to reduce the contribution to below 0.5 dB(A) under similar conditions.

It should be noted that in this trial the barriers were not primarily designed to provide noise screening since there were small gaps of about 0.1m between the ground and the bottom of the barriers which would leak sound and the barrier placed at the foot of the cutting slope would be ineffective and unnecessary for obvious reasons. However, it would be a relatively simple matter to modify the design and position to overcome these deficiencies.

## 7 Other implementation issues

The UK Government is committed to reducing the greenhouse gas emissions by 12.5% below base year levels by 2008-12, and a more ambitious national goal of reducing carbon dioxide emissions by 20% below 1990 levels by 2010 (HM Government, March 2005). In its 2003 Energy White Paper, the Government set a long term goal of reducing carbon dioxide emissions by some 60% by about 2050, with real progress to be shown by 2020 (HM Government, February 2003). In the latter Paper it was stated that “the electricity distribution networks will need to adapt to more renewables often in peripheral parts of the country or offshore and to small-scale, decentralised power generation in homes and businesses, sometimes drawing from the grid, sometimes contributing to it”.

In addition to consideration of cost effectiveness, particular issues facing the Highways Agency in more widely implementing the use of solar panels on highway noise barriers are as follows.

- The position of the Highways Agency in being able to sell renewable energy on the open-market to electricity companies for profit is not clear-cut. For this reason the Agency may need to adopt the less flexible approach of reaching agreement with their various electricity suppliers in each area to defray solar energy production against their current usage<sup>2</sup>. The return for the renewable energy will therefore vary from area to area depending on whether their supplier is meeting its renewable energy quota.
- Solar power energy production peaks in the daylight hours when Highways Agency’s electricity demand is at a minimum, primarily because highway lighting is not required. If inputting power to the HA private grid, the solar generator is therefore better placed near to where there is a daytime demand (eg. tunnel, maintenance depot, highway junction) to minimise transmission losses in the cables. Locations such as these are very often in built-up areas where there may be environmental pressure for highway noise barriers. If there is no justification for a barrier, consideration can of course be given to installing solar panels on building roofs, etc.
- There may be remote areas on the highway network where the provision of electricity is required but there is no convenient supply available. The use of a photovoltaic installation may then be cost effective against the high cost of cable laying over a long distance. A battery backed photovoltaic system will however be required to provide continuity of supply and issues of battery maintenance will need consideration.

## 8 Summary and conclusions

Incorporating photovoltaics into highway noise barriers to recover solar energy is an application that has been steadily gaining interest. The initial attraction of mounting photovoltaic modules on noise barriers is that a proportion of land and support structure costs can be avoided. Renewable energy technologies are likely to become more important as other energy sources become depleted and the cost of power generation using fossil fuels rises. Renewable sources of energy have considerable potential for increasing security of supply and reducing CO<sub>2</sub> emissions although, in most cases, they require significant initial investment. This report describes a full scale trial to recover solar energy using photovoltaic noise barriers installed on the M27.

Two 54m long barriers were designed and installed; one (2m high) was at the top and the other (2.5m high) at the bottom of the cutting slope. The photovoltaic capacity was achieved by using triple junction amorphous technology in the form of both framed modules and flexible laminates. Amorphous technologies are potentially more suited to mass production and their cost may reduce in the future more quickly than other types, which was an important consideration for this trial. Forty

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<sup>2</sup> The Highways Agency have raised the issue of reimbursement for photovoltaic schemes of this type at the Unmetered Supplies User Group (UMSUG). The position was not clear, but suitable monetary settlement was clearly more readily obtained if the supplies were actually metered and comprised larger scale embedded generation to the grid. At this particular demonstration trial, electricity resale of 7.8p/kWh (which includes ROCs of 4p/kWh) has been negotiated although contractual arrangements on this basis have not been finalised.

framed Uni-Solar US-64 modules were incorporated in each of two rows to form the upper barrier. Ten Uni-Solar PVL-128 laminates were arranged in four rows to form the lower barrier. The rating of each barrier was therefore 5.12kW peak, ie. 10.24kW peak for the whole system.

The main findings from the study are as follows:

1. AC and DC currents and voltages, together with AC power and daily (and total) energy were monitored from each of the four inverters and the data retrieved by mobile phone link. Solarimeters and temperature sensors were also installed to monitor the global and in-plane incident solar radiation and the temperatures of the solar modules respectively. The AC energy exported to the local grid over a period of the first year in service from 1<sup>st</sup> April 2004 was monitored as 6.398MWh. The energy exported to the grid during the second year in service was 6.421MWh and therefore near identical. Both the upper and lower photovoltaic barriers contributed equally to these totals. Throughout the two year period the conversion efficiency of the inverters remained at about 93% when operating at input DC powers exceeding about 500 watts per inverter. The reliability of the whole system remained excellent throughout this period and no electrical maintenance was required.
2. In terms of maintenance, the control of vegetation remains an important issue in the design of photovoltaic barriers of this type and the whole life costs of either (a) establishing a maintenance regime of annual/biannual cutting back, or (b) installing the barrier in a paved or asphalt area, needs to be considered. Although the lower edge of each module/laminate was designed to be about 300mm above ground level to avoid shading by vegetation, this height proved to be on the low side at this particular site and annual strimming of vegetation was necessary. No cleaning of the modules/laminates was undertaken at this site as occasional heavy rainfall proved effective in this respect.
3. Actual installation cost data were analysed for each 54m long barrier at the M27 and, based on this data, the cost of constructing a 2km length of similar barrier was estimated. The use of framed modules was found to be less costly than using flexible laminates. Whole life cost analyses were investigated based on the framed module form of construction; the following main points arose:
  - In the first analysis no allowance was made for the added value of the barrier in its noise reducing capacity. The initial installation costs of the photovoltaic system were then far greater than the cost of the power generated by the solar modules over a 30 year period. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and/or significant reductions in the costs of the components. For example, an early life increase in the price of electricity by a factor of about ten would be needed to be near payback over 30 years. Therefore, it is concluded that it is unlikely that an investment in a photovoltaic installation will give any financial benefits unless the initial cost of the installation and its operation and maintenance are considerably lower than those assumed and/or there are significant environmental cost benefits or subsidies that have not been taken into account in these analyses.
  - In many cases the costs of installing a conventional noise barrier would be incurred in any event, so it is only the additional costs of providing and installing the photovoltaic components which need consideration in the whole life costing. If the costs of the photovoltaic barrier are therefore defrayed against those of a conventional noise barrier, payback over a 30 year accounting period is then achieved if there is an early life increase in the electricity price (possibly through government subsidy) to approaching six times its current value. Payback is not achieved over the same period if a steady increase in electricity price is assumed.
  - Although in remote areas it is unlikely that there is a need for a highway noise barrier, a source of electricity may be invaluable in avoiding the probable high cost of laying cable from a remote grid supply. Site specific issues, including those of needing a maintained battery backed system to provide continuity of supply, then need consideration.

4. A study was carried out into the potential impact of the array on road safety as there was a concern that the array may prove distracting to drivers and as a result may lead to a general reduction in safe driving at the site. The study utilised video techniques and indicated that under similar road and weather conditions, no significant difference in braking behaviour was observed before and after the installation of the solar array. Additionally there was no observed driver behaviour that might indicate driver distraction. However it should be noted that the solar array was separated from the motorway by an unused access road. It is possible that the array may have been more distracting if placed closer to the side of the road at a different site.
5. An important issue with regard to the construction of any noise barrier alongside a highway is the potential for increasing the reflected noise received by properties situated along the opposite carriageway. The findings from a noise survey at this site found that the photovoltaic barrier does increase traffic noise levels on the opposite side of the motorway by 0.3dB(A), although this would not be expected to cause any change in the disturbance from road traffic noise. The effects of tilting the barrier to optimise electrical output were expected to help minimise the impact of any reflected noise.
6. Other issues of implementation are discussed in Section 7 of the report. These include the position of Highways Agency in being able to sell renewable energy on the open-market to electricity companies, and the incompatibility between peak solar energy production in the daylight hours when Highways Agency's electricity demand is at a minimum.

## 9 Acknowledgements

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The assistance of Mr G Berresford and Mr R Cameron of Highways Agency (Dorking) and of Mr T Davies of Scottish and Southern Energy PLC is also gratefully acknowledged.

Particular thanks are due to Mr R Jordan, Mr R Gorell, Mr R King, Mr G Watts and Mr P Abbott of TRL who authored specific areas of the study presented in the appendices; namely whole life costing, driver behaviour and noise issues. Other members of the TRL project team include Mr G Helliwell and Mr M Balsom and their assistance is gratefully acknowledged.

The authors are also grateful to Dr R J Woodward and Dr A Parry who carried out the quality review and auditing of this report.

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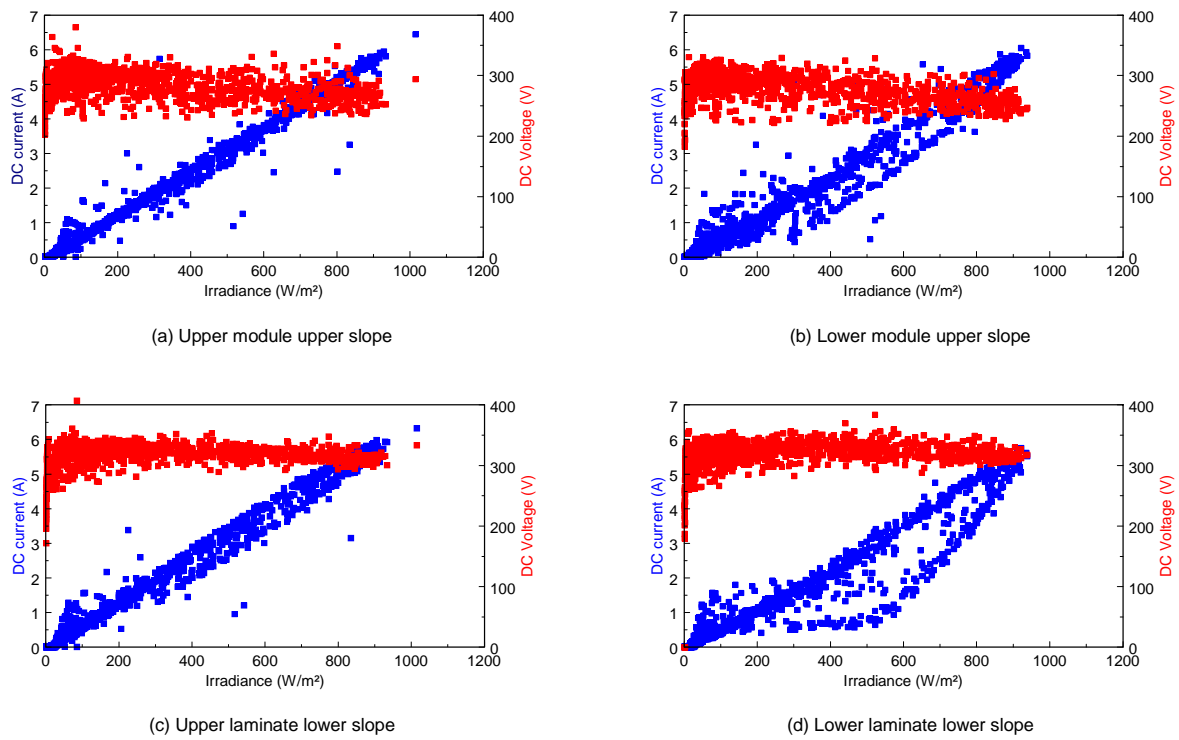


## Appendix A. Data for second year in service

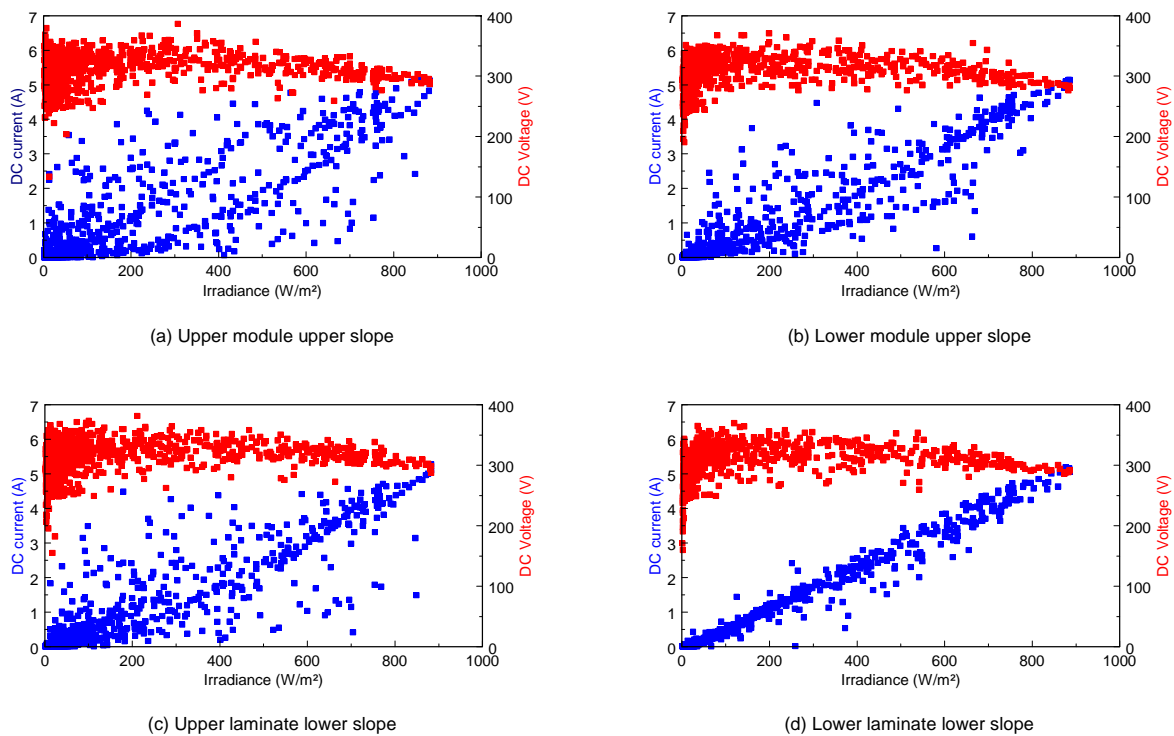
Comprehensive data were recorded during the second year in service (April 2005 to March 2006 inclusive). Essentially information was very similar to that recorded during the first year in service and the discussion of this in the main body of the report is therefore also relevant to the second year data.

For completeness this data for the second year is now presented and the following figures are included:

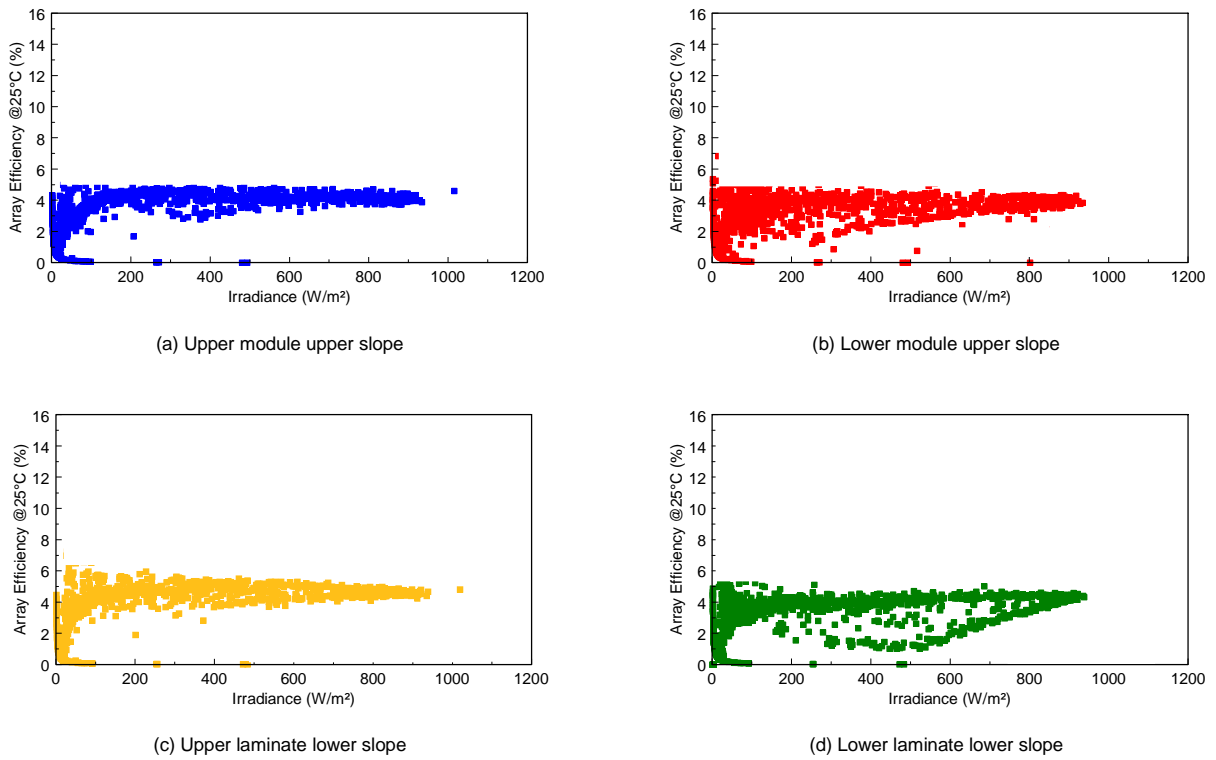
- Variation of DC voltage and current with irradiance during June 2005 (Figure A1)
- Variation of DC voltage and current with irradiance during January 2006 (Figure A2)
- Array efficiency (corrected to 25°C) against irradiance during June 2005 (Figure A3)
- Array efficiency (corrected to 25°C) against irradiance during January 2006 (Figure A4)
- Conversion efficiency for each of the inverters during June 2005 (Figure A5)
- Conversion efficiency for each of the inverters during January 2006 (Figure A6)



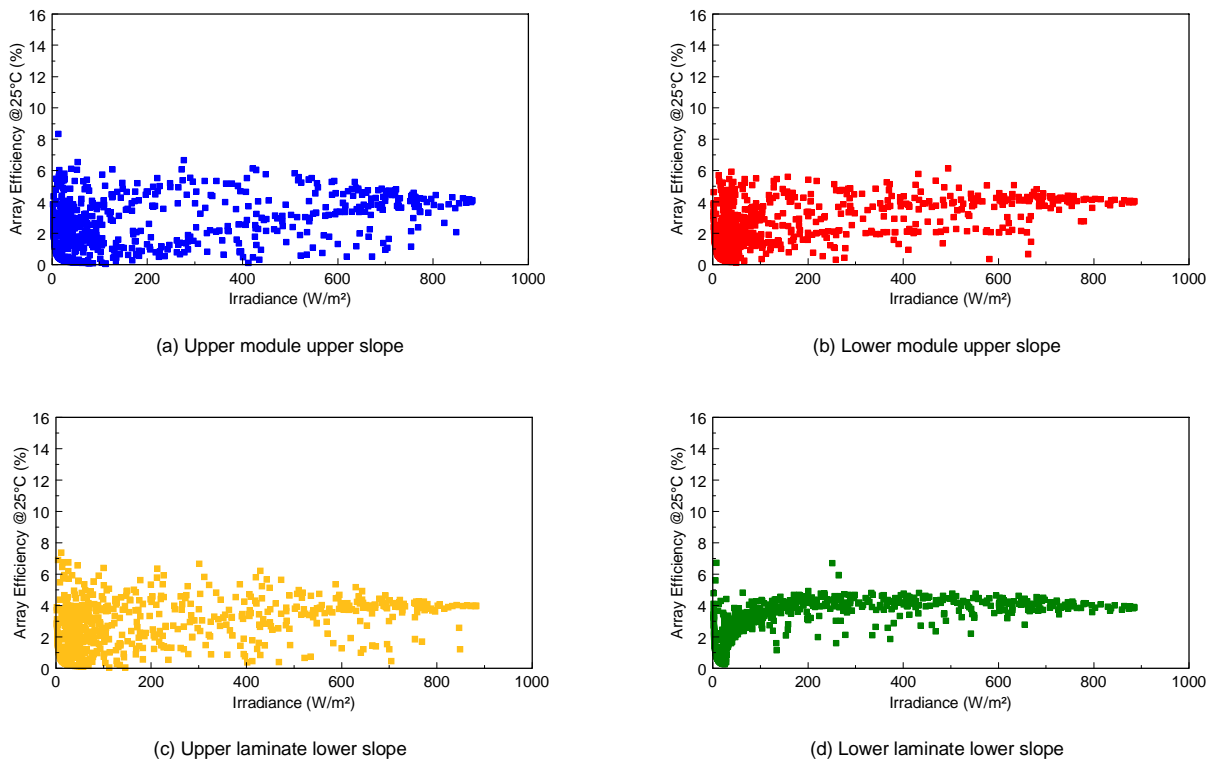
**Figure A1. Variation of DC voltage and current with irradiance during June 2005**



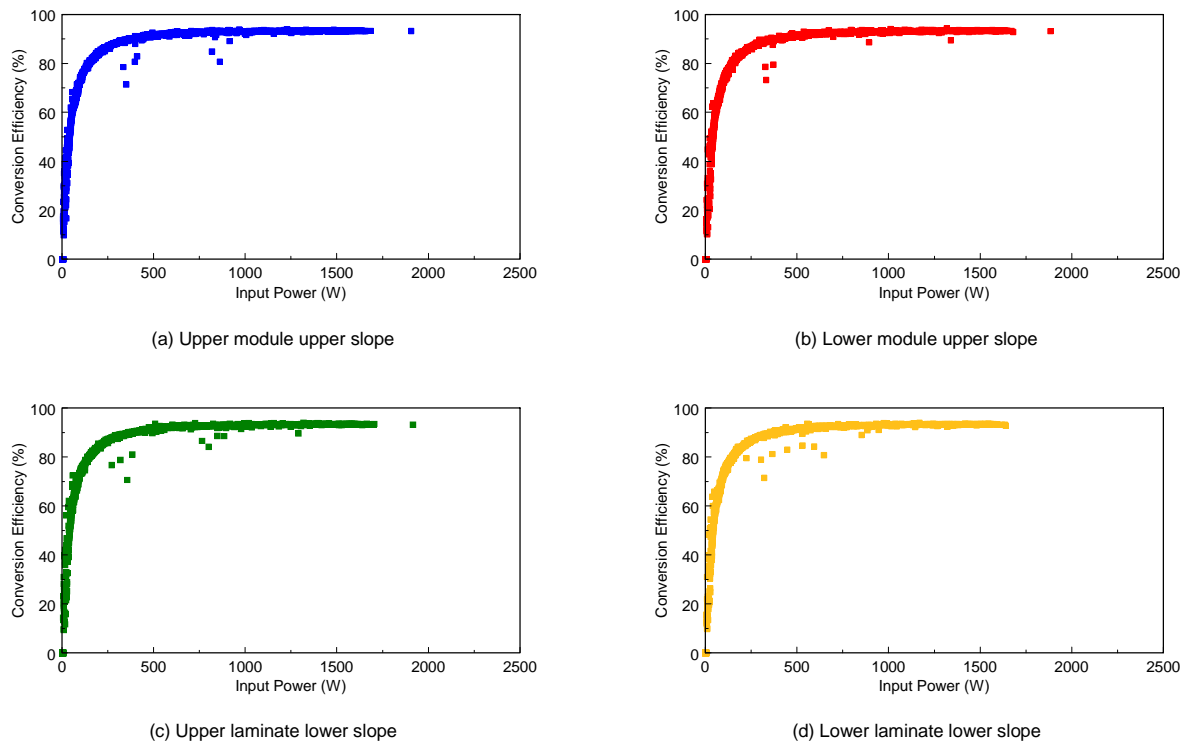
**Figure A2. Variation of DC voltage and current with irradiance during January 2006**



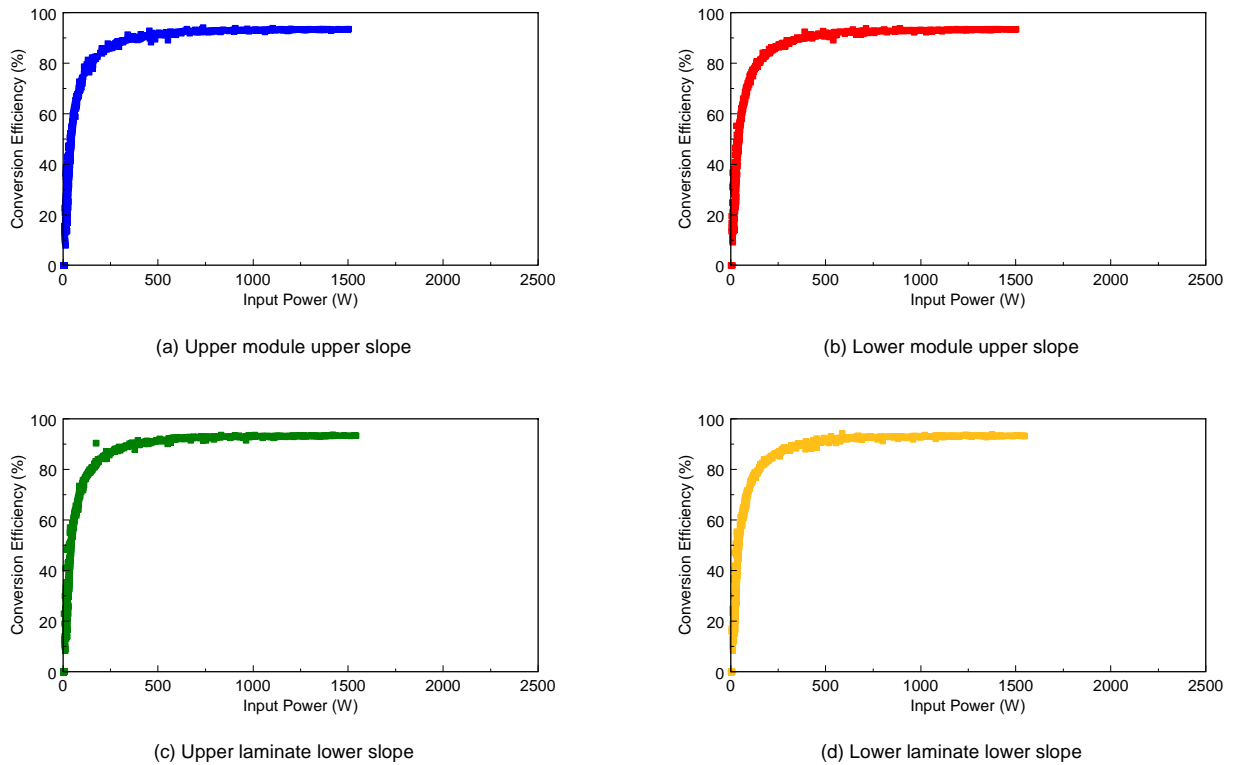
**Figure A3. Array efficiency (corrected to 25°C) against irradiance during June 2005**



**Figure A4. Array efficiency (corrected to 25°C) against irradiance during January 2006**



**Figure A5. Conversion efficiency for each of the inverters during June 2005**



**Figure A6. Conversion efficiency for each of the inverters during January 2006**

## Appendix B. Whole life costing

by R Jordan (TRL Limited)

### B.1 Whole-life cost of photovoltaic installation on noise barriers

A model has been developed to determine the whole-life cost (WLC) of a 2km long photovoltaic installation comprising solar modules (not laminates) using the cost information given in Table 1. The principle of whole-life cost analysis is to calculate all the costs associated with a project throughout its life to a common base so the cost effectiveness of the project can be determined and comparisons can be made between options. In practice, the WLC represents the sum of money to be set aside today to meet all the eventual costs, both present and future, after allowing for the accumulation of interest on that part of it intended for future commitments (Tilly, 1995).

The WLC (or net present value) is estimated by discounting all the anticipated costs or benefits, calculated at present day prices, by a factor which takes account of time from the start of the project to when expenditure would be incurred. It is defined as follows:

$$\text{WLC} = \sum_{t=1}^N \frac{(c_t)}{(1 + r/100)^t} \quad (1)$$

where

- N = Analysis period (years)
- r = Discount rate (%)
- t = Year of cost/benefit
- c<sub>t</sub> = Cost or benefit (e.g. initial costs, operation & maintenance costs, electricity sold/saved)

Generally, three sets of data are required for whole-life cost analyses, namely:

- cost data,
- performance data,
- discount rate data.

#### B.1.1 Cost data

The cost data covers all costs associated with the installation from conception to decommissioning. The following cost components have been considered for the 2km photovoltaic installation:

- design,
- installation,
- power generated by solar modules (a benefit),
- operation and maintenance,
- decommissioning and salvage (end-of-use).

Traffic management and traffic delay costs have not been included in the analysis, but they should be taken into account for installations near to the highway.

### ***B.1.2 Performance data***

The performance data concerns all aspects of the performance of the photovoltaic installation, as follows:

- the efficiency of the solar modules, including the effects of failure, damage and theft,
- the service life of the modules,
- the service life of the inverters,
- the service life of the cabling and ancillary electrical equipment.

### ***B.1.3 Discount rate data***

In accordance with current Treasury rules, an annual discount rate of 3.5% throughout the accounting period of 30 years has been assumed in the analyses. As the discount rate has fallen from 8% to the current rate over recent years, the factor by which future costs (and benefits) are discounted has decreased significantly. For example, the discounted costs of an operation costing £10,000 after 20 years are £2145 and £5026 for discount rates of 8% and 3.5%, respectively. Therefore, costs incurred and benefits received in the future have a greater effect on the whole-life cost when the discount rate is lower.

### ***B.1.4 Cost and performance data assumed for the photovoltaic installation***

This section describes the cost and performance data not given in Table 1 that have been assumed in order to determine the WLC.

#### ***B.1.4.1 Power generated by panels***

It has been assumed that the power generated by a 2km long photovoltaic installation would be 125MWh in its first year. This amount of power is equivalent to the 54m long trial installation generating 3.375MWh in its first year, whereas the amount of power actually generated was 3.209MWh<sup>3</sup>. The power generated by this particular installation is being exported to the Scottish and Southern Energy PLC low voltage grid.

The current price paid for power generated by non-renewable energy sources is about £20/MWh and this is increased to £60/MWh for suppliers of green energy that have Renewable Obligation Certificates. However it should be noted that there is considerable variation in buy-in prices for renewable energy between the various electricity suppliers.

The power generated could reduce the power that the Highways Agency purchase from an electricity company. The cost saving would be dependent on the unit cost of electricity. Electricity prices from power stations vary according to the time of day and the season. The Highways Agency has several types of electricity supply contract, dependent on the usage. Certain contracts for street lighting are for the supply of unmetered electricity. However, most electricity is metered and is supplied at a fixed rate per MWh, the rate varying with the type of contract. For comparison, prices to domestic users are currently about £70/MWh for the standard day/night rate and £27/MWh for the night rate.

The price of electricity will increase in real terms over the next few years, but increases above the rate of inflation may not be sustained in the long term because of the dependence of the national and world economies on the price of electricity. For the purposes of this study, certain assumptions have been made about the electricity price in order to investigate its effect on the whole-life cost. For some analyses, the electricity price has been assumed to be up to eight times the current price with no

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<sup>3</sup> The predicted output used for the analysis was about 5% higher than that measured, although this was to some extent balanced out as the assumptions of losses of 0.8%/year did not occur in the first two years of service,



increases above the rate of inflation. For others, uniform annual percentage increases over 30 years from the current price up to eight times the current price have been assumed.

Some of the solar modules may fail in service, be damaged by vandalism or be stolen. For these analyses, it has been assumed that the loss of power due to these effects is equivalent to a 1.5% decrease in the initial number of solar modules every 10 years after the first 5 years. Solar modules could be replaced to nullify these effects, but periodic replacement of small numbers of panels is unlikely to be economical.

It has been assumed that because the panels would have a 25-year performance warranty to deliver 80% of their rated power, panels that failed or performed poorly as a result of manufacturing defects would be replaced free of charge. The rate of decrease in the power generated from 100% to 80% has been assumed to be constant over the 25 years (i.e. 0.8%/year). Past experience has shown that panels still provide power long after their warranty period, so replacement is not required immediately after 25 years. It has been assumed that the rate of decrease of power generated would be 1.6%/year after 25 years, and for most analyses, that the panels would be replaced/refurbished after 30 years.

It has been assumed that the inverters would perform with no loss of efficiency until they require replacement. It has not been necessary to take into account the actual efficiency of the inverters, about 93%, because the power generated by the photovoltaic system has been based on measurements made during the site trial for the whole photovoltaic installation. It has been estimated that the time taken to replace a failed inverter (1 week) would result in a loss of power of 0.033MWh, i.e. the loss would be negligible.

If the modules generate 125MWh in the first year, the total generated over 30 years will be 3232MWh if the assumptions described above apply.

#### *B.1.4.2 Operation and maintenance costs*

Operation and maintenance costs could be incurred for:

- washing panels,
- landscaping,
- routine electrical testing,
- replacement of damaged or stolen panels,
- refurbishment of panels at end of useful life,
- replacement of inverters at end of useful life,
- replacement/maintenance of cabling at end of useful life,
- replacement/repair/maintenance of support structure at end of useful life.

#### *Washing panels*

Whereas some contamination of the solar modules has been noted at certain times during the trial, this has been washed off by rainfall. It is likely, however, that some washing will be required periodically so it has been assumed that the 2km long solar array will be washed every five years at a cost of £1000 per operation. No decrease in power generated has been assumed because of the accumulation of contamination on the panels between each wash.

#### *Landscaping*

Vegetation has grown at the trial site and threatened to shade the solar modules. Therefore, vegetation must either be cut back or chemicals must be used to suppress its growth on a regular basis. It has been assumed that such landscaping will cost £2000/year. This cost may not be incurred where the noise barriers are installed in an asphalt or paved surface.

### *Electrical testing*

It has been assumed that the cost of electrical testing will be £500 every 5 years.

### *Replacing panels*

As indicated above, it has been assumed that failed, damaged or stolen solar modules would not be replaced, but the loss in power generated due to such circumstances has been taken into account.

It has been assumed that the solar modules will not be refurbished until after 30 years.

### *Replacing inverters*

The suppliers of the inverters have indicated that their service lives should range from 15 to 25 years.

The service life of each of the 73 inverters required for the 2km installation has been estimated using a random number generation algorithm. For checking purposes, the results based on this method have been compared with those based on an average service life of 20 years, and they have been found to be very similar. The cost of installing and commissioning a replacement inverter has been assumed to be £300. As indicated above, it has been assumed that the time for replacement will result in a loss of power generated equivalent to 0.033MWh (1 week).

### *Replacing/maintaining meter and cables*

It has been assumed that the useful life of the cables from the inverters to the grid connection is 60 years, and that the electrical connections from the solar modules to the inverters will be free of defects until they are replaced at the same time as the modules.

### *Maintaining support structure*

The galvanised steel and alu-zinc support structure should be maintenance free for over 40 years, provided the galvanising layer is not broken down by de-icing salts transmitted by spray, coastal spray or heavy industrial pollution. To minimise or prevent such damage, a high quality protective treatment could be applied to the support structure, but it has been assumed that the support structure will not require an application of a protective treatment until after 30 years.

#### *B.1.4.3 Decommissioning and salvage (end-of-use costs)*

When the solar modules, inverters and support structure have useful years of service at the end of the accounting period, an end-of-use cost has been calculated assuming a linear decrease in their value and installation costs over their assumed service life.

It has been estimated that the cost of removing the inverters from site will be negligible and that they will have no salvage value.

The cost of removing the solar modules and the support structure to clear the site will be significant. However, the modules will have a salvage value as they can be refurbished after the useful life of the photovoltaic material. The support structure will also have some salvage value and, presumably, could be refurbished and used at the same or another site. On this basis, it has been assumed that the salvage value of both the modules and the structure will equal the cost of removing them from the site.

#### *B.1.4.4 Summary*

The power, operation and maintenance, and end-of-use costs and the performance data described above are summarised in Table B1.

**Table B1. Summary of assumed power, operation and maintenance, and salvage costs**

| ELEMENT  | COST (£) | FREQUENCY  |
|--|----------|--|
| <b>Power output</b>  |          |  |
| Power output   | 125MWh   | Annually, but decreasing due to loss of performance, and failure, damage and/or theft<br>Loss due to performance: 0.8% each year for first 25 years, 1.6% each subsequent year<br>Loss due to damage and/or theft: 1.5% every 10 years after 5 years<br>Loss due to inverter replacement: 0.033MWh |
| <b>Routine maintenance</b>                                       |          |  |
| Washing panels   | 1000     | 5 years  |
| Landscaping  | 2000     | Annually   |
| Electrical inspection  | 500      | 5 years  |
| Purchase, installation and commissioning of replacement inverter | 1475     | Randomly between 15 and 25 years   |

### ***B.1.5 Effect of price of electricity on the whole-life cost***

Table B2 shows the variation in the whole-life cost of the photovoltaic installation with the price received for the electricity generated by the solar modules.

As shown in Table 1, the initial cost (the cost of the design, components and their installation) is estimated to be £1,345,800. If the initial electricity price is £60 and there are no increases above the rate of inflation, the net present value (NPV) of the 3232MWh generated will be -£126,600. The NPV of the operation and maintenance costs will be £96,500, comprising £53,800 for the replacement of the inverters, £38,100 for landscaping and £4,600 for washing the panels and electrical inspection. Therefore, the NPV of the electricity generated will exceed the NPV of the operation and maintenance costs by only £30,100. Overall, when the end-of-use costs are taken into account, the whole-life cost will be £1,194,300, i.e. only £150,500 less than the initial costs.

An eight-fold increase in the electricity price to £480 will reduce the whole-life cost to £308,300, but the installation becomes cost effective (i.e. the whole-life cost is less than zero) only if the electricity price is greater than £626. A likely scenario is that the electricity price will increase above the rate of inflation over a number of years. Table B2 shows that a four-fold price increase over 30 years will give an NPV for the electricity generated of -£229,100 and a whole-life cost of £1,091,800, i.e. only £254,000 less than the initial costs.

### ***B.1.6 Effect of the performance of the installation on the whole-life cost***

The whole-life costs given in Table B2 will be lower if the initial cost of the installation is lower or the service life of the components is longer than those assumed so their residual value is higher after 30 years. It is not considered to be appropriate to assume a service life of more than 60 years for the components other than the inverters and the solar modules. If the service life of the modules was increased from 30 to 60 years, the whole-life costs given in Table B2 would be £85,400 lower.

### ***B.1.7 Effect of the cost of the components on the whole-life cost***

The components that have the largest influence of whole-life cost are the support frame and posts, and the solar modules. The initial cost of these components and their installation is about £942,800; approximately £463,500 for the support frame and posts and approximately £479,300 for the modules. If these costs are reduced by 50% and the design costs and end-of-user costs are reduced accordingly, the initial cost of the installation will be £850,800 and the whole-life cost will be £740,600 if the solar modules have a service life of 30 years. The installation will be cost effective if the electricity price was greater than £411/MWh, assuming no price increases above the rate of inflation.

**Table B2. Variation in whole-life cost with price of electricity**

| <b>ELECTRICITY PRICE (£/MWh)</b>        | <b>WHOLE-LIFE COST (£)</b> | <b>NET PRESENT VALUE OF POWER GENERATED (£)</b> | <b>NET PRESENT VALUE OF OPERATION AND MAINTENANCE (£)</b> | <b>NET PRESENT VALUE OF DECOMMISSION AND SALVAGE (£)</b> |
|---|----------------------------|---|---|--|
| 60                                      | 1,194,200                  | -126,600  | 96,500  | -121,500   |
| 120                                     | 1,067,700                  | -253,100  | 96,500  | -121,500   |
| 240                                     | 814,500                    | -506,300  | 96,500  | -121,500   |
| 480                                     | 308,300                    | -1,012,500                                      | 96,500  | -121,500   |
| Increasing from 60 to 120 over 30 years | 1,153,800                  | -167,000  | 96,500  | -121,500   |
| Increasing from 60 to 240 over 30 years | 1,091,700                  | -229,100  | 96,500  | -121,500   |
| Increasing from 60 to 480 over 30 years | 993,900                    | -326,900  | 96,500  | -121,500   |

### ***B.1.8 Conclusions***

The whole-life cost analyses have shown that, for the assumptions made, the initial installation costs of the photovoltaic installation will be far greater than the cost of the power generated by the solar modules. This is the case even assuming increases in the price of electricity significantly above the rate of inflation, and/or significant reductions in the costs of the components. Therefore, it is concluded that it is unlikely that an investment in a photovoltaic installation will give any financial benefits unless the initial cost of the installation and its operation and maintenance are considerably lower than those assumed and/or there are significant environmental cost benefits or subsidies that have not been taken into account in these analyses.

The above conclusion is based purely on photovoltaic and energy production criteria, no allowance is made for the added value of the barrier in its noise reducing capacity. This factor is separately considered in Section 6.1.2. Also considered in Section 6.1.3 is the added value when electricity is required at a remote location on the highway network, where the cost of cable laying would outweigh other considerations.

### ***B.1.9 Reference***

**Tilly G (1995).** *The implications of whole-life costing.* Proceedings of Concrete Bridge Development Group seminar on whole-life costing. TRL Limited, Wokingham.

## **Appendix C. Evaluation of driver behaviour**

by T Brightman (TRL Limited)

### **C.1 Introduction**

The Highways Agency is currently investigating the generation of electricity from large solar panel arrays installed on land adjacent to existing motorways. TRL were commissioned to carry out a demonstration trial which involved the installation of a 54m long by 1.8m high solar panel array as a south facing noise barrier next to the M27 motorway at junction 9.

As part of the research, a study was carried out into the potential impact of the array on road safety. In particular, there was a concern that the array may prove distracting to drivers and as a result may lead to a general reduction in safe driving at the site. The solar array is blue in colour and, although generally non-reflective, can have a slightly shimmering appearance at times.

This document outlines the study that was undertaken and reports on its results.

### **C.2 Experimental design**

Three experimental designs were considered for this study. The first involved utilising the TRL driving simulator. Here subjects would 'drive' past a 3-dimensional computer simulation of the site. The speed and position of their vehicle would be analysed along with their individual reactions to the array. The latter would be achieved by video recording the facial expressions and eye movements of the subjects as they passed the array.

Although the design of the experiment was sound, it was ruled out on cost grounds. It was also considered that the model of the solar panel array would not be realistic enough.

A second design involved collecting speed and lateral displacement directly from the road. This would have involved disrupting the flow of traffic as inductive loops were installed. This option was considered unacceptable because of the disruption it would cause.

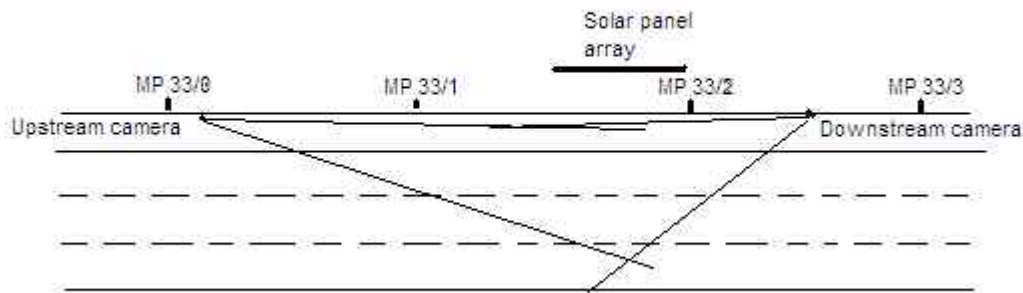
A third design involved using video cameras to record vehicles as they passed the array. The video tapes would then be studied and conclusions drawn. The advantage of this experimental design was that 'real' data could be collected before and after solar panel installation. After careful consideration it was decided that this approach was the most appropriate at this particular site.

### **C.3 Data collection**

The study utilised two video cameras, one mounted upstream of the solar panel site, located just above the safety barrier, and one mounted downstream on a 5m high mast.

The upstream camera filmed vehicles from the rear as they approached the site. The downstream camera filmed vehicles from the front as they approached the site.

The upstream camera was mounted at marker post MP 33/0A, and the downstream camera was mounted about halfway between MP 33/2A and 33/3A. The solar panel array is located up just before MP33/2A as shown in Figure C1.



**Figure C1. Location of video cameras and fields of view.**

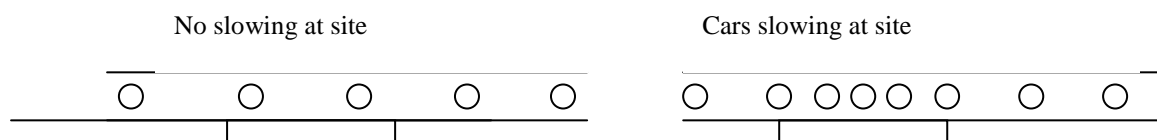
Video recordings were carried out on three separate days. Two of these (23<sup>rd</sup> December 2003 and 19<sup>th</sup> January 2004) were before the installation of the solar panels. The third (13<sup>th</sup> May 2004) was undertaken a number of weeks after the array had been installed.

On each of these days, recordings were made from both cameras from 0800 to 1600 hours.

#### **C.4 Choice of analysis parameters**

It was hypothesised that the solar array would have some measurable impact on driver behaviour which could be measured from the video footage. Several parameters were considered for analysis. Of these, three were considered in more detail.

- *Brake application:*  
By analysing the proportion of the drivers that applied their brakes at the site before and after the installation of the solar panel array, it would be possible to determine whether there had been any difference in braking behaviour (which in turn would be a measure of the level of distraction).
- *Vehicle speed:*  
By sampling the number of cars in a set area of the carriageway at a given moment it is possible to indirectly measure speed of cars at the site. If cars slow at the site more cars will be found within the area approaching the site at any given instant (see Figure C2).



**Figure C2– Car sampling.**

- *Lateral displacement:*  
Distraction caused by the solar panel array may lead to a greater variation in the lateral displacement of vehicles passing the site. For example, it may lead to more vehicles travelling along the rumble strip between the hard shoulder and lane 1.

After considering the benefits and difficulties associated with measuring these parameters from video footage it was decided to first concentrate on the brake application parameter before moving onto or considering the others.

Although it could be argued that the measurement of all the above parameters are dependent on the flow levels being similar before and after, it was considered that the derivation of speed from video footage was likely to be the most sensitive to changes and composition of flow. Only large lateral displacements could be identified with confidence from the video footage.

### C.5 Analysing the videos

In order to best compare the video footage before and after the installation of the array, it was decided to concentrate on periods when the conditions at the site were as similar as possible before and after. This involved matching light levels, weather conditions, and traffic volumes.

The use of the above factors revealed that the most comparable before and after video footage was recorded on the afternoon of the 19<sup>th</sup> January 2004 and the afternoon of 13<sup>th</sup> May 2004 respectively.

Random 15 minute intervals from these periods were sampled, counting total traffic flow and number of drivers applying the brakes. These samples were then compared to look for any difference in braking behaviour that might indicate driver distraction at the solar panel array site.

### C.6 Results

Table C1 shows the counts of all the vehicles passing the solar panel array site in five randomly selected 15 minute periods. Also included in this table is the number of these vehicles that had their brakes applied.

**Table C1. Counts of vehicles passing the site and vehicles with brakes applied**

| Sample | Before array installation |         | After array installation |         |
|--------|---------------------------|---------|--------------------------|---------|
|        | Vehicles                  | Braking | Vehicles                 | Braking |
| 1      | 594                       | 8       | 617                      | 6       |
| 2      | 609                       | 5       | 595                      | 8       |
| 3      | 687                       | 9       | 722                      | 9       |
| 4      | 610                       | 6       | 601                      | 5       |
| 5      | 596                       | 6       | 589                      | 7       |

From Table C1 it can be seen that for each sampling period approximately the same numbers of vehicles passed the site before and after the installation of the array. The same is true for the number vehicles where brakes were applied. This suggests that there is no difference in braking behaviour.

A Chi<sup>2</sup> test was performed on the data presented in Table C1. The hypothesis was that there was a difference in the pattern of braking before and after the installation of the array. The result proved non-significant indicating that there is no evidence of a difference in braking pattern.

### C.7 Observations

Two of the 15 minute samples, one before and one after array installation, were observed carefully for unusual behaviour that might indicate driver distraction. This included actually observing what the

drivers were doing. No change in behaviour was noted. There were incidents involving cars merging onto the motorway from the slip lane just before the trial site, but these were observed on both videos and can be considered “normal driving” that would not have been influenced by the presence of the solar panel array.

## **C.8 Conclusions**

Under similar road and weather conditions, there is no significant difference in braking behaviour with or without the presence of the solar array. Additionally there is no observed driver behaviour that might indicate driver distraction.

The solar array was separated from the motorway by an unused access road. It is possible that the array may have been more distracting if placed closer to the side of the road.

There is also the possibility that, although the solar panels are essentially non-reflective, the slightly shimmering appearance of the solar panels (which occasionally occurs) could prove distracting at certain times of day. This effect was not observed during the trials. Therefore, it was not possible to determine if this was likely to cause any distraction to drivers.



## Appendix D. Evaluation of noise implications

by R King, G Watts and P Abbott (TRL Limited)

### D.1 Introduction

An important issue with regard to the construction of noise barriers alongside roads is the potential for increasing the noise received at properties situated along the opposite carriageway. If this increase was found to be significant there would be concerns that there would be a degree of public dissatisfaction with such installations. There have been several studies to estimate the increase in noise from road traffic due to reflection effects associated with noise barriers. A full-scale measurement survey was carried out by TRL in the mid-1970's along the M6 at Perry Bar before, during and after the construction of a 3m-high noise barrier erected along both sides of the carriageway. One of the conclusions from this survey was that any increase in noise along the opposite carriageway due to reflections from the adjacent noise barrier was less than 1dB(A) (Nelson et al, 1976). A more recent study on the M4 which controlled for wind direction and strength and used a control microphone similar to that in the present study concluded that a vertical reflective barrier 3m tall increased the average noise levels  $L_{Aeq}$  by  $0.50 \pm 0.15$ dB at a 2m high receiver near the edge of the opposite carriageway when compared with a highly sound absorptive barrier (Watts and Godfrey, 1999). This sets an upper limit to the differences that can be expected from the presence of the barrier in the present study. In a previous phase of the study numerical modelling of tilted barriers using the boundary element method (BEM) has indicated a very small increase of less than 0.1dB(A) can be expected due to the presence of a 2m high tilted barriers inclined at 20 and 30 degrees (Watts and Morgan, 2003).

The following sections of this appendix describe a noise survey which was designed to estimate the increase in noise at a site located on the far side of the road adjacent to where the solar panels were constructed, to compare the results with predictive estimates and to report on the likely impact on public perception. The first section describes the experimental design including a description of the site and details of the surveys carried out. This is followed by a section describing the analysis and results from the survey, followed by a summary and conclusions.

### D.2 Experimental Design

This section describes the experimental design, which was tailored to the location of the site where the panels were constructed and to the time and constraints set by the project.

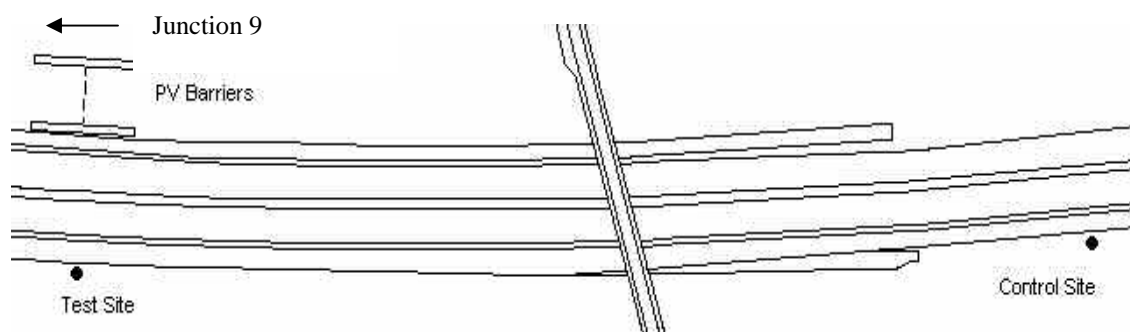
For optimum efficiency in power output, the panels are best-suited to be installed at a south-facing location. The site chosen on the M27 near Junction 9 is where the road is in-cutting and depending on the type of soil and condition of the cutting may provide some reflection of the noise from road traffic, although the slope of the cutting is likely to reflect this noise away from measurements sites alongside the opposite carriageway i.e. at the foot of the opposite slope.

The generation and propagation of road traffic noise is dependent on many different variables including the volume, composition and speed of the traffic flow; the site layout conditions including features which may cause noise to be reflected towards the receiver as well as meteorological factors such as precipitation, wind speed and direction which effect propagation. To estimate the change in noise level due to the reflection from a barrier erected on the far side of the carriageway would normally require long term monitoring to enable before and after noise levels to be normalised under the same traffic and meteorological conditions. Due to project time and cost constraints an alternative approach was adopted.

The experimental design was based on comparing traffic noise levels at two similar locations, a test site where the solar panels were erected and a control site about 500m due west of the test site where the site layout was similar i.e. in-cutting. Simultaneous noise measurements carried out before and after the solar panels were constructed would provide a direct comparison of the reflection effects of

the panels on road traffic noise. Adopting this method of approach assumes that although the sites were similar, any differences would be negligible on traffic noise levels. It was considered that providing the traffic noise samples were sufficiently long and the traffic dense but moving steadily, differences in traffic variables or traffic distribution across the carriageway due to the time difference for individual vehicles to travel between the sites could be safely ignored.

Figure D1 shows a plan of the M27 east of Junction 9 where the noise surveys were carried out. Included in the Figure are the locations of the PV barriers, the test site opposite the mid point of the barriers and the location of the control site which was positioned about 500m east of the test site. It can be seen that there is an off-ramp at both control and test sites. As vehicles must decelerate it is likely that under free flow conditions vehicles passing the control site will be travelling slower than at the test site and therefore emitting less noise. However, it was considered that during most of the day the flows leaving were relatively low compared with the total flow on the main carriageway so this difference was not thought to introduce significant bias into the results. During off-peak periods it is possible that the vehicles leaving the motorway may have greater influence and so the difference between control and test noise levels may change. There is some evidence for this effect when the differences at different noise exposure levels are compared (see Section D7).



**Figure D1. Plan view of M27 survey sites**

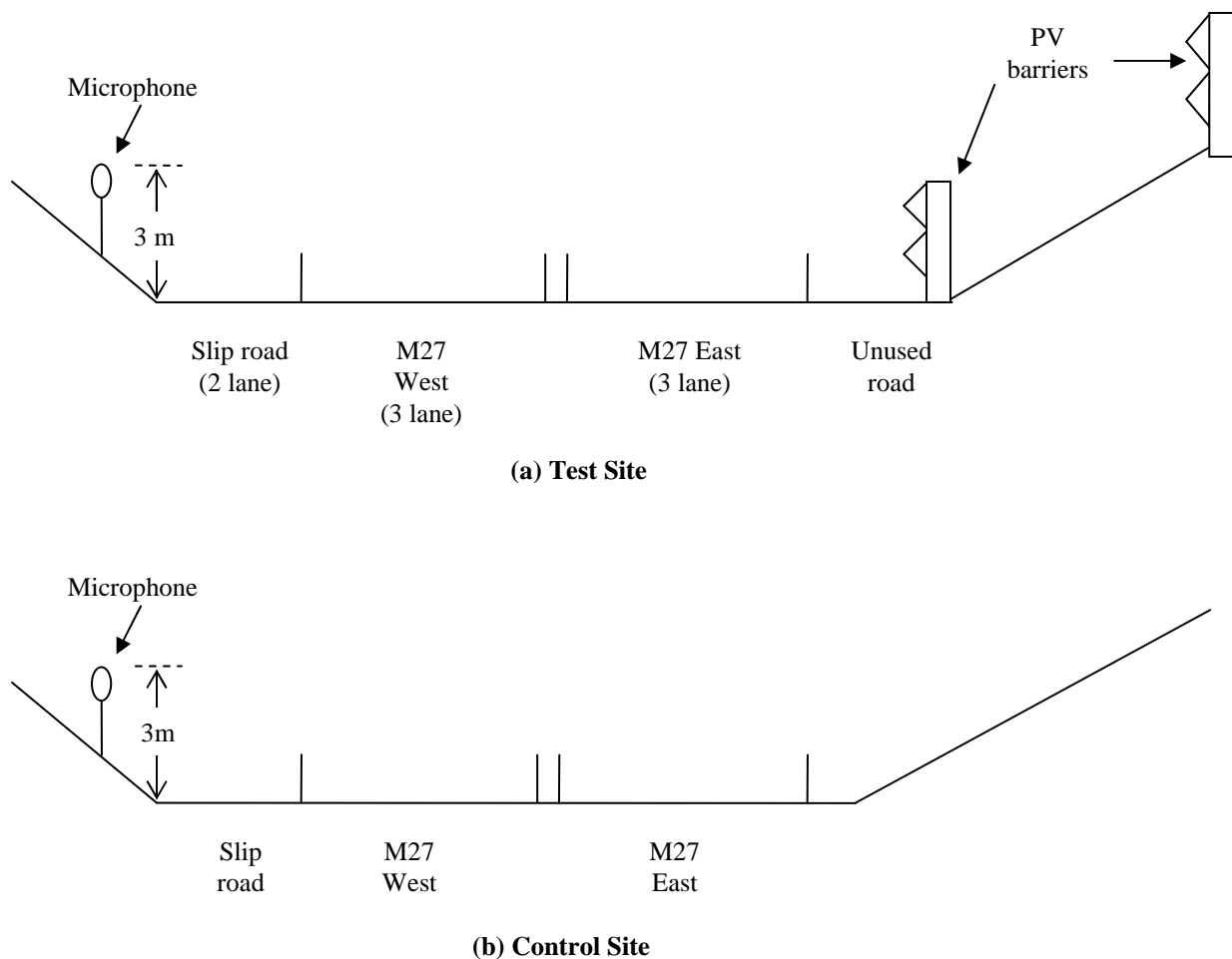
Figure D2 (a) and (b) show a cross-section through both the test and control sites, respectively.

At each site a noise logger and microphone were positioned at similar distances from the edge of the slip road on the westbound carriageway with the height of the microphone at 3m above the road surface. The microphones were fitted with windscreens to prevent the influence of wind turbulence affecting the noise recordings. It is clear from Figure D2 that the site layout prior to erecting the solar panels alongside the eastbound carriageway adjacent to the location of the test site was similar.

Table D1 provides details of when the noise surveys were carried out. Prior to the installation of the solar panels a before survey was carried in December 2003 at both the test and control sites. Similar noise surveys were carried out 3 months later at the same microphone positions after the solar panels were erected.

**Table D1. Date of noise surveys**

| Survey | Date of Survey  |
|--------|---|
| Before | 17 <sup>th</sup> December 2003 – 26 <sup>th</sup> December 2003 |
| After  | 17 <sup>th</sup> March 2004 – 26 <sup>th</sup> March 2004       |



**Figure D2. Cross-section view through test and control sites**

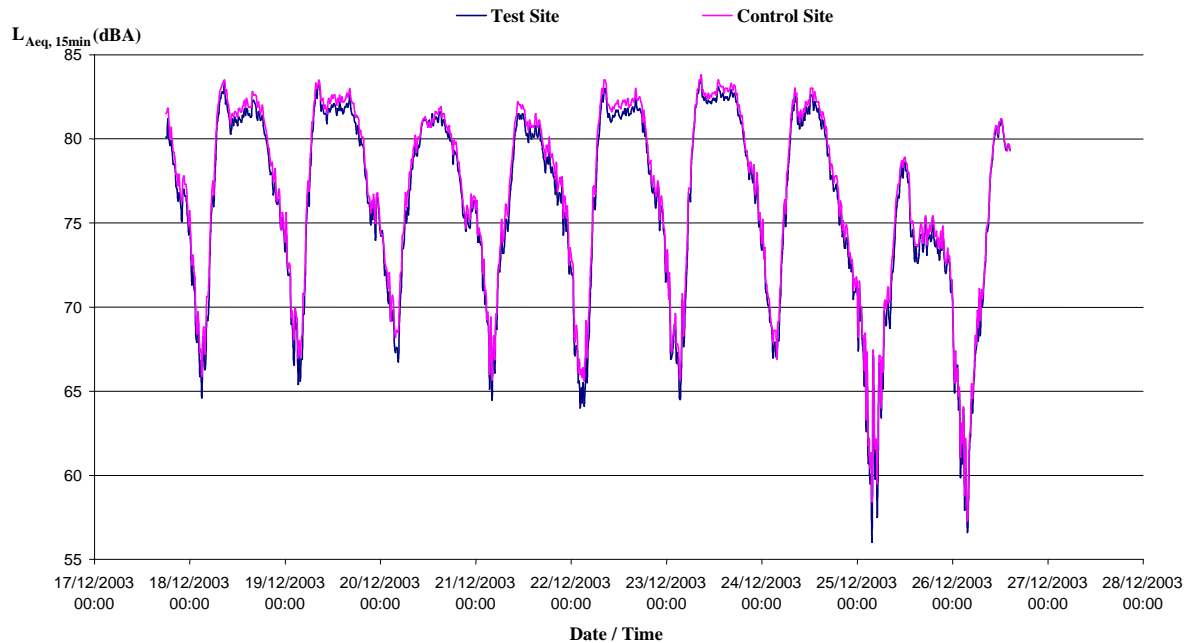
During each survey at both the test and control sites the microphones were connected to an environmental sound level meter capable of being left unattended for long periods of time. The instruments were configured to record the standard noise indices for traffic noise assessment<sup>4</sup>. Traffic noise levels were sampled over a period of 15 minutes, continuously over the time periods shown in Table D1. A sampling period of 15 minutes was adequate to ensure that traffic conditions at each site during a sample period were similar and that a sufficient number of samples were collected for the purposes of statistical comparison. All samples were recorded on the A-weighted scale and were downloaded via a modem link, enabling the instruments to be unmanned for the entire survey duration. Prior to each survey period the instruments were calibrated using a known sound source and subsequently checked after each 24-hour period of monitoring and at the end of each survey.

<sup>4</sup> In the UK, the noise index used for assessing the environmental impact from road traffic noise is based on the  $L_{A10,T}$  scale and is defined as the noise level exceeded for 10% of the time within a time period T, normally 1 hour. The symbol 'A' refers to the requirement that the frequency response should be A-weighted i.e. that the response of the recording equipment approximates to that of the human ear. Elsewhere in Europe, the index used is based on the  $L_{Aeq,T}$  scale which is the equivalent steady noise level that has the same energy as the time varying noise level in a time period T. For road traffic under steady flow conditions, differences in noise levels measured on either of these scales is numerically similar.

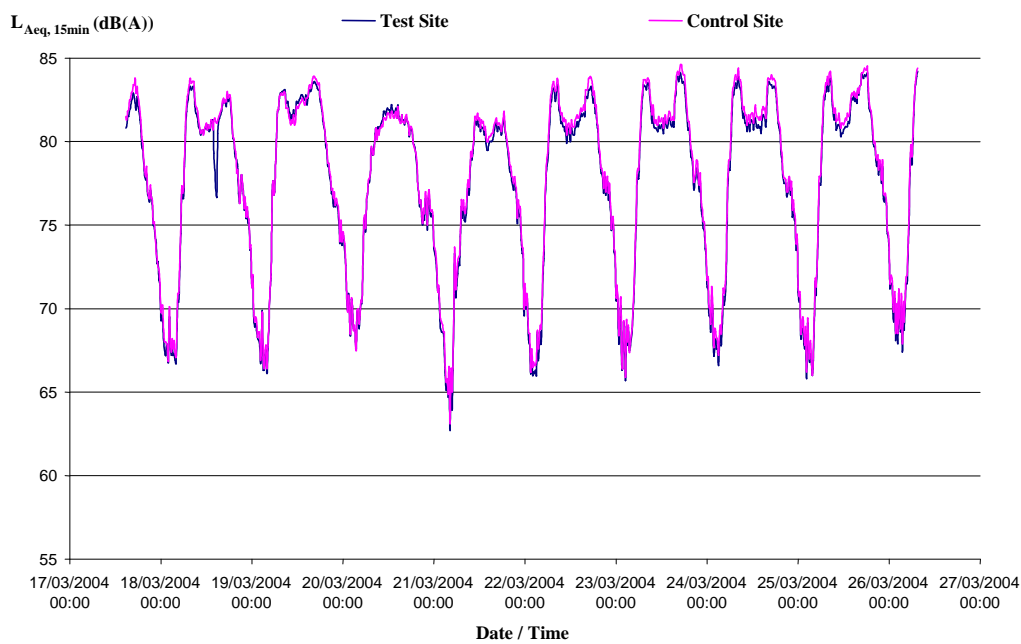
### D.3 Results

The analysis of the data initially consisted of plotting the sampled noise levels recorded in each period throughout the total period of each survey carried out at each site.

Figure D3 shows the variation in noise levels,  $L_{Aeq,15min}$ , recorded during each survey at each site.



(a) Before survey



(b) After survey

Figure D3. Variation in 15 minute sampled noise levels during each survey at both sites

During both the before and after noise surveys the variation in noise levels at each site is very similar and generally, noise levels at the control site were marginally higher than those recorded at the test site. During the before survey these differences may be attributed to small differences in the site layout between the two sites. As the microphones in both surveys at each site were located in the same positions, a comparison of the differences in noise levels between sites during the before and after surveys provides an estimating of the influence of the solar panels on traffic noise levels recorded on the far side of the motorway at the test site.

It should also be noted that the daily variation in noise levels follow closely the traffic flow pattern expected over the 24-hour period. Where noise levels rise and fall comparatively steeply provides an indication of similar variations in traffic flow e.g. during the night time period and during the morning and evening rush hour periods. From the before survey, samples recorded between 10:00 to 16:00 on 18<sup>th</sup>, 19<sup>th</sup>, 22<sup>nd</sup> and 23<sup>rd</sup> December were selected and similarly from the after survey corresponding samples on 22<sup>nd</sup> to 25<sup>th</sup> March were selected. It can be seen from Figure D3 that during these periods traffic noise levels were high and reasonably steady and that traffic conditions were most likely to be the same at both sites during each survey sample i.e. relatively high volumes and similar speed and composition. The reasoning behind the selection of this sub sample is described more fully in the annex to this appendix.

Under low flow conditions individual vehicles may dominate average levels and because such vehicles may use the off-ramp and travel at different speeds past the control and test sites, as noted earlier, this may lead to bias. In addition under low flow conditions relatively loud extraneous noise such as aircraft noise may dominate the average levels influencing the measured differences between sites. Other possible factors affecting the results are meteorological factors especially changes in wind vector. Where the wind direction is from the source to the receiver, noise levels can increase over those recorded under neutral conditions. Sound reflected upwards from the tilted PV barriers could curve back towards the ground under adverse conditions resulting in higher noise levels.

Table D2 shows the results of the statistical analysis carried out on all and the selected samples which used the statistical t-test to establish whether the change in the average difference between surveys was significant i.e. unlikely to be due to chance. The results show that prior to the installation of the PV barrier the average difference in noise levels between the test and control sites was 0.60dB(A) and that after the installation this difference was reduced to 0.30dB(A) i.e. the installation of the barriers apparently increased noise levels by 0.30dB(A). Using the statistical t-test, this mean difference between the two surveys was shown to be statistically highly significant at the 0.1% level. Using the restricted data set the estimated increase was smaller at 0.08dB(A). Again this difference is statistically highly significant.

**Table D2. Results of statistical analysis on selected sample**

| Survey        | Average difference<br>(Test – Control) | Standard deviation | Sample size | Change in<br>difference <sup>1</sup> |
|---------------|--|--------------------|-------------|--------------------------------------|
| <i>Before</i> |  |                    |             |                                      |
| All           | 0.602                                  | 0.350              | 851         | -                                    |
| Selected      | 0.502                                  | 0.113              | 125         | -                                    |
| <i>After</i>  |  |                    |             |                                      |
| All           | 0.304                                  | 0.252              | 828         | <b>0.298</b>                         |
| Selected      | 0.419                                  | 0.142              | 100         | <b>0.083</b>                         |

<sup>1</sup> Mean difference between surveys is highly significant at the 0.1% level.

Although the results from this analysis supports the view that the PV barrier has a significant influence to increase noise levels on the farside of the motorway, any increase in noise at this site is small, less than 0.5dB(A). The exact increase will depend on traffic volume and weather conditions.

As noted in the Introduction the result of modelling work using BEM (Watts and Morgan, 2003) showed an estimated increase of 0.06dB(A) for a 2m high barrier tilted at 20 degrees and 0.03dB(A) when tilted at 30 degrees. The results from the measurement survey using the restricted data set (0.08dB(A)) are comparable to these low values. Note that BEM predictions were for a neutral atmosphere and for a continuous line source. Under windy conditions and low flow these assumptions are no longer valid and higher values may result.

#### D.4 Summary and Conclusions

A noise survey was carried out on the westbound carriageway of the M27 adjacent to the site where a PV barrier was installed as a trial demonstration of the use of a photovoltaic (PV) system in a highway situation e.g. incorporated into the design of noise barriers. An important aspect of this work was to assess the potential public response to the installation of the PV (solar panels) barrier including possible noise impacts.

Results from surveys carried out prior to and after the construction of the barrier showed that:

- Although it was found that the PV barrier at this site does increase traffic noise levels on the opposite side of the motorway, the average increase over all periods sampled was 0.3dB(A) and would not be expected to cause any change in the disturbance from road traffic noise.
- The results for high steady traffic flow conditions are comparable with predictions made with the boundary element method i.e. less than 0.1dB(A).
- Under relatively low flow conditions and under adverse wind conditions higher values may result. The exact size of the effect is difficult to quantify because traffic volume and weather conditions that may have introduced these changes under low flow conditions were not recorded as part of this limited study. However a previous study of the effects of a 3m tall plane reflective barrier under a range of wind conditions indicated an increase of  $0.5 \pm 0.15$ dB(A) when normalised to zero wind speed. In the current study the effects of tilting the barrier would be expected to reduce the contribution to below 0.5dB(A) under similar conditions.

#### D.5 Acknowledgements

The work described in this report was carried out in the Environment Group of TRL Limited. The authors are grateful for the assistance of Mr M Balsom in the measurement surveys.

#### D.6 References

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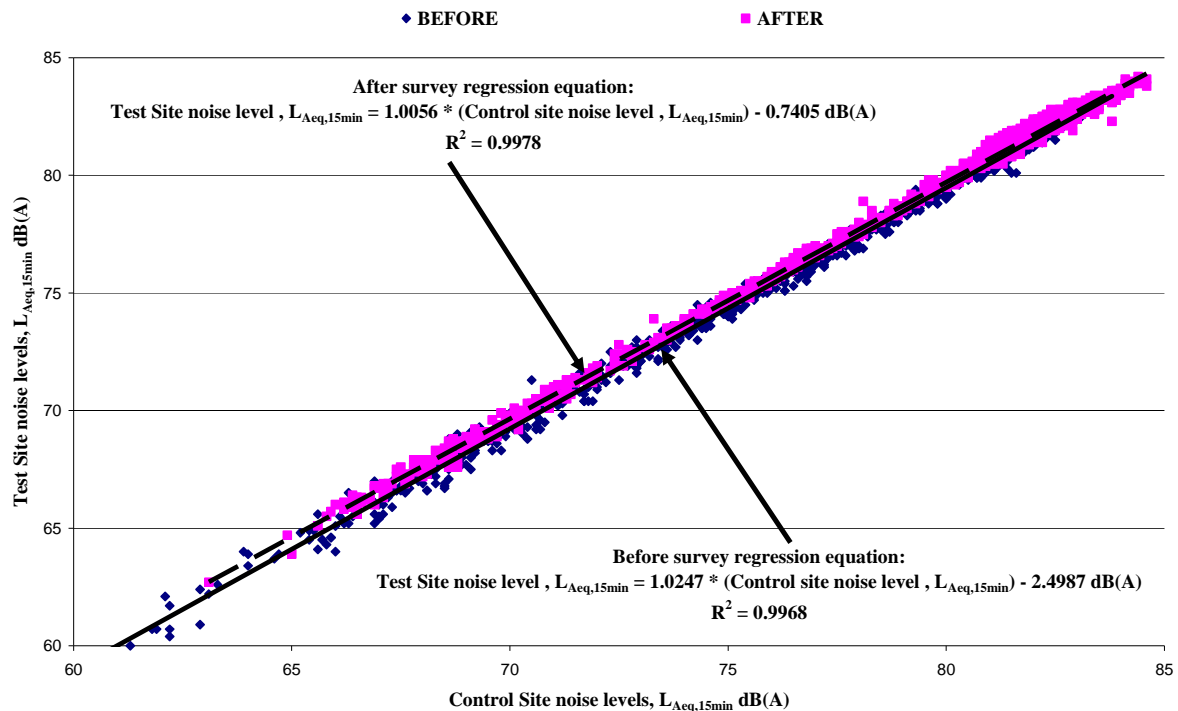
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## D.7 Annex: Analysis of samples under steady high flow conditions

Figure D4 shows the relationship between the noise levels recorded at the control site with corresponding levels collected at the test site during the entire duration of each survey.



**Figure D4. Relationship between noise recorded at control and test sites throughout each survey**

The Figure clearly illustrates that there is a high correlation between noise levels at each site during both surveys. Comparing the regression lines shows that after the solar panels are installed noise levels at the test site increased relative to the noise levels recorded at the control site. However, the small differences in the slope of the regression lines suggest that this increase is possibly dependent on traffic flow<sup>5</sup>. If traffic conditions during each paired sample were not identical then the true magnitude of the influence of the solar panels on the reflected noise may not be accurately quantified. It was considered that reducing the sample size to include only times of the day when traffic flows are high and relatively steady will help to reduce these bias effects.

Figure D5 shows the same relationship based on samples selected only from the hours between 10:00 to 16:00 hours on normal weekdays when traffic flows are high and reasonably stable and there is little variation in traffic noise levels<sup>6</sup>. Again, the noise levels recorded at each site during both surveys are highly correlated. However, unlike the previous analysis the slopes of the regression lines are very similar and it would be expected that the influence of any differences due to variations in traffic flow has been significantly reduced. This reduced sample was also used in the statistical analysis described in Section D3 to establish whether the average difference in noise levels recorded at the control and

<sup>5</sup> The regression lines move further away from each other as noise levels decrease due to lower traffic flows.

<sup>6</sup> Traffic during the weekends and weekday traffic which may have been affected by the Christmas holidays were excluded i.e. 24<sup>th</sup> – 26<sup>th</sup> December 2003. In addition, it was also noted that on the 18<sup>th</sup> and 19<sup>th</sup> March 2004, see Figure 3.1(b), traffic noise levels during the day were not stable and this data was also excluded from analysis.

test sites for the surveys carried out before and after the solar panels were installed are statistically significant.

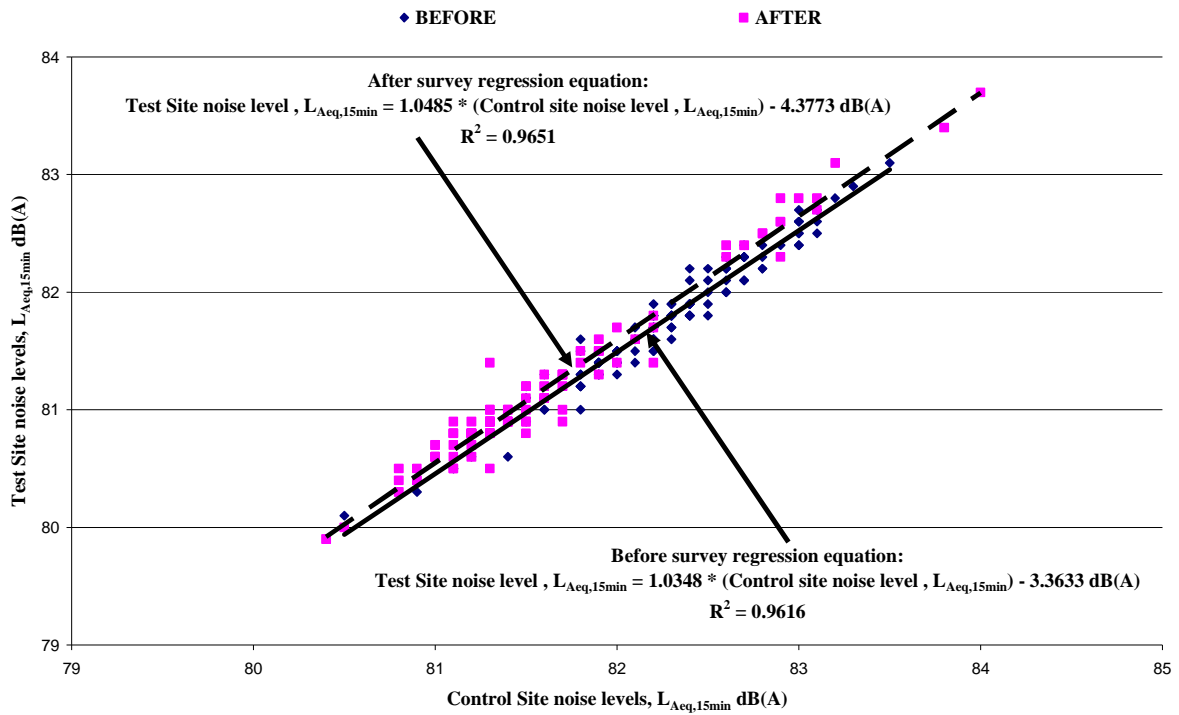


Figure D5. Relationship between noise recorded at control and test sites from selected samples